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San Luis Basin Sustainability Metrics Project: A Methodology for Evaluating Regional Sustainability

Office of Research and Development
National Risk Management Research Laboratory

Front Cover Photo Credits

Top - Medano Creek; Photo M. Hopton; Intermittent flow of Medano Creek in the Great Sand Dunes National Park and Preserve, San Luis Valley, Colorado.

Bottom Left - solar panel close-up; Photo by A. Karunanithi; Solar panel at a solar farm under construction in the San Luis Valley.

Bottom Right - SLV Potato Harvest; Photo by Stephen Ausmus; Potatoes being harvested in the San Luis Valley of south-central Colorado. Rotating potatoes with cover crops provides many benefits, including nitrogen management, improved soil and water quality, and bigger potatoes and higher yields. http://www.ars.usda.

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Table of Contents

List of Tables

List of Figures

List of Abbreviations

aa_i	Area Appropriated Per capita
ARS	Agricultural Research Station
bc	Biocapacity Per Capita
BC	Biocapacity for the Population
BEA	Bureau of Economic Analysis
BLM	Bureau of Land Management
C	County
CDSS	Colorado's Decision Support System
CDWR	Colorado Division of Water Resource
CFC	Consumption of Fixed Capital
C_i	Consumption Item
CO_2	Carbon Dioxide
CON	Consumption
CPP	Community Partnership Program
CSERGE	Center for Social and Economic Research on Global Environment
CWCB	Colorado Water Conservation Board
DEM	Demographic
Dwt	Dry weight
EBT	Estimated by Team
EF	Ecological Footprint for population
ef	Ecological Footprint per person
EFA	Ecological Footprint Analysis
EGY	Energy
EIA	Energy Information Administration
ELR	Environmental Loading Ratio
EmA	Emergy Analysis
ENV	Environmental
ESI	Emergy Sustainability Index
EST	Energy Systems Theory
ET	Evapotranspiration
ExA	Exergy Analysis
EYR	Emergy Yield Ratio
FS	Forest Service
FI	Fisher information
<FI>	mean Fisher information
GDI	Gross Domestic Income
GDP	Gross Domestic Product
gha	Global Hectares
GI	Global Insight
GNDP	Green Net Domestic Product
GNRP	Green Net Regional Product
GRP	Gross Regional Product
GS	Genuine Savings
GSA	General Service Administration
GUI	Graphical User Interface
I	Fisher Information (historical usage)
ha	Hectares
LEI	Local Effect of Investment
MBF	Million Board Feet
Misc	Miscellaneous
MLRA	Major Land Resource Area
MSY	Maximum Sustainable Yield
NAICS	North American Industry Classification System
NASS	National Agricultural Statistics Service
NDP	Net Domestic Product
NGO	Non-governmental organization
NRCS	Natural Resource Conservation Service
NRI	National Resource Information
NRP	Net Regional Product
ORD	Office of Research and Development
PI	Personal Income
PCA	Principal Components Analysis
PROD	Production
R	Region
S	State
sej	Solar Emjoule
SIC	Standard Industrial Classification
SLB	San Luis Basin
SLV	San Luis Valley
U	Emergy Use
USDA	United States Department of Agriculture
USEPA	United States Environmental Protection Agency
UN	United Nations
WEQ	Wind Erosion Equation
WERU	Wind Erosion Research Unit
Wwt	Wet weight

Foreword

The U.S. Environmental Protection Agency (USEPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, USEPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

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This publication has been produced as part of the Laboratory's strategic long-term research plan. It is published and made available by USEPA's Office of Research and Development to assist the user community and to link researchers with their clients.

Sally Gutierrez, Director

National Risk Management Research Laboratory

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Abstract

Sustainability relates to finding and maintaining conditions that can support social and economic development without adversely altering the environment to too great an extent. Moreover, in order to satisfy the definition of sustainability, the environmental, social, and economic characteristics of the system must effectively meet the needs of current and future generations, indefinitely. Our definition of sustainability depends on the extent to which the environment can be altered and still maintain a high quality of life for people, without jeopardizing the quality of life for future generations. Consequently, to assess sustainability, information is needed to understand the requirements for human well-being and the linkages and demands of human activity (e.g., society, economy, government, industry, etc.) on environmental systems. One way to collect needed information is through metrics that quantify the environmental, social, and economic characteristics of a system. We used a collaborative, interdisciplinary approach to investigate this complex problem. Specifically, we set out to: 1) determine the applicability of using existing datasets to estimate metrics of sustainability at a regional scale, 2) calculate the metrics through time (1980-2005), and 3) compare and contrast the results to determine if a regional system is moving toward or away from sustainability. This information can help decision makers determine if their region is on a sustainable path (i.e., moving toward sustainability).

As a starting point, we identified and tested a set of four metrics that capture some of the most basic properties of an environmental system. The metrics represent: 1) ecological impacts of human activity to produce the resources consumed and to assimilate the wastes generated using Ecological Footprint Analysis; 2) economic well-being or welfare with Green Net Regional Product; 3) flow of available energy through the system using Emergy Analysis; and 4) overall system order with Fisher information (i.e., a well-functioning system is orderly and departure from such a state can lead to decreased function). Each of these metrics is most sensitive at capturing some particular aspect of the system, although there is some overlap or redundancy (e.g., consider a physician using multiple tests to examine a patient's health). We tested the methodology on the San Luis Basin (SLB) in south-central Colorado. The SLB is a rural, agricultural region with a limited population. This seven county region contains the Upper Rio Grande River Basin, the San Luis Valley, and the Great Sand Dunes National Park and Preserve.

Even though data for some of the variables were not available at the county level, we were able to calculate the metrics through time. From our analyses, Ecological Footprint Analysis indicated the SLB was moving away from sustainability. Green Net Regional Product appears to have an upward trend over the 26-year period providing no indication that the SLB was moving away from sustainability (this one-sided test can only tell if a system is moving away from sustainability). Due to data unavailability, a complete Emergy Analysis was estimated only for an 11-year period (1995-2005). One emergy index (fraction of renewable emergy used) that captures sustainability within the system suggested a gradual movement away from sustainability, but a second index (Emergy Sustainability Index) revealed the region improved its relationship with the larger system, (i.e., other states and US) from 2003 until the end of the period. Finally, the results of the Fisher information assessment revealed that, although the system was relatively stable during the 26 years, there was an indication of slight movement away from sustainability near the end of the study period.

We consider the entire system moving away from sustainability if any one metric reveals movement away from sustainability. Therefore, the weight of the evidence from our results indicate that the broad trend of the SLB was moving away from sustainability over the period examined. Because this was a pilot study, we offer a number of recommendations for future research based on what we learned while developing and using this approach.

Executive Summary

ES.1 Introduction

There are several established, scientifically supported metrics of sustainability. Many of these metrics require extensive data collection and detailed computations. Moreover, it is difficult for one metric to capture all aspects of a system that are relevant to sustainability. A pilot project was initiated to test an approach to measure, monitor, and maintain prosperity and environmental quality in the context of sustainability for a regional system. Sustainability relates to finding and maintaining conditions that can support social and economic development without adversely altering the environment to too great an extent. The goal of this study was to produce a straightforward, relatively inexpensive methodology that was simple to use and interpret. This approach required historical data to be readily accessible, that metrics be applicable to the relevant scale, and that results meet the needs of decision makers.

Because sustainability is a multidimensional concept, the research group consisted of an interdisciplinary team in which the members represented expertise associated with several fundamental components of an environmental system. This project utilized available environmental, economic, and social data to calculate four sustainability metrics: 1) environmental footprint as characterized by Ecological Footprint Analysis (EFA), 2) economic well-being as ascertained from Green Net Regional Product (GNRP), 3) energy and emergy flow through the system as computed from an Emergy Analysis (EmA), and 4) dynamic order estimated from the computation of Fisher information (FI).

The San Luis Basin (SLB), a region in south-central Colorado, was selected as the pilot study area because of its natural hydrological boundaries, limited population, large amount of publicly owned land, and interest expressed in the study by USEPA Region 8 and other government officials. We define the SLB as the following seven counties: Alamosa, Conejos, Costilla, Hinsdale, Mineral, Rio Grande, and Saguache. This region contains the Upper Rio Grande River Basin, the San Luis Valley, and the Great Sand Dunes National Park and Preserve.

ES.2 Sustainability Metrics

We reviewed the literature to summarize different metrics that quantify the major components of an environmental system. This resulted in a review of potential metrics for this pilot study. We reviewed studies that examined sustainability using multiple metrics and studies that measured sustainability over time. Both are important attributes of the *San Luis Basin Sustainability Metrics Project.*

No single metric should be considered a perfect measure of sustainability because of the multiple definitions and interpretations of sustainability and the difficulties in measuring it. The four sustainability metrics we selected provide a holistic view of what we considered to be the fundamental aspects of an environmental system.

At a basic level, we recognized that an environmental system has some inherent order, whether the factors responsible for maintaining that order are clearly identified or understood. Furthermore, it takes available energy (i.e., energy with the potential to do work) to maintain order in an environmental system. Finally, sustainability is inherently an anthropocentric issue and how well off humans are may dictate their influences on the system. For example, an individual or population that is meeting its needs for existence has the luxury of being concerned about the effect they have on their environment, whereas a population that is barely surviving may not be intensely concerned with sustainability.

We selected metrics that capture each of these fundamental aspects; they also represent both strong and weak measures of sustainability. Weak sustainability assumes ecological functions and/or materials can be substituted by technological or man-made surrogates whereas strong sustainability assumes ecological functions are not replaceable or natural capital cannot be substituted with other forms of capital (e.g., Dietz and Neumayer 2007, Mayer 2008, Mayer et al. 2004, Neumayer 2010, Pearce 2002).

EFA was selected to capture the impact a population has on environmental resources resulting from consumption and waste production. We chose EmA because it measures the flow of available energy through a system, by converting all types of energy to a common unit (i.e., solar emjoule). Both of these metrics are considered measures of strong sustainability. GNRP was chosen to capture the overall economic well-being of the population and FI was selected to measure dynamic order of the overall system (both measures of weak sustainability). Out of the four metrics, using FI to characterize sustainability is a relatively new metric (Mayer 2008). Application of the other metrics is relatively common and they are established as metrics of sustainability in the scientific literature (e.g., Mayer 2008). The next four sections summarize each of the metrics.

ES.3 Ecological Footprint

This chapter describes the data sources and methodology used to estimate a simplified Ecological Footprint Analysis (EFA) at a regional scale. EFA captures the human impact on the environmental system by identifying the amount of biologically productive land necessary to support a person's level of consumption and waste generation. EFA is a commonly used metric of sustainability because it is easy to conceptualize and the calculation is relatively straightforward. A typical EFA requires estimation of the supply of biologically productive land in the geographic region of interest (called the biocapacity) and the demand placed on the biologically productive land to support the population (called the ecological footprint). The supply is estimated by identifying the number of hectares in each of six land categories (arable, pasture, energy, forest, sea, and built-up land). Consumption levels for food, energy, and other consumables, are assigned to a land category and the amount of land necessary to meet the level of consumption is calculated as the demand. An ecological balance is calculated by subtracting the ecological footprint from the biocapacity. If the ecological footprint is less than the available biocapacity, the system has an ecological remainder. If the ecological footprint is greater than the available biocapacity, the system is said to possess an ecological deficit. If the ecological balance is decreasing, resulting from an increasing ecological footprint and/or a decreasing biocapacity, the system is said to be moving away from sustainability.

Utilizing free, readily available data, we calculated an EFA for the SLB. Gathering existing data at a regional scale can be difficult because data are often collected at national or state levels. The lack of data is further confounded by the fact that data are often collected at intervals greater than one year. Variables that were missing data for certain years were estimated using linear interpolation. Other data were from state or national level data and were scaled to the region. For example, energy consumption data were reported for the State of Colorado. A per capita consumption was calculated by dividing the annual consumption by the population of the state for the year of interest. This per capita value was assumed to represent the level of consumption for the region under investigation. Food consumption was reported as average per capita for the US. This value was assumed to represent the level of consumption for individuals in the region.

Thirty-five variables from 1980-2005 (26 years) were collected and used to calculate a time-dependent EFA and the resulting trend was visually examined. The available biocapacity in the region did not decrease during the period, but per capita biocapacity is decreasing due to population growth. Per capita biocapacity was at a period high of nearly 36 hectares per person (ha/ca) in 1980 and steadily decreased to a low of just over 27 ha/ca in 2005. Ecological footprint remained relatively constant over the 26-year period, with a low of 5.10 ha/ca in 1997 to a high of 5.5 ha/ca in 1985. A steady ecological footprint combined with a decreasing per capita biocapacity, implies the ecological balance (i.e., remainder) is decreasing and thus the region is moving away from sustainability. Although per capita consumption did not increase substantially during the 26 years, more people are drawing on a set quantity of resources. Sustainability, as defined by EFA, requires that people reduce their footprint to free up resources for a growing population or to increase biocapacity. Lastly, it is important to remember the region is part of a larger system and provides much of its natural resources to support the larger system.

Our methodology is a simplified approach to EFA and does not follow standards that are currently being established. Adhering to the suggested standards would require obtaining data sets that consist entirely of national data. The national-level data are replaced with data specific to the geographic area under examination when they are available. Although national data may represent the sub-national region under study, the idea requires further investigation, especially in large, geographically and culturally varied nations such as the US.

ES.4 Green Net Regional Product

This chapter describes the data sources and methodology used to estimate Green Net Regional Product (GNRP). GNRP is equal to aggregate consumption minus the depreciation of man-made and natural capital. It captures the economic well-being, or welfare, measured in US dollars. Welfare, as defined by economists, incorporates benefits obtained outside of market transactions such as environmental amenities, but allows for the possibility of trade-offs between market and non-market goods. GNRP is a measure of weak sustainability that incorporates the assumption that human and man-made capital can be substituted for natural capital. We measure the movement toward or away from sustainability by examining the change in GNRP over time.

Any attempt at green accounting requires both economic and natural capital data. The economic data used in our study came from the Bureau of Economic Analysis (BEA). We collected natural capital data from the Energy Information Administration, Agricultural Statistics for Colorado, The Colorado Water Conservation Board and the Colorado Division of Water Resources as well as professional contacts in the SLB.

Our approach to estimating GNRP required transforming BEA economic data at the national, state, and county levels to the level of the SLB. Nationally, Gross Domestic Product (GDP) and Consumption of Fixed Capital for the US were required. At the state level, the approach required Personal Income and GDP for Colorado and New Mexico. For the seven counties in the SLB, we used Personal Income from the BEA.

Given the contribution of agribusiness to the SLB, we included the depletion of both groundwater and soil as components in the depreciation of natural capital. In addition, we captured the effect of the consumption of energy on future generations through carbon dioxide (CO_2) emissions. We utilized the Upper Rio Grande database from Colorado's Decision Support System to estimate the depletion of groundwater in the SLB. We averaged per capita CO_2 emissions for Colorado and New Mexico and applied this to the population estimates of the SLB. Wind is the main cause of soil erosion in the SLB. Finding reliable, county-level soil erosion data was challenging and required us to make many assumptions, consult with experts, and spend many hours doing the calculations. Future studies are likely to find this to be one of the more difficult aspects of applying our approach.

After collecting data for changes in natural capital, we needed to estimate the value of the change in the natural capital. The shadow price of groundwater for irrigation, the economic damages from wind erosion, and the social cost of carbon emissions were obtained from the literature and applied using benefit transfer.

Aggregating Net Regional Product (NRP; i.e., Gross Regional Product adjusted for the depreciation of man-made capital), Groundwater Storage Depreciation, Soil Erosion Damage, and CO_2 Damage Costs, we estimated GNRP for the SLB from 1980-2005. GNRP had a slight upward trend (based on a visual examination). Although there are peaks and troughs, the upward trend suggested that there is no definitive evidence of moving away from sustainability.

We have some concerns about our approach for estimating values for natural capital depreciation. A sensitivity analysis of the shadow prices and marginal damages indicated trends in GNRP did not differ for either low or high estimates. We developed and used an approach for estimating GNRP using publicly available data. Although the natural capital depreciation estimates will differ by region, the general approach can be applied to other regions.

ES.5 Emergy

Emergy is an unfamiliar term to many people, yet it is a quantity of great importance for the accurate evaluation of the condition of systems on all scales from the chemical reactions of molecules to the birth and death of stars and galaxies. Several aspects of system sustainability can be measured with emergy indices. The potential for sustaining the condition of the present system is indicated by the percent of renewable emergy used to support current system structure. The overall sustainability of the relationship between a system and its next larger system is given by the Emergy Sustainability

Index (ESI; Brown and Ulgiati 1998). This index is the ratio of the emergy yield to the larger system, the Emergy Yield Ratio (EYR), divided by the potential environmental damage done to the local system, Environmental Loading Ratio (ELR). Greater emergy yield for less environmental damage is preferable.

In this summary, our emergy evaluation of the San Luis Basin (SLB) region of Colorado, we focus on explaining emergy and the results of our analyses. Emergy Analysis (EmA) is another way to estimate the value that the environment contributes to society. EmA uses nature's accounting system (that is the flow of available energy[2]) to determine where a system stands and to judge its current condition. Nature does not and cannot accept money as payment for the real work that it does to support society in the SLB and elsewhere, yet emergy analysis shows that almost 50% of the work that is done in the region is done by the natural systems of the environment. Furthermore, the greatest amount of nature's work done annually is contributed by the snowpack that stands on the high mountains surrounding the valley. The existence of stored water at high elevations allows all of the geopotential energy of this water to be released in a short period of time and in the process, it recharges the groundwater and maintains unique geological and ecological features of the valley like the Great Sand Dunes and wetlands. One consequence of this fact is that the natural and agricultural systems of the region are vulnerable to climate changes that affect the snowpack. One of the largest natural assets of the region, as shown by EmA, is the stored available energy in groundwater. Everyone that lives in the region knows this and the history of increasing groundwater use that was a major factor in the rapid growth of agriculture from the 1880's to 1980 (Emery 1996). The advantage that EmA gives managers is it allows them to evaluate all aspects of the system in common biophysical terms (i.e., the amount of solar energy required for environmental, economic, and social products and services of the system). In this manner, all aspects of the system for which they are responsible in equal terms, that is disparate quantities (like environmental damage and economic production) are put on the same biophysical basis so that changes in each are directly comparable. Economic value serves this purpose in economics, but a different perspective of value is used and the scaling of relative values is often different in the two approaches. Information on the emergy value of aspects of a system compared with economic values for the same aspects has the potential to lead to better and fairer decisions on contentious issues faced by land managers. An explanation of emergy in more technical language is given in the following paragraph.

EmA assesses the condition of a system based on the flow of available energy required to develop and operate that system. The quality of energy flows is normalized by expressing all kinds of available energy in a common unit, the solar equivalent joule (sej), by converting the quantities of energy in joules or materials in grams used to make a product or service. The product is converted to emergy by multiplying the original units (J or g) by an emergy per unit factor, called a transformity (sej/J) or specific emergy (sej/g), to obtain emergy. For example, a bushel of wheat weighs about 60 lbs and a gram of wheat contains about 14,200 J of available energy or 3.87 $X10^8$ J/bu. If we sum all the inputs required for the production of the annual wheat crop in Minnesota (Campbell and Ohrt 2009), including the evapotranspiration of water, topsoil erosion, fuel, potash, phosphate, nitrogen, pesticide, herbicide, electricity, and groundwater we find that $2.89X10^{13}$ sej were required to produce the bushel of wheat. Thus, the transformity of wheat, without human services (labor), included was 7.47 10^4 sej/J. This factor can be applied to wheat production in a similar area (i.e., the SLB) to estimate the emergy of the crop given that the harvest in bushels is known.

The emergy of any environmental, economic, or social product and service can be determined in this manner as long as the production process for these items is known. Once converted to emergy the results are directly comparable so the relative advantages and disadvantages of any change due to alternative policies can be readily determined by direct inspection of the values. Relative advantage is judged by movement toward greater emergy flow through the system network, that is in the direction of greater competitiveness, and therefore toward a higher probability that the system's condition will be sustained given no change in the set of inputs available to the system. According to Emergy Systems Theory, maximizing empower is hypothesized to be the variable deciding the outcome in evolutionary competition among alternatives (Odum 1996). If this is true, then system

[2] Available energy is energy with the potential to do work. For example water in the mountains can do work, such as drive a turbine as it flows to a lower elevation.

empower is a master variable that serves as a reference point to characterize system operations (i.e., increasing system empower flow moves toward greater overall well-being, whereas a decline indicates a less healthy system that will not compete as successfully with other systems). From this perspective, every manager should know the projected effect of alternative policies on the empower (emergy/time) of their systems as well as the effect on system dollar flows, before making a decision.

In this study, information was gathered via government agencies, literature surveys, interviews with experts, the purchase of a dataset, and meetings with knowledgeable people from the region. EmA requires data on all aspects of a system; and therefore, data on several important variables were shared with EFA and GNRP data sets. The data needs to construct an EmA of a region can be categorized as follows: 1) data on renewable energy inputs to the system and information on renewable production carried out in the system; 2) data on nonrenewable energy inputs, production, and consumption, including any renewable energy sources used in a nonrenewable manner; 3) data on imports to the system including raw and finished materials and services; and 4) data on exports from the system including raw and finished materials and services. We performed an evaluation of the annual emergy flows of the SLB region synthesizing data for the seven counties and the associated Upper Rio Grande River Basin. Out of the numerous indices calculated during a typical EmA, we selected the fraction of renewable emergy used to total emergy used as the index on which to focus because it would provide the best indication if the SLB was moving toward or away from sustainability. The ESI is also used to examine the sustainability of the relationship between the SLB and its next larger system.

The limiting factor for determining a time series of emergy flows for the SLB was the need for complete and accurate data on imports and exports. This required the purchase of relevant data from a private economic data service. The firm compiled freight movement by county and these data were available for the seven-county region for the years 1995 to 2005. Therefore, the complete EmA of the region was limited to these 11 years.

More often than not, the SLB exported more emergy than it imported. Thus, the SLB serves as a hinterland supplying raw products and resources to the larger system of Colorado and the US. Although there was some variability during the 11-year period, the fraction of renewable emergy to total emergy used had a slight decline over the period. Thus, we can infer that during this time the SLB was gradually moving away from sustainability. These trends culminated in 2002 when a large groundwater withdrawal compensating for decreased precipitation in that year brought the fraction of renewable emergy to a low point. In 2003, renewable emergy inflow recovered, and exports began to recover, while imports remained about the same level. This led to an increase in this emergy index of sustainability, which reversed its general downward trend, resulting in upward movement from 2003 to 2005. However, the total emergy used in the SLB, which is an indicator of well-being of the local system, recovered much more slowly with a relatively modest increase (6%) in total emergy flow over this time. The total renewable emergy used per person in the region also declined for the study period due to population growth. In summary, although both indices show a decline and resurgence in later years, overall, they indicate an underlying trend for the region of gradually moving away from sustainability for the period examined.

ES.6 Fisher Information and Order

This chapter describes the theory, data sources, and methodology for using Fisher information to assess the order and stability of the SLB regional system. Fisher information (FI) was developed as a measure of order in data and is an important method in information theory. The method is based on the amount of information available in a time series of data and is focused on determining patterns of behavior. Because the presence of patterns implies a level of organization, FI can be seen as a measure of dynamic order. In the context of system sustainability, order relates to the ability of a system to maintain a desirable steady state (i.e. regime) even in the presence of natural fluctuations. Assessing dynamic order enhances environmental management in its effort to monitor and manage the impact of human activity on ecosystems. Through this approach, changes in complex system behavior may be observed over time with the aim of maintaining desired regimes and avoiding catastrophic shifts.

Our adaptation of FI provides a means of monitoring variables of a system to characterize its dynamic order and self organization, and, accordingly, its regimes and regime shifts. FI over time denotes changes in dynamic order such that decreasing FI indicates movement away from sustainability, no net change in FI denotes the system is maintaining its current state and increasing FI indicates that system is becoming more orderly and possibly moving toward a new dynamic regime that is different from the present regime.

In this chapter, we provide the basic theory on the method, describe the computation approach, and list the variables used in the assessment. To enhance understanding of the method, we provided a pedagogic exercise to "walk through" the steps for computing Fisher information. Further, we compute FI for the SLB data and discuss the results, as well as, the strengths and weaknesses of the approach.

One of the main goals of this project was to use readily available data to assess regional sustainability. Based on the three pillars of sustainability, it is paramount that data used to compute FI encompass the environmental, social, and economic components of the system. Because data compiled to calculate EFA, GNRP, and EmA incorporate the pertinent aspects of activity in the region, key primary variables were selected from these data sets. These variables which capture the consumption of food and energy, agricultural production, environmental characteristics, demographic properties, and changes in land use for the SLB system from 1980-2005 are listed in the chapter. However, the source and details of the data are provided in the corresponding metric chapters.

Our analysis revealed that there was no indication of a regime shift. The system exhibited small changes in dynamic order during the study period, with a slight decreasing trend near the end of the period (i.e., 1998-2001). Accordingly, we deduce that although conditions in the SLB are relatively steady, there was an indication of slight movement away from sustainability.

A primary benefit of using this information theory approach is the ability to collapse data from intricate, multivariate systems into a metric that can be computed over time. This is particularly important considering the complex, multi-disciplinary nature of sustainability. Further, the method is robust in that it assesses dynamic behavior of both model and real systems. One key output of this project is the MATLAB code and graphical user interfaces (GUI) developed to simplify the computation and evaluation procedure. Key considerations surrounding the computation of FI include establishing the integration window parameters (*hwin* and *winspace*), the need for determining a measure of uncertainty for the state variables (which is used to set the size of states for each variable), and the availability and quality of data characterizing the state of the system. Accordingly, we used a simple example to perform sensitivity analysis on *hwin* and *winspace* to determine the impact of those parameters on the result of FI. In addition, we provided guidance for determining the size of states parameter.

ES.7 The San Luis Basin Sustainability Metrics Project: Results, Conclusions, and Recommendations

This chapter examines the sustainability metrics holistically, using the results of the previous four chapters, to decipher whether the SLB is on a sustainable path (i.e., moving toward sustainability). Although each of the four metrics captures different aspects of the system, they appear to have similar results based on the concept of weak and strong sustainability. EFA and EmA, measures of strong sustainability, indicate movement away from sustainability whereas GNRP provided no definitive evidence of movement away from sustainability, and FI suggests relative stability, both metrics are measures of weak sustainability. Overall, the weight of evidence led us to the assessment that the region is moving slowly away from sustainability. The growth of population from 1980 to 2005 and the increased pressure on environmental resources that is the inevitable result of human use of the environment also supports our conclusion. However, we recognize the estimates are not perfect and have identified the limitations of each metric in their respective chapter. For example, the best we can do for a trend analysis is a visual examination without statistical tests given the lack of uncertainty measurements for the variables.

The majority of the limitations for the methodology relate to data needs and data manipulation. Because much of the data needed for these metrics are typically not collected at the county level, we needed to rescale or convert state or US data to the county or regional level. Other challenges are related to quantitatively assessing trends for the metrics and using the methodology in other regions besides the SLB.

We believe that our methodology adequately characterized and evaluated sustainability of the SLB, in part, because our results are plausible and our observations and conclusions have been validated to a certain extent in public meetings with stakeholders in the SLB and by anecdotal evidence. The methodology demonstrated that this framework was not entirely straightforward or simple, nor was it inexpensive, but it suggests the multidisciplinary approach does a sufficient job of assessing whether a region is moving toward or away from sustainability. We do not contend that this methodology is definitive; however, we do argue that each metric identified changes to major components of the system. We propose that together, these metrics adequately represent the complexity of a regional system.

We offer the following recommendations for future research based on the results of our study:

1) Examine previous management decisions in the SLB to see if and how the metrics changed. For example, the Great Sand Dunes National Park and Preserve was created in 2000 and increased the National Monument land area by almost four times (NPS 2007). This recommendation would help to determine if any of the changes in the metrics could be linked back to the management decision to increase the public land area.

2) Continue calculating the metrics in the SLB for subsequent years to examine how sensitive the metrics are to management decisions.

3) Use stakeholder meetings to determine major sustainability issues in the region and better link the metrics on those issues and concerns. Determine if there are other established metrics that may better assess sustainability of a region by addressing known issues. This relationship with stakeholders will help ensure the metrics are capable of capturing changes pertinent to issues of public concern. The meetings can be used to gauge whether stakeholders and decision makers can understand the results of the metrics. More research can focus on simplifying the interpretation of results for various groups of people: managers, regulators, landowners, educators, policy makers, etc.

4) Develop trend analyses and/or approaches for estimating confidence intervals for individual metrics. Although a trend may appear obvious, recognizing and identifying the variation in the data and resulting metric will better identify significant trends. One example might be using econometric methods (e.g., Greene 1993, Hay et al. 2002) or sensitivity analyses.

5) Develop models of alternative future scenarios and estimate multiple metrics (Baker et al. 2004, Kok and van Delden 2009, Yeh and Chu 2004) that are sensitive to relevant changes in a system or region. For example, how would the installation of solar farms affect the metrics?

6) Test these multiple metrics in other regions and determine if the metrics are indeed capturing the trend in sustainability of regional systems.

7) Examine the correlation among alternative metrics to determine whether certain metrics could be dropped from analysis (i.e., one metric moves in a similar or opposite pattern to another over time) in order to reduce the resources needed (e.g., Bastianoni et al. 2008 used Principal Components Analysis).

8) Consider the use of other scientific approaches, rather than limiting analysis to visual examination of graphs, for deciphering the holistic results of multiple metrics, such as multicriteria methods (e.g., Shmelev and Rodríguez-Labajos 2009); data envelopment analysis (e.g., Despotis 2005, Kortelainen 2008); mathematical programming (e.g., Zhou et al. 2007); or other integrated sustainability metrics (e.g., Mayer 2008).

ES.8 References

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1.0 Introduction

1.1 Concept of Sustainability

The concept of sustainability and the efforts to implement sustainability are, at their core, an undertaking to insure the needs of current and future generations are met. This fundamental concept is embodied in one form or another in a number of public pronouncements on the subject of sustainability. One frequently cited quote from the World Commission on Environment and Development (1987: 43) defines sustainability as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” It is important to note the associated economic, social, and supporting environmental systems must work in concert to maintain a desired level of functioning and these are sometimes referred to as the pillars that support sustainable development (e.g., UN 2002). Sustainability, however, is an anthropocentric issue that speaks to the need for maintaining those interrelated systems over the long term for the benefit of humanity.

The concept of sustainability is very broad, complicated, and challenging and it can lead to different interpretations (e.g., see Prugh et al. 1999). For example, in the political arena, sustainability is often associated with ideas from social science including social justice and equity of wealth distribution (Prugh et al. 1999). In an economic sense, Pezzey and Toman (2002: 3-4) state a sustainable economic development path occurs when “expected well-being per capita (broadly defined to include more than just material or market goods) rises over the long term.” Stavins et al. (2003) provide another economic perspective that requires both dynamic efficiency and intergenerational equity for their definition of sustainability. In a strict ecological sense, sustainability is concerned with the conservation of ecosystem processes, including aspects such as biological diversity (Callicott and Mumford 1997, Aarts and Nienhuis 1999). Engineers focus on the efficiency of energy and material use in industrial processes, and in reducing waste with some consideration of social and economic factors (Mihelic et al. 2003, Sikdar et al. 2004).

Although there is not a consensus on defining sustainability, there is general recognition the current level of human activity appears to damage the systems that support us. Sustainability relates to finding and maintaining a set of system conditions that can support the social and economic development of a human population. To be sustainable, development must not have major adverse effects on the environmental systems that support the population. Consequently, metrics are needed to help us understand the linkages and demands of human activity (e.g., society, economy, government, industry, etc.) on environmental systems (Cabezas et al. 2005a).

When choosing sustainability metrics, researchers should be aware of relevant issues such as the paradigms of weak and strong sustainability, which relate to how much man-made and other capital can substitute for natural capital (described in Chapter 2 of this report, Neumayer 2010). In addition, there is some amount of uncertainty and unreliability in measures of sustainability and most measures have many simplifying assumptions that complicate this type of research. Given these complexities, a collaborative, interdisciplinary approach could alleviate some of the conflict and ambiguities in these interpretations and approaches.

The Federal government’s sustainability research strategy recognizes that an integration of economic, social, and environmental policies is required to achieve sustainability (USEPA 2007). Therefore, the strategy states (USEPA 2007: 23):

> EPA and its partners will develop integrating decision support tools (models, methodologies, and technologies) and supporting data and analysis that will guide decision makers toward environmental sustainability and sustainable development.

To translate the aforementioned mandate from the USEPA strategy into a practical plan of action requires a working definition of sustainability. Thus, we define sustainability as identifying and maintaining a set of conditions that support environmental, social, and economic systems that meet the needs of both current and future generations, thereby addressing the three pillars of sustainability. Moreover, in order to satisfy the definition of sustainability, the environmental, social, and economic systems must effectively meet the needs of current and future generations, indefinitely. To assess sustainability, information is needed to evaluate human well-being, how the different components of a system are linked, and the stresses of human activity (e.g., society, economy, government, industry, etc.) on environmental systems. One way to approach this and guide decision makers toward sustainability is through metrics that quantify changes in environmental, social, and economic systems.

The research and results presented in this report will provide decision support through the estimation of metrics that relate to sustainability. These metrics will help decision makers understand the movement of their system toward or away from environmental sustainability at the regional level. The San Luis Basin (SLB), in south-central Colorado, was used as a pilot study to develop and test the applicability of the methodology.

1.2 The San Luis Basin Sustainability Metrics Project

Over the long-term, the maintenance of intact and sustainable ecosystems depends on the ability of all landowners to manage and utilize their lands in a sustainable manner. Because the Federal Government owns more than 265.9 million hectares (GSA 2004), the US has a vested interest in managing these lands in a sustainable manner. For example, the US Forest Service Mission is to "Sustain the health, diversity, and productivity of the Nation's forests and grasslands to meet the needs of present and future generations" (USDA 2007: 2). Understanding the effects of facility operations and management decisions on the environment at the regional scale is essential to the work of several programs within the USEPA. This is especially relevant in the west, where the majority of the US public lands are located. In fact, over thirty-three percent of the land within USEPA Region 8, where the SLB is located, is publicly owned (USEPA 2009a). Thus, choices made daily by land managers are an important component of how well the environment in the Region's six states (Colorado, Montana, North Dakota, South Dakota, Utah, and Wyoming) is protected.

Public land managers make decisions daily that can affect the quality of the land for which they are responsible. These decisions are based on several factors, including the mission of the agency they serve; the directives of the current political administration; and the wishes of the surrounding population. To assist land managers and the surrounding communities in making sustainable choices, USEPA needs to develop integrated, system-based tools that provide feedback on how these collective decisions are affecting ecosystems and their services. To fulfill this need, the USEPA Office of Research and Development initiated the *San Luis Basin Sustainability Metrics Project* in 2006. The results of this project will provide a set of sustainability metrics for use on the regional scale that are scientifically credible and assist land managers. Land managers can use the methodology to identify trends as the system progresses through time, and provide early warning of abnormal conditions. This will help them better protect and manage healthy ecosystems.

This report presents an overview of the *San Luis Basin Sustainability Metrics Project*, a five-year research program. The purpose of the report is to present the methodology, discuss approaches used to estimate the individual metrics, and examine results that could inform decision makers in the region. The goal of this study was to produce a straightforward, relatively inexpensive methodology that was simple to use and interpret.[3] This required historical data to be readily accessible, that metrics be applicable to the relevant scale, and that results meet the needs of decision makers. The objectives were: 1) determine the applicability of using existing datasets to estimate metrics of sustainability at a regional scale, 2) calculate the metrics through time (initial proposal was 1980-2005), and 3) compare and contrast the results to determine if the system is moving toward or away from sustainability.

1.2.1 Measuring Sustainability

In general, identifying major properties (e.g., climatic, soil, biological diversity, etc.) and cycles (e.g., water, carbon, phosphorus, oxygen, nitrogen, etc.) of a system may seem relatively simple and straightforward, but it is difficult to list and quantify many of the specific details of the properties and cycles critical to the needs of humans and, therefore, to sustainability. As a starting point, we identified and tested a set of four metrics that capture some of the most basic properties of a system. The four metrics included Ecological Footprint Analysis (EFA), Green Net Regional Product (GNRP), Emergy Analysis (EmA), and Fisher information (FI; more discussion on the choice of metrics can be found in Chapter 2). These metrics, respectively, represent human burden on the environment, economic well-being, flow of available energy through the system, and overall system order. Each metric captures particular aspects of the system, but may not account for every aspect pertinent to sustainability. There is some overlap or redundancy (e.g., consider a physician using multiple tests to examine a patient's health) in the variables used and, therefore, the pillars they quantify and how sensitive each metric is to the pillars of sustainability. In

[3] We believe the method is relatively inexpensive because we have identified the majority of data sources for these types of calculations leading to reduced time and resources necessary for others to compute the metrics. However, whether we met the goal and objectives would be based on anecdotal evidence and discussions with stakeholders in the region.

fact, this issue of sensitivity is one of the main reasons we initially used multiple metrics.

Note that for this report, we use metric and index interchangeably; however, we acknowledge a difference between indicator and either of the terms we use. Mayer (2008) defines an indicator as measuring one characteristic (e.g., CO_2 emissions or biodiversity), but an index (or metric) combines many indicators (or variables) through aggregation (e.g., GNRP). Therefore, indices or metrics can provide a multidimensional view of sustainability.

The four metrics we utilized are capable of measuring sustainability in an absolute sense. For example, if the ecological footprint (demand) is larger than the available biological capacity (supply), then the system is considered unsustainable following the assumptions and methods of that approach. It is, however, conceptually and practically difficult to compute values for these metrics with absolute accuracy. The conceptual difficulty arises because each of these metrics attempts to convert many disparate variables or indicators into one common measure. For example, consider that EFA converts everything into land area, EmA converts all quantities into solar emjoules, GNRP requires that all quantities be expressed monetarily, and FI converts system variables into a measure of dynamic order. This conversion exercise is relatively simple and accurate as long as the quantity is closely related to the common measure of the metric (e.g., converting agricultural production into land area). This is more difficult and less accurate when converting a quantity that is not closely related to the common measure (e.g., converting human transportation needs into information). The practical difficulty comes from the impossibility of measuring or estimating values for the innumerable variables or indicators needed to characterize a system well enough to compute accurate values for the metrics. Hence, it is likely that even under the most extraordinary efforts inaccurate values for the metrics would result because of measurement errors, errors in the conversion of unrelated variables into a common measure, and/or missing variables.

The aforementioned reasons have led us to adopt the strategy of focusing not on computing absolute values for the metrics but on identifying changes in the value of the metrics through time.[4] We believe the benefits of this strategy are: 1) errors incurred in complicated calculations due to either conceptual or practical issues often tend to cancel out when differences are taken, 2) it is easier to formulate scientifically defensible criteria for changes than for absolute values (but see Alonso 1968), 3) components that do not change over time can be dropped or simply approximated, and 4) trends in the metrics rather than absolute values are most likely to indicate movement toward or away from sustainability. Knowing how the system is evolving over time rather than its state at a point in time is, perhaps, the most critical issue. There is a body of scientific theory that tells us what changes in these metrics mean in terms of sustainability (e.g., Campbell 2001, Heal and Kristöm 2005, Mayer 2008). We established criteria for each metric to determine if a system is moving toward sustainability. For EFA, ecological balance (biocapacity - ecological footprint) is stable or increasing with time. For EmA, the fraction of renewable emergy used to total emergy used is trending to one. FI and GNRP are one-sided tests of weak sustainability and they cannot technically show if the system is moving toward sustainability. Criteria for these one-sided tests indicate if the region is moving away from sustainability when FI is steadily decreasing with time (Karunanithi et al. 2008) and GNRP is decreasing with time (i.e., Pezzey et al. 2006). Note these criteria do not presuppose any particular version of the system; rather they address the maintenance and preservation of basic properties and processes that are necessary for continued human existence. An unsustainable path is defined as one where any of the following are observed - human welfare (as defined by GNRP), ecological balance, emergy flows into the system, or Fisher information - are in violation of the aforementioned criteria. We considered a system that is moving away from sustainability, for that particular aspect of the system, to be on an unsustainable path, when one or more of the four criteria are not satisfied and/or a one-sided test is satisfied.

1.2.2 Choice of Region

The SLB in Colorado (Fig. 1.1) was selected as the study area because of its distinct natural hydrological boundaries, limited population, large amount of publicly owned land, and interest expressed in the study by USEPA Region 8 and other government officials. Surrounded by the Sangre de Cristo Mountains to the east and the San Juan Mountains to the west, approximately seventy-eight percent of this region is publicly owned, making it an optimal system for our study. This study has fostered a partnership for sustainability research between USEPA Region 8 and the USEPA's Office of Research and Development. Moreover, it will expand existing partnerships between land management agencies within USEPA Region 8 such as the National Park Service, USDA Forest Service,

[4] Without a measure of uncertainty for any of the metrics, it is not possible to determine if any change over time is statistically significant. We address this in detail in Chapter 7.

US Fish and Wildlife Service, and Bureau of Land Management (BLM). Some 202342 hectares (ha) on the borders of the valley (adjacent to National Forest lands) are managed by BLM and much of this land is leased to neighboring ranches for grazing. The Great Sand Dunes National Park and Preserve is the most well known feature of the valley. Directly west of the Sangre de Cristo Mountains, the dunes (the largest in North America) rise to a height of over 213 m, and are under the protection of the Park and Preserve.

1.2.2.1 Description of the San Luis Basin

We define the SLB as the following seven counties: Alamosa, Conejos, Costilla, Hinsdale, Mineral, Rio Grande, and Saguache. This region contains the Upper Rio Grande River Basin, the San Luis Valley, and the Great Sand Dunes national Park and Preserve. The Upper Rio Grande River Basin is nearly 21000 km^2 in size (USDA 1978) and the San Luis Valley, a primary feature of the basin, is a high desert, sitting at an average altitude of approximately 2300 m (CWCB 2000).

The SLB is home to approximately 50,000 people (US Census Bureau 2002). Although the study area is in the State of Colorado, the region borders New Mexico to the south and, based on conversations with local stakeholders, is closely related to that state culturally and economically. This relationship is not surprising considering the geographic features that define the region to the north, east, and west. The economy is predominantly based on agriculture (San Luis Valley Development Resources Group 2007). The agriculture is dominated by potatoes, small grains, and alfalfa and is dependent on irrigation (approximately 85% of the water consumption in the valley is for agriculture; CWCB 2000, Wurster et al. 2003, NASS 2009) and future demand for irrigation water could increase one-hundred percent (HRS Water Consultants 1987). Most of the irrigation water comes from surface water that is collected and channeled through a series of historic canals (San Luis Valley Development Resources Group 2007).

The SLB sits atop the Rio Grande Rift and is drained to the south by the Rio Grande River (Mayo et al. 2007). The northern section does not drain into the Rio Grande River and is referred to as the Closed Basin (CWCB 2000). The Rio Grande River begins to flow just south of the Closed Basin (Mayo et al. 2007). The San Luis Valley has an annual average precipitation in the basin ranging from 17 cm at Alamosa to 114 cm at Wolf Creek Pass (CWCB 2000), but much of the surface water begins as snowmelt coming out of the mountains (Emery 1979).

Given the structure of the region, the groundwater system is complex. According to Mayo et al. (2007), there are three groundwater sources within 1200 m of the surface: 1) an unconfined aquifer, 2) an upper active confined aquifer, and 3) a lower active confined aquifer. The unconfined aquifer is the closest to the surface compared to the confined aquifer (Mayo et al. 2007) and it provides water to valley residents and farmers and maintains the levels of the San Luis Lake and other wetlands just to the west of the dunes (Wurster et al. 2003). The confined aquifer occurs between about 305 m to 1829 m below the surface (HRS Water Consultants 1987). Although layers of clay separate the different aquifers, there is some leakage between the unconfined and confined aquifers (Mayo et al. 2007). In addition to aquifer leakage, recharge occurs through stream infiltration, mountain underflow, overland infiltration, and canal and irrigation infiltration (Mayo et al. 2007).

The combined use of ground and surface water has been, and will continue to be, of major importance to proper management of the valley's water resources (Emery 1979). The Conejos River has lost some of its flow from withdrawal from the confined aquifer and increased consumptive use near the river (Emery 1979). This loss of water has caused problems with meeting the Rio Grande Compact, which requires Colorado to deliver a certain amount of water to New Mexico and Texas (Emery 1979, CWCB 2000). In order to meet the water requirements of the Compact, the Closed Basin Project pumps water from the Closed Basin using wells and canals and discharges the water into the river (CWCB 2000).

1.2.3 Community Outreach

In order to produce a useful product, the USEPA needed to bring the local residents into the project to let them know what we were doing, why we were doing it, and what the potential outcomes might be. The purpose of the outreach is that once the project is complete, the metric tools would be accepted and used by the community. In addition, USEPA needed to advertise the project well enough so as we collected information in the SLB, local residents could contact us with questions.

The outreach approach developed and implemented by USEPA Region 8 focused on involving people who were identified as community representatives and leaders:

- Federal Land Managers – Because 69% of the land is federally owned and managed (San Luis Valley Development Resources Group 2007), federal land managers from the National Park Service, USDA Forest Service, BLM, and US Fish and Wildlife Service played a significant role in the outreach efforts.[5] These managers were engaged in developing the metric tool for their own use and are seen as leaders within the SLB community and its members. Our connection with the federal land managers in the valley served to identify key community leaders. Because these individuals were well known and respected within the community, their support and introduction of ORD scientists to the community was vital to being accepted by community leaders.

- Community Organizers and Non-profit groups – We had a list of community organizers and interested parties from previous work the USEPA performed in the San Luis Valley on drinking water (USEPA 2009b).
- Adams State College (ASC) – ASC, a prominent institution in the community, has a stated goal of reaching out as a partner in the community and has a well-established Community Partnerships Program (CPP) whose mission is to connect ASC resources with the community in order to increase the quality of life for all residents of the SLB. ASC CPP was instrumental in helping USEPA scientists connect to the community.
- National and State representatives – The Secretary of the Interior (Kenneth Salazar) and Colorado Congressman (John Salazar) are residents, landowners, and farmers in the community. These local representatives, as well as US Senators Michael Bennet and Mark Udall, were informed of the project and engaged in the community outreach efforts.

Once we established contact with local leaders, a USEPA Region 8 representative spent a week in the community meeting with these leaders. Desired outcomes included informing the individuals about the project; receiving feedback on how to inform the community about the project; integrating their concerns into the project design; receiving feedback on the use of the tool within the community; and developing an expanded list of community leaders that we should contact. More than 30 such meetings were held and the results were shared with the project team. Community leaders collectively asked for a formal project overview in order to understand better the usefulness and application of the metrics to the local community. Working with ASC and CPP, the USEPA representative scheduled a project overview meeting and held a question and answer event. Seventy-five letters of invitation were sent to community leaders who were identified during the first phase of the outreach effort. Over 40 people attended the project overview meeting and USEPA received positive feedback and an indication the community welcomed the project focus.

CPP notified the USEPA of an opportunity to develop and present a challenge to an upper level advertising class (BUS 345) in the School of Business as their class project. The USEPA representative presented an overview of the project and challenged the students to develop an outreach campaign directed to the SLB community. The campaign would inform the community about the project and provide information on who to contact within the project to get questions answered or provide feedback from the general community about the project. The students selected the challenge as the class project and developed a work plan that included a public meeting, press releases, and identification of potential media connections for additional outreach efforts.

The class research identified five areas of outreach opportunity and/or concern: 1) the SLB residents were unaware of the project, 2) the most effective form of advertising in the SLB is through the local newspaper, 3) the primary concern the residents had with the project was USEPA's purpose for conducting the research, 4) public meetings are an effective form of informing the SLB residents, and 5) SLB residents initially viewed the project as having a negative impact on the region. Based on these findings, the class requested a conference meeting with a USEPA representative to establish firm goals and objectives for the outreach activities and brainstorm ideas for an advertising project. The approach developed by the class included an organized town meeting to inform the community about the project. The class advertised the town meeting in the newspaper and placed notification of the meeting on the Chamber of Commerce web page. This effort revealed the community was concerned the project could result in new regulations, more government control of land use decisions in the region, and concern that USEPA would acquire land from farmers and residents. Based on these findings, we sought opportunities to meet with the public and hand out information describing the overall project. The information on these postcards included a contact name and phone number for the Region 8 representative and had the following text (see footnote 3 above for the six counties of the Valley):

> This is to let you know that the Environmental Protection Agency is working in your community to gather information for a research project. The project will help build a scientific foundation for sound environmental decision-making. This

[5] The San Luis Valley Development Resources Group defines the Valley as the following six counties: Alamosa, Conejos, Costilla, Mineral, Rio Grande, and Saguache. This differs from our definition of the SLB by not including Hinsdale County and accounts for the difference in the proportion of land publicly owned (~78%) stated previously.

is a research project only. Our goal is to provide the San Luis Valley with useful tools for future planning. This research project will not result in any action by the USEPA in the San Luis Valley.

These postcards were distributed at public events identified by the community leaders as places where the community gathered and would be receptive to hearing about the project. Additional outreach was conducted by CPP and included seminars open to the public. For example, USEPA received invitations to speak at public events. One such event was Focus the Nation, a national effort to have colleges and universities focus on one significant issue for one day. Another public event was the annual meeting of the San Luis Valley Resource Conservation and Development Board, a USDA program designed to assist communities to accelerate the conservation, development, and utilization of natural resources in order to improve their economic activity. USEPA held its annual team meetings in the region and in 2007 and 2008 invited community leaders to participate and provide valuable community perspectives to the project.

This community outreach approach was effective in meeting our goal of informing the community in order to increase the probability the community would accept and use the tools. We presented preliminary results from the project to the community and they were well received by the community and the attendees provided valuable feedback and comments to the research group.

1.3 Outline of Report

Having introduced some of the background for this pilot project, the report proceeds as follows: first, we present a literature review of sustainability metrics in Chapter 2. Because of the abundance of literature on sustainability metrics and classification systems, we only reference studies that report lists of metrics. The chapter focuses on metrics that fit within categories of ecology, economics, energy, and system order. In addition, this chapter summarizes studies that have looked at multiple metrics over time. Chapters 3 through 6 present the four metrics used in the SLB pilot project: EFA, GNRP, EmA, and FI, respectively. Each of these chapters presents an explanation of the methodology, the data and their sources, results, and discussion. The remaining chapter summarizes the results of all the metrics and discusses the strengths and limitations of estimating four sustainability metrics over time using publicly available data. Seventeen appendices cover additional results or methodologies (e.g., estimates for wind erosion) used in estimating the metrics.

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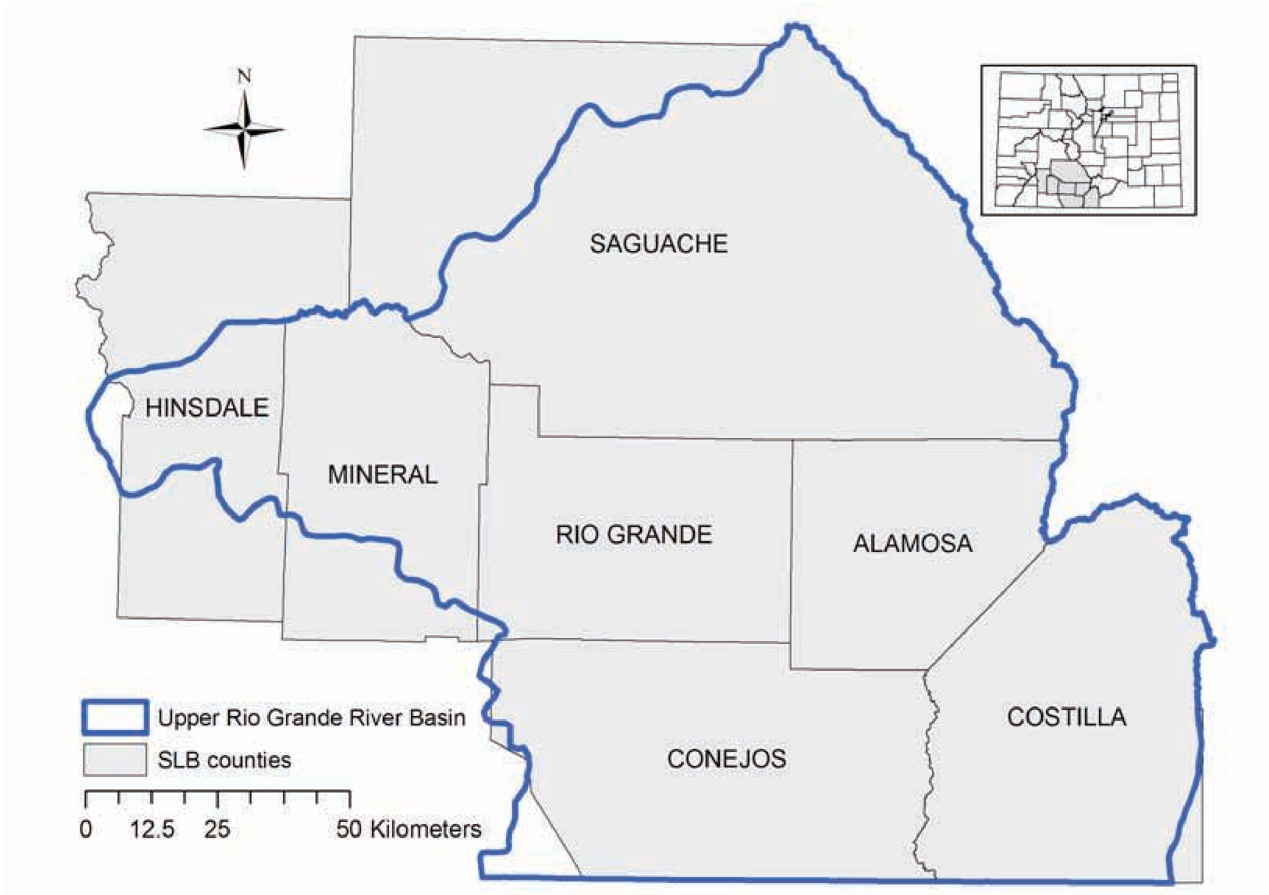

Figure 1.1 – Seven county region referred to by the investigators as the San Luis Basin (SLB), in south-central Colorado.

2.0
Sustainability Metrics

2.1 Introduction

In this chapter, we review the literature of different measures of sustainability for the four categories described in Chapter 1: ecology, economics, energy, and system order. Once we provide background on our selected metrics, we review the literature of studies that have examined sustainability using multiple metrics, and those studies that examined sustainability over time. Both are important attributes of the *San Luis Basin Sustainability Metrics Project*. The last section justifies our choice of the four metrics from within the four broad categories.

2.2 Literature Review of Ecological, Economic, Energy, and System Order Metrics

Articles such as Böhringer and Jochem (2007), Gasparatos et al. (2007), Hák et al. (2007), Mayer et al. (2004), Mayer (2008), Ness et al. (2007), Singh et al. (2009), UN (2007), and Wilson et al. (2007) summarize different sustainability metrics and indicators. Many of these papers group the indices and indicators into broad categories and then summarize the individual measures in those groups. Neumayer (2010), for example, presents the two opposing paradigms of weak and strong sustainability along with metrics that fall under these paradigms. Weak sustainability assumes ecological functions and/or resources (i.e., natural capital) can be replaced by technological or man-made surrogates, whereas strong sustainability assumes ecological functions are not replaceable and natural capital cannot be substituted for with other forms of capital (e.g., Dietz and Neumayer 2007, Mayer et al. 2004, Mayer 2008, Neumayer 2010, Pearce 2002). For additional detail on how the specific indices mentioned in this report relate to sustainability, we suggest examining some of the papers listed above. Rather than repeating the extensive efforts above, we present a subset within the group of ecological, economic, energy, and system order metrics of sustainability.

2.2.1 Ecological Sustainability

A number of indices have been proposed that measure environmental or ecological sustainability and are based on population biology. Specifically, the indices are based on the concept of carrying capacity and they attempt to assess the number of individuals an ecosystem can maintain by quantifying the load a system can support and the impact organisms have on the system (Caughley 1976). In other words, carrying capacity is the number of individuals of a given species that can be supported by the available resources in an ecosystem (Sharkey 1970). Three such metrics based on carrying capacity that have been suggested as measures of sustainability are maximum sustainable yield (MSY), IPAT, and Ecological Footprint Analysis (EFA).

MSY attempts to identify the resilience of a population to harvest or extraction (e.g., Fry 1947, Ricker 1958, Schaeffer 1954, but see Pitcher and Hart 1982). To be sustainable, resources must be harvested at a rate that allows a population to replace or renew the extracted biomass to avoid depleting the supply. Implementing this management strategy has been difficult (Larkin 1977) due to extreme variability in stock recruitment for some species, which was noted as a possible flaw by Russell (1931).

Another such metric adapted from carrying capacity by Ehrlich and Holdren (1971) is IPAT. IPAT proposes the **I**mpact a population has on its environment is directly related to the product of **P**opulation size, level of **A**ffluence, and the **T**echnology employed by the population (e.g., York et al. 2003). Ehrlich and Holdren (1971) assumed an increase in any of the parameters would result in higher overall impact on the environment. A number of modifications have been made to the metric to examine if each parameter should have equal contribution (e.g., Sutton 2003, Waggoner and Ausubel 2002, York et al. 2002 and 2003) or if additional factors should be included (e.g., Fan et al. 2006, Schulze 2002). For example, Dietz and Rosa (1994) converted IPAT to STIRPAT, a non-linear regression equation that allows random errors (i.e., stochasticity) in the estimation of the parameters and permits hypothesis testing (e.g., Dietz et al. 2007, Mayer 2008). Interestingly, Dietz et al. (2007) use ecological footprint (see below) as their measure of anthropogenic stressors in their STRIPAT approach.

Rees (1992) and Wackernagel and Rees (1996) applied the concept of carrying capacity to humans by inverting the number of individuals a system can support and measuring the amount of biologically productive (bioproductive) land that is required to support a population of a given size. This area of land necessary for the production and maintenance of goods and services consumed by the population was termed the ecological footprint (the metric is named after this component of the overall analysis). Ecological footprint is based on the concept of strong sustainability and it attempts to capture ecological impacts of human activity from resources consumed and wastes generated (Neumayer 2004). Specifically, ecological footprint includes consumption of crops, meat, seafood, wood and fiber, energy, and living space, which are converted to one of six biologically productive land types (i.e., arable, pasture, sea, forest, energy, and built lands, respectively). Comparing the “supply” of bioproductive land to the “demand” of resource consumption and waste generation can reveal if the system is sustainable at the current levels of human impact. Although there has been a number of modifications and adaptations to improve the ecological footprint methodology since its inception (e.g., Lenzen and Murray 2001, Luck et al. 2001, Monfreda et al. 2004, Medved 2006, Venetoulis and Talberth 2005, 2008, Wackernagel 2009), there has been a push for standardizing the methods (e.g., Wackernagel 2009). Nonetheless, new metrics have been proposed that combine existing indexes with ecological footprint such as emergy (e.g., Hu et al. 2009, Siche et al. 2010a, 2010b, Zhao et al. 2005), exergy (e.g., Hau and Bakshi 2004), and net primary production (e.g., Siche et al. 2010b, Venetoulis and Talberth 2005 and 2008), for example.

Each of these metrics relates, perhaps indirectly, to a fourth sustainability metric, resilience. Resilience refers to the amount of perturbation a system can absorb before shifting to an alternate dynamic regime (Grimm and Wissel 1997, Holling 1973). Human activities can increase or decrease the resilience of a regime, or set of system conditions, that provides desirable ecosystem services (Mayer et al. 2004) and is beneficial to humans (Carpenter et al. 2001, Jackson et al. 2001, Orr 2002), thereby increasing or decreasing the carrying capacity.

2.2.2 Economic Metrics

Economists define sustainability as non-declining welfare or well-being over generations (Neumayer 2010, Pearce and Atkinson 1995, Tietenberg 2000). Welfare, as defined by economists, incorporates benefits obtained outside of market transactions such as environmental amenities, but allows for the possibility of trade-offs between market and non-market goods. In this sense, the field of economics can offer useful metrics that are based on the concept of weak sustainability.

Augmented economic accounts, often referred to as green accounting, is a common approach to estimating welfare, with the trends in augmented accounts measuring sustainability (Adamowicz 2003). Green Net Domestic Product (GNDP) and Genuine Savings are two of the most important economic metrics that account for depreciation of natural resources (e.g., Dasgupta 2001, Pearce and Atkinson 1993, 1995, Pezzey et al. 2006). We define both GNDP and Genuine Savings in this Section.

Gross Domestic Product (GDP) is one measure that captures the market value of a country’s output (and therefore, its aggregate consumption). However, it does not measure welfare because it excludes the value of leisure time and services produced by nature (van den Bergh 2009). Changes in GDP over time are often assumed in casual discourse to approximate changes in welfare over time. However, such a measure is unsatisfactory for purposes of measuring sustainability.

An economy that eats the proverbial seed corn or allows natural capital to depreciate faster than it is replaced, destroys the region’s capacity to maintain the current standard of living into the future and is, by definition, unsustainable. The productive capacity of the economy will be reduced in future years, eventually resulting in a decline in human welfare. However, such an economy is likely to show positive GDP growth for some period of time. GDP measures the consumption and production of market goods, while ignoring depreciation, pollution, and the services produced by nature. Consumption of seed corn and unsustainable natural resource extraction contribute to GDP by increasing current consumption, while the costs of reduced productive capacity in the future are not reflected in current GDP. Therefore, trends in GDP do not indicate the sustainability of an economy.

For the economic accounts to measure sustainability, the depreciation of all capital stocks should be included in the calculation. Net Domestic Product (NDP) is a step in the right direction. It modifies GDP by subtracting the depreciation of man-made capital. However, it does not incorporate all types of capital such as human, social, and natural capital; therefore, it is not an ideal measure of sustainability (Azqueta and Sotelsek 2007, Hartwick 1990, Weitzman 1976). Natural capital stock can include both non-renewable and renewable resources, which use different approaches for their estimation (see Hartwick 1990, Vincent 2000). Hartwick (1990) shows how pollution control costs could be incorporated into GNDP and how the stock of pollution, when it enters the utility function (i.e., pollution is a capital bad rather than a capital good), changes the calculation of GNDP.

GNDP explicitly incorporates the depreciation of man-made, human, and natural capital. Following Weitzman (1976, 2000) and Vincent (2000) who provide a good summary, we define GNDP as

$$GNDP(t) = C(t) + \lambda_m(t)\dot{K}^m(t) + \lambda_h(t)\dot{K}^h(t) + \lambda_n(t)\dot{K}^n(t) \qquad (2.1)$$

For this equation, C(t) is aggregate consumption through time, t; λ(t) are the shadow prices (i.e., the value of having an additional unit) of the different capital stocks; total capital stock includes man-made capital (K^m), human capital (K^h), and natural capital (K^n); and the stock of man-made, human, and natural capital changes over time is represented with the dot notation. The first two terms on the right side of Equation 2.1 are the standard definition of net domestic product (NDP) which includes the depreciation of man-made capital. The last two terms transform NDP into GNDP (Cairns 2002, Pezzey et al. 2006). Although it is not included in Equation 2.1, Dasgupta (2001) includes the changes in the stock of knowledge in GNDP.

A single year measurement of GNDP does not demonstrate sustainability (Heal and Kristöm 2005). Only trends in GNDP can give an indication of whether an economy is moving toward or away from sustainability. Dasgupta and Mäler (2000), and later corrected by Asheim and Weitzman (2001), test to see if

$$\Delta GNDP \geq 0 \qquad (2.2)$$

GNDP measured in real prices (adjusted for inflation) must be increasing over time for a region to be moving toward sustainability. Using this type of intertemporal welfare analysis will allow stocks of capital to be dropped from the analysis if they are not changing over time (Usher 1981 in Ahlroth 2003 and Hartwick 1990).

Some arguments against using the change in GNDP as a measure of sustainability and issues related to estimating the depreciation of natural capital can be found in Azqueta and Sotelsek (2007), Dasgupta (2001), Hanley et al. (1999), Mayer (2008), and Nordhaus and Kokkelenberg (1999). For example, Dasgupta (2001) concludes that GNDP could increase over time while the country becomes poorer and well-being decreases. Rather than Equation 2.2 representing sustainability, Dasgupta (2001: 151) states

> social well-being increases during a brief interval of time, if, and only if, the value of changes in consumption services plus the change in the value of net changes in capital assets is positive.

Genuine Savings (GS), which is based on the Hartwick Rule, was introduced by Pearce and Atkinson (1993). As stated above, a constant capital stock is necessary in order to achieve a sustainable consumption flow, which is the basis for GS. It is defined as

$$GS = \frac{S}{Y} - \frac{\Psi K}{Y} \qquad (2.3)$$

For this equation, S is savings, Y is income, ψ is depreciation on all capital stock, and K is total capital stock that is defined as above in Equation 2.1 but with different depreciation rates for each stock (Pearce and Atkinson 1993, 1995). To move toward sustainability, a region's GS would have to be 0 or positive. This condition for sustainability does not have any restrictions for substitution between man-made and natural capital. As long as GS remains constant or increasing, natural capital could be degraded (Pearce and Atkinson 1995). Hamilton and Clemens (1999) have published GS results for developing countries through the World Bank. An argument against GS can be found in Pillarisetti (2005) and criticisms related to GS are described in Dietz and Neumayer (2004).

Before we discuss whether GNDP or GS are appropriate for measuring sustainability, we recognize there is a relationship between GNDP and GS such that GNDP is equal to consumption plus GS (Dasgupta 2001). Put another way, GS is measured as GNDP minus consumption (Hamilton et al. 1997, Pearce and Atkinson 1995). Pezzey et al. (2006) define augmented Green Net National Product[6] equal to consumption expenditures plus augmented GS, where the augmentation term relates to exogenous technical progress.

Recent papers have stated that examining the trend of GNDP or GS actually is not an appropriate measure for sustainability. Some describe it as a one-sided measure and it only reveals when the region is moving away from sustainability (e.g., Pezzey 2004, Pezzey et al. 2006). Hanley et al. (2002: 6) summarizes this discussion:

> The academic consensus at the moment is that both green NNP [what we call GNDP] and GS are one-sided indicators of weak sustainability in that negative GS or falling green NNP signal non-sustainability. However, the measurement of a positive genuine savings rate/rising green NNP at a given point in time is not sufficient to lead to the conclusion that the economy is on a sustainable path and further evidence must be sought before any firm judgement can be made.

Apart from the one-sidedness identified by Hanley above, several factors may influence the relationship between GNDP (and GS) and sustainability. Exogenous technological progress changing world interest rates or terms of trade may compensate for changes in net investment. Some of these factors are reflected in trends in GNDP, but Pezzey (2004) addresses exactly how this

[6] Gross Domestic Product and Gross National Product both measure the market value of goods and services but they differ in terms of who produces the goods and services (US residents regardless of location counts towards Gross National Product) and where the goods and services are produced (within the US regardless of nationality counts towards Gross Domestic Product).

should be accounted for on a theoretical level. Like most practical estimates of GNDP, we do not address these issues in our estimates. For instance, the business cycle may lead to deceptive trends in GNDP, or a recession may lead to declining GNDP due to a drop in consumption that reflects the business cycle rather than moving away from sustainability.

Whereas some studies have attempted to estimate GS or GNDP for countries (e.g., Hamilton and Clemens 1999, Hanley et al. 1999), other studies have focused on a particular sector of an economy. For example, Matero and Saastamoinen (2007) examined forest ecosystem services in Finland's forestry accounts and Seroa da Motta and Ferraz do Amaral (2000) estimated the depreciation from timber harvest in Brazil. Hrubovcak et al. (2000) developed a green accounting framework for US agriculture.

Other indices, such as the Index of Sustainable Economic Welfare (Daly and Cobb 1989) and the Genuine Progress Indicator (Cobb et al. 1995), could be described in more detail in this section, although Hanley et al. (1999) describe these more as socio-political measures. The Index of Sustainable Economic Welfare and the Genuine Progress Indicator focus on expenditures (e.g., defensive expenditures that mitigate pollution damage) that reduce sustainability because they do not increase welfare (Cobb et al. 1995, Daly and Cobb 1989, Mayer 2008).

2.2.3 Energy

The transformation of available energy potentials underlies all action in the observable universe and, as a result, all known processes and systems can be analyzed using energy-based methods. Although all processes have an energetic aspect, most energy-based methods limit their scope of application. There are several energetic approaches that might be used to determine if a given system regime is sustainable, but two energy-based methods are examined in this section; Exergy Analysis (ExA) and Emergy Analysis (EmA). ExA was first developed to enhance scientific understanding of thermal and chemical processes and to identify the thermodynamically most-efficient manner in which a process can be carried out within its environment. EmA recognizes that Energy Systems Theory (Odum 1994), conceptually, can be applied to analyze all known systems, but that boundaries must be arbitrarily set, based on the particular problem or research question under consideration. In general, the boundaries set for an EmA tend to be more broad and more comprehensive than those that would be set for an ExA of an equivalent problem (Sciubba and Ulgiati 2005).

2.2.3.1 Exergy Analysis

Preliminary work that eventually gave rise to exergy analysis was carried out in Europe during the latter half of the 19th Century. The work of Joule on energy conservation established the first law of thermodynamics and that of Clausius, Thomson, Tait, Maxwell, and primarily Gibbs gave rise to the idea of the maximum work that can be obtained from an energy potential or the second law of thermodynamics (Szargut et al. 1988). Gouy (1889) and Stodola (1898) independently showed that for work performed under real conditions, the amount of work actually obtained from a given thermal energy potential is always smaller than the maximum possible work, because of the irreversibility of thermal processes. Because of these different interpretations of the same word "energy," Rant (1956) proposed the term "exergy" to describe the ability of energy to perform work in a transformation (energy quality), especially under the conditions occurring in technical processes (Szargut et al. 1988). In an exergy analysis, the quality of energy is accounted for, not just the quantity as in an energy analysis (Dewulf et al. 2005). The primary purpose for exergy analysis has been to give information about the possibilities for improving thermal processes, but it cannot say whether such improvements are practicable. However, exergy and economic analyses have been combined in an attempt to answer such questions (El-Sayed and Evans 1970, Evans 1961, Evans and Tribus 1965).

Exergy can be used as an indicator of the renewability of industrial processes (Berthiaume et al. 2001), as a metric of sustainability for technology (Dewulf et al. 2005) and bioenergy systems (Dewulf et al. 2005). Further, ExA allows for the assessment of the efficiency of production chain, which has obvious potential benefits for industry (Dewulf et al. 2005), and has been made possible via Cumulative Exergy Consumption, which sums the exergy values of all resource inflows (Zhang et al. 2010). For assessing the sustainability of systems, an extended form of exergy analysis, (e.g., cumulative exergy analysis; Sciubba and Ulgiati 2005) should be employed. If ExA is extended to the boundaries of the biosphere, it effectively approaches an EmA as evidenced by the analysis of Ukidwe and Bakshi (2007), who defined a quantity "ecologically cumulative exergy," which was effectively emergy. Exergy does not take into account ecosystem services, except some provisioning services, which is an obvious limitation when exergy is advocated as a "holistic" sustainability metric (Zhang et al. 2010).

2.2.3.2 Emergy Analysis

EmA developed from Energy Systems Theory (EST), a discipline derived from the union of the fields of ecology, irreversible thermodynamics, and general systems theory (Odum 1994). EST identifies and develops general laws and principles that help understand and interpret natural phenomena. The transformation of available energy is the fundamental, underlying causal factor behind all action in systems of many kinds, including ecological, social, and economic systems, all of which can be characterized and analyzed in terms of a network of energy flows.

EmA builds on the tools of the energy systems approach (Odum 1971, 1994, 1996) to evaluate the sustainability of present and possible future human activities. EmA focuses on the system's use and exchange of emergy, which is the available energy of one kind previously used up, directly and indirectly, to make a service or product. The balance of emergy for a system is expressed in terms of the emergy inputs from renewable and nonrenewable resources of local or imported origin observed relative to the economic and social activities supported by the system. Emergy like exergy is a concept grounded in the second law of thermodynamics (i.e., based on the quantity of available energy [exergy] used up in an irreversible transformation). Both exergy and emergy must initially satisfy first law constraints (i.e., the conservation of energy).

Sustainability is not a unitary idea because it can have different meaning for different individuals or groups. In addition, sustainability itself is a relative term. In this context, emergy analyses have been conducted at various spatial scales; historical studies of nations have been performed (e.g., Rydberg and Jansen 2002, Tilley 2006) and nations have been evaluated over decades (e.g., Huang et al. 2006). Once the various spatial and temporal parameters of sustainability have been decided, different aspects of sustainability can be examined using the appropriate emergy indices (Brown and Ulgiati 1997, Lu et al. 2003, Lu and Campbell 2009, Ulgiati and Brown 1998). Finally, emergy and exergy methods have been used together to examine energy conversion processes (Tonon et al. 2006) and emergy has been combined with, and compared to, other metrics of sustainability such as ecological footprint (e.g., Giannetti et al. 2010, Hu et al. 2009, Siche et al. 2010a, 2010b, Zhao et al. 2005).

2.2.4 System Order

Researchers have studied the impact of global trends on sustainability recognizing both positive and negative movement of classes of indicators affecting the transition to a sustainable future (Kates and Parris 2003). Such work underscores the importance of evaluating and managing patterns of change related to growth and development. Because human and natural systems are complex and integrated, no action exists in isolation. As a result, any action starts a chain of events propagating through multi-dimensional spatial and temporal scales. Although some systems are brittle and unstable, others (e.g., ecosystems) are evolutionary and adaptable. If a system is resilient, it typically will be able to withstand periodic fluctuations and still maintain function. However, it is possible for a system to reach a dynamic threshold and abruptly shift from one set of system conditions (i.e., regimes) to another.

Regime shifts have been demonstrated for a multitude of ecological and social systems, and often have significant ecological and economic consequences. A classic example of a regime shift is a shallow lake where a system may shift from an oligotrophic to an eutrophic regime due to inflow of phosphorus resulting in algae overgrowth, depletion of oxygen needed for survival of fish, a loss of biodiversity, and reduced water quality. Subsequently, the human-desired function and utility of the system is lost. In the context of dynamic change and regimes, sustainability is related to finding and maintaining a set of system conditions (i.e., a dynamic regime) that can support the social and economic development of human and environmental systems without major, irrecoverable environmental consequences (Karunanithi et al. 2008). Furthermore, sustainability is predicated on the human preference for the persistence of a particular regime over another in order to maintain desired system function and support current and future generations, (Mayer et al. 2006). Hence, quantifying and identifying regime shifts is critically important to sustainability.

There has been a great deal of research on developing regime shifts indicators (Biggs et al. 2009, Carpenter 2003, Carpenter and Brock 2006, Chisholm and Filotas 2009, Dakos et al. 2008, Scheffer et al. 2009, van Nes and Scheffer 2007). In real, complex systems, this task involves tracking multiple system variables simultaneously over time. Although variance, skewness, kurtosis, and critical slowing down are common indicators of regime shift, research is still needed to determine whether these indicators will signal shifts in real, complex systems (Scheffer et al. 2009). One method of assessing the dynamic changes in complex systems is information theory.

Information theory generally relates to the quantification of information in data and has enhanced the ability to assess organizational complexity even in the presence of imperfect observations (e.g., noisy data; Mayer et al. 2006). It has been used to understand various types of systems (Fath et al. 2003) including food web models (Fath and Cabezas 2004) and ecosystem functioning (Patricio et al. 2004), and is commonly used for monitoring ecosystem complexity (Anand and Orlóci 2000, Svirezhev 2000) and stability (Fath and Cabezas 2004, Ulanowicz 1997). Key methods within information theory include Shannon information (Shannon and Weaver 1949), Gini-Simpson information (Colubi 1996), and Fisher information (Cabezas et al. 2005a). Both Shannon and Gini-Simpson information have been used, for example, as estimates of biological diversity as they use number of species and species abundance to calculate system information. One feature of these measures is that given a different ordering of the same species probabilities, both indices result in the same level of information. However, changes in order are crucial for evaluating the dynamic behavior and regimes in complex systems (Cabezas et al. 2005a, Fath et al. 2003).

Unlike other measures of system information, Fisher information (FI) provides a means of monitoring system variables to characterize a system's dynamic order including its regimes and regime shifts (Cabezas et al. 2003). The ability to detect regimes and regime shifts permits the identification of fundamental changes occurring in the system and provides insight into what can be done to abate negative consequences. In practice, FI has been applied to deriving fundamental equations of physics, thermodynamics, and population genetics (Frieden 1998, Frieden 2001). It has been used as a measure of dynamic order in complex systems (Fath et al. 2003, Mayer et al. 2006). It has been proposed as a quantitative index for the detection and assessment of ecosystem regime shifts (Karunanithi et al. 2008, Mayer et al. 2006) and as a sustainability metric (Cabezas and Fath 2002). Moreover, FI has been used to study model systems including the stability of a multiple compartment food web (Cabezas et al. 2005a, Cabezas et al. 2005b, Fath and Cabezas 2004) and to optimize control of dynamic model systems for sustainable environmental management (Shastri et al. 2008a, Shastri et al. 2008b).

2.3 Sustainability Studies That Use Multiple Metrics

No single metric should be considered a perfect measure of sustainability because there are multiple definitions of sustainability and few, if any, metrics encapsulate all the definitions; most metrics also are difficult to calculate (Hanley et al. 1999). Neumayer (2010) finds that no conclusion can be made about which sustainability paradigm (i.e., weak vs. strong sustainability) is most appropriate (but see Dietz and Neumayer 2007). This would suggest using various ways to measure sustainability in order to cover both paradigms.

Several papers suggest there are three dimensions, or pillars, of sustainability: economic, environmental, and social (Adamowicz 2003, Böhringer and Jochem 2007, Hanley et al. 1999, Tanzil and Beloff 2006, UN 2002). It seems clear that different types of indices will be required to assess the three pillars of sustainability. To help select metrics Böhringer and Jochem (2007) summarize five criteria for choosing the right sustainability metrics: 1) a connection to the definition of sustainability, 2) indicators from holistic fields, 3) good data that are available for many years, 4) process-oriented selection, and 5) the ability to derive political objectives.

Whereas some studies have focused on particular metrics, a number have applied multiple metrics in an attempt to address sustainability. Although some of these studies discussed major differences in comparing measures of sustainability, others focused on capturing multiple aspects of sustainability. For example, Hanley et al. (1999) used a time series analysis to compare seven sustainability measures for Scotland. The seven measures included: (green) Net National Product, GS, EFA, Environmental Space, Net Primary Productivity, Index of Sustainable Economic Welfare, and Genuine Progress Indicator. These measures were used to examine Scotland from 1980-1993. Overall, they found Scotland to be unsustainable; however, the individual measures provided results for different aspects of the system under study.

Pezzey et al. (2006) compared Green Net National Product and the interest on augmented GS for Scotland during 1992-1999. The theory suggests that both the augmented Green Net National Product and the interest on augmented GS should be equal. The authors found that both measures were positive, suggesting that Scotland was sustainable over the time period, but the two measures differed in magnitude. They believe the mismatch was related to assumptions used in their approach.

In a special issue of the *Journal of Environmental Management*, Pulselli et al. (2008) and Tiezzi and Bastianoni (2008) presented a summary of a large sustainability project for the Siena Province using ecological metrics. The authors proposed a "sustainability diagnosis" where the diagnosis is accomplished using a systemic approach, in order to develop sustainable policies. The methods included Emergy Evaluation (i.e., EmA), EFA, Greenhouse Gas Inventory, Life Cycle Assessment, and Extended Exergy Analysis. The results from these measures were then analyzed using Principal Component Analysis (PCA) to examine similarities and differences among the methods.

Bastianoni et al. (2008) discussed the comparisons of the different metrics using PCA for the territory. PCA examines the correlation among many metrics and creates a smaller set of uncorrelated variables, or principal components (Jolliffe 2002). The authors found some interesting results when examining correlations related to particular territories. For example, the largest urban areas have similarities with population, population density, total income, CO_2, and purchased non-local resources. In addition, Bastianoni et al. (2008) were surprised to see a low correlation between Emergy and EFA. They suggested the low correlation could be caused by EFA not calculating the extraction of non-renewable materials explicitly and only focusing on household consumption. Because Emergy did include extraction and incorporated industrial consumption, the result was a low correlation between the two metrics.

Wilson et al. (2007) compared six sustainable development indices for 132 nations. The metrics included EFA, Surplus Biocapacity Measure, the Environmental Sustainability Index, the Well-being Index, Human Development Index, and GDP. Using the Pearson product-moment correlation, they found the environmental sustainability index and well-being index were positively correlated, as were the well-being index, the human development index, and GDP. Negative correlations were identified among EFA, the Well-being Index, the Human Development Index and GDP.

Eight metrics were estimated for 1990-2000 to examine the sustainability pattern of France (Nourry 2008). The eight metrics were (green) Net National Product, GS, EFA, Indicator of Sustainable Economic Welfare, Genuine Progress Indicator, Pollution-sensitive Human Development Indicator, Sustainable Human Development Indicator, and French Dashboard on Sustainable Development. Nourry (2008: 10) defines this last indicator as a "non-monetary measure composed of non-aggregated indicators."[7] Some of the 15 indicators used were life expectancy without disability, overfishing, GS, waste production and population, and public debt (Nourry 2008). The results suggest that France satisfies weak sustainability but not strong sustainability.

Lee and Huang (2007) examined 51 indicators of sustainability for Taipei from 1994-2004. Those indicators were categorized into four dimensions and reduced to estimate a composite sustainability index. For example, the environmental dimension included indicators such as per capita CO_2 emissions, reservoir water quality, and tap water quality. Social indicators included urban population density, the wealth gap, and crime rate among others. The economic dimension included average personal income, female/male unemployment rate, and percentage of households with internet connection. The institutional dimension incorporated enforcement of local environmental plans, joint international cooperation related to sustainable development, and the ratio of the environmental and ecological budget to total budget in its calculation. The four different dimensions were aggregated into one measure (i.e., metric) using equal weighting and suggested that Taipei was moving towards sustainability. However, only the environmental and social dimensions indicated this movement. The economic dimension only started increasing after 2002 and the institutional dimension was inconsistent.

[7] There is not a consensus on the use of the terms indicator and metric. Nourry's (2008) use of indicator is equivalent to our use of metric in this report.

Graymore et al. (2008) focused on South East Queensland as a regional case study. The metrics examined included EFA, Well-being Assessment, Ecosystem Health Assessment, Quality of Life, and Natural Resource Availability. The authors determined that calculating these metrics at the regional scale was not informative for a few reasons. For example, data limitations at the regional scale caused problems with calculating the metrics, especially when attempting to examine trends. In addition, the metrics examined were not always easy to understand or did not reveal information about sustainability. Graymore et al. (2008) conclude that a new approach is necessary given the limitations of their approach for calculating regional sustainability metrics.

Similar to Hanley et al. (1999), the special issue of the *Journal of Environmental Management* (2008), and Nourry (2008), we propose an approach that includes multiple metrics in order to measure the sustainability of a region. Rather than comparing the metrics for different areas (e.g., Wilson et al. 2007), we think the sustainability measures we chose will capture various attributes of the SLB region, providing a holistic view similar to that of the Pulselli et al. (2008) "sustainability diagnosis."

2.4 Choice of Metrics for San Luis Basin Sustainability Metrics Project

This project utilized available environmental, economic, and social data to calculate four indices of sustainability. The metrics or indices included: 1) environmental footprint as characterized by EFA, 2) economic well-being as ascertained from Green Net Regional Product (GNRP; similar to GNDP but defined on a smaller spatial scale), 3) energy flow through the system as computed from an EmA, and 4) dynamic order estimated from FI. We chose several metrics for a few reasons. First, we suspect that no single metric will provide sufficient information for planners to assess adequately different aspects of the system. We also think that multiple metrics are necessary because no metric is perfect in capturing a specific aspect of the system. In addition, these four metrics cover both paradigms of weak and strong sustainability (as described above). GNRP is a measure of weak sustainability (e.g., Neumayer 2010, Pezzey et al. 2006) and we believe FI and the associated Sustainable Regimes Hypothesis are measures of weak sustainability. Although the approach is not directly indicative of resource substitutability and focuses on the functionality of a system, it is possible for resources (e.g., species) to be replaced as long as the system does not become disorderly (i.e., it continues to function). EFA is based on the concept of strong sustainability (e.g., Ferguson 2002, Mayer 2008, Neumayer 2010, Rees 2002, but see Dietz and Neumayer 2007, McManus and Haughton 2006) and so is EmA (e.g., Giannetti et al. 2010).

We note these multiple metrics do use similar variables, and therefore, there is some redundancy in the metrics. This redundancy in variables could result in similar behavior in the metrics over time, under some circumstances, depending on the influence of the particular variables. Table 2.1 summarizes the different metrics and the data needed for estimation. It presents the spatial scale of the data and the years the data were available. EmA is the most data intensive with FI following. However, EmA has specific data requirements (e.g., energy inflows and outflows), whereas FI has no requirements other than data that adequately represent the system behavior. Of the broad categories of variables presented, EFA and GNRP are the least data intensive. The only variable that all metrics include is population, but each uses it in different ways. For example, GNRP uses it to estimate CO_2 emissions for the SLB based on per capita estimates for Colorado and New Mexico. EFA calculates the land required for each land category to support both an individual and entire population of the region. It may be one of the easiest of the sustainability metrics for decision makers to understand and conceptualize and may be one of the most commonly computed. Although most of the variables are required by at least two of the metrics, each metric plays a unique and important role in measuring sustainability for the SLB as we describe below.

This suite of metrics will give public land managers, the local community, and the USEPA a methodology for monitoring the effect of land management and decision-making on environmental quality and economic sustainability. We believe the sustainability metrics selected will assist with the review of public land development and management decisions and promoting environmental quality.

2.4.1 Components Basic to Environmental Systems

The four metrics we selected capture what we determined to be fundamental aspects of an environmental system and its sustainability. We built our methodology based on these primary aspects and selected metrics in an attempt to capture or quantify those aspects. At a basic level, we recognized that an environmental system has some inherent order, whether the factors responsible for maintaining that order are clearly identified or understood. Furthermore, it takes energy to maintain order in an environmental system. Finally, sustainability is inherently an anthropocentric issue and how well off humans are may dictate their influences on the system. An individual or population that is meeting its needs for existence has the luxury of being concerned about the effect it has on its environment, whereas a population that is barely surviving may not be intensely concerned with long-term sustainability.

We selected metrics that capture each of these fundamental aspects. FI was selected to measure dynamic order of the overall system. We chose EmA because it measures the quality-normalized flow of energy through the system. GNRP was chosen to capture the overall economic well-being of the population and EFA was selected to capture the impact a population has on environmental resources resulting from consumption and waste production. Out of the four metrics, using FI to characterize sustainability is a relatively new metric (Mayer 2008). Application of the other metrics is relatively common and they are established as metrics of sustainability in the scientific literature (e.g., Mayer 2008).

Although the metrics were selected because they measure what we identified as primary or fundamental aspects of an environmental system, they assess some component of the economic, social, and environmental pillars of sustainability and these three pillars, traditionally, are considered to support sustainable development (Bobylev 2009, UN 2002). Measurements relevant to each pillar of sustainability will enable decision makers to assess where the regional environmental system is in need of management actions and help them make choices that can directly guide the path of the regional system toward sustainability.

Finally, although a certain suite of metrics was chosen for this study, it does not mean that we view these as providing the final word on system sustainability. The issue of sustainability is complex and we expect that other metrics exist, or may be developed, that will provide improvements in the methods of calculating indices in the future. In the next four chapters, we present the methodology and results of EFA, GNRP, EmA, and FI, respectively.

2.5 References

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Table 2.1 – Broad categorical list of data collected on key variables, showing which metric used the variable, the source of the data, the scale at which the data were collected, and the available years of data reported.

Variable	Metric[1]				Source[2]	Scale[3]	Years
Population	EmA	EFA	GNRP	FI	BEA	C, S	1980-2005
Personal income	EmA		GNRP	FI	BEA	C, S	1980-2005
Land area	EmA	EFA		FI	NASS	C	1980-2005
Precipitation	EmA			FI	PRISM Group	C	1980-2005
Solar and Wind	EmA			FI	NASS	C	1980-2005
Food consumption		EFA		FI	USDA-ARS	N	1980-2005
Food production	EmA			FI	NASS	C	1980-2005
Imports	EmA				GI	C	1995-2005
Exports	EmA				GI	C	1995-2005
Forest harvest	EmA	EFA		FI	USDA-FS	C	1980-2005
Energy consumption	EmA	EFA		FI	EIA	S	1980-2005
CO_2 emissions			GNRP	FI	EIA	S	1980-2005
Water balance	EmA		GNRP	FI	CDSS	R	1980-2005
Wind erosion	EmA		GNRP	FI	Multiple sources	C	1980-2005

[1]EmA = Emergy Analysis; EFA = Ecological Footprint Analysis; GNRP = Green Net Regional Product; FI = Fisher information. [2]BEA = Bureau of Economic Analysis; NASS = National Agricultural Statistics Service; PRISM Group = Parameter-elevation Regressions on Independent Slopes Model Group; USDA-ARS = United States Department of Agriculture, Agricultural Research Station; USDA-FS = United States Department of Agriculture, Forest Service; CDSS = Colorado's Decision Support Systems; GI = Global Insight, Inc.; EIA = Energy Information Administration.
[3]C = county; R = region; S = state; N = national.

3.0 Ecological Footprint

3.1 Introduction

In this chapter, we introduce data sources and the methodology employed to perform an Ecological Footprint Analysis (EFA) for the San Luis Basin (SLB). We present and discuss the results, interpret what they mean, and discuss methodological issues in an attempt to make the approach more useful to decision makers.

EFA, more appropriately called environmental footprint (Eaton et al. 2007) analysis, is a commonly used metric of sustainability because it is straightforward in theory and easy to conceptualize. EFA attempts to capture human impacts on the regenerative capacity of an environmental system (Chambers et al. 2000) by identifying the amount of bioproductive land required to support a person's average annual consumption and waste production (Wackernagel and Rees 1996). Since Wackernagel and Rees (1996) introduced it, EFA methodology has been continually evolving as researchers have attempted to improve the methodology (e.g., Lenzen and Murray 2001, Luck et al. 2001, Monfreda et al. 2004, Medved 2006, Wackernagel 2009). In general, EFA categorizes bioproductive land into one of six types: energy, arable, forest, pasture, built, and sea. Land that does not meet one of these six categories is deemed non-productive and is not included in EFA accounting (Chambers et al. 2000). Furthermore, in the accounting twelve percent of the land is set aside for biodiversity (Chambers et al. 2000, but see Noss and Cooperrider 1994 for discussion of the appropriate percentage). EFA calculates the supply (biocapacity) of land available to support a population and the demand (ecological footprint) a population places on these six land categories by estimating how much land is being used to support the population. The biocapacity in a given region is compared to the ecological footprint of the population by subtracting demand from supply. Examining this balance sheet over time will reveal if there is an ecological reserve or deficit and if a population is moving toward or away from sustainability as defined by the EFA method.

This metric has been applied to numerous systems. For instance, EFA accounting has been conducted at global (e.g., WWF 2008), national (e.g., Erb 2004, Lammers et al. 2008, Lenzen and Murray 2001, Medved 2006, Wackernagel and Yount 1998, Wackernagel et al. 1999, Wackernagel et al. 2004a, WWF 2008), regional (e.g., Graymore et al. 2008, Huang et al. 2007, Pulselli et al. 2008, Zhao et al. 2008), and municipal (e.g., Collins et al. 2006, Scotti et al. 2009, Wood and Garnett 2009) spatial scales. EFA has been conducted for industry or product level (e.g., wine – Niccolucci et al. 2008, university campus – Li et al. 2008, tourism - Patterson et al. 2007), and individual or household levels (e.g., Chambers et al. 2000) as well. Some researchers have conducted EFA analysis by comparing and contrasting multiple spatial scales (e.g., Lenzen and Murray 2003, Luck et al. 2001).

We conducted conventional EFA accounting using the compound approach as introduced by Wackernagel and Rees (1996) and expanded by Chambers et al. (2000) because it is more inclusive and robust compared to the component-based approach (Chambers et al. 2000). In general, an EFA calculation requires four components or sets of variables: 1) the size of the population in the region of interest, 2) the amount of consumables in various categories used per individual, 3) the amount of energy of various types consumed per individual, and 4) the amount of biologically productive land, as defined by EFA, available in the region of interest. The consumption component includes the biotic resources such as meat, dairy, fruits, and vegetables. Consumption is usually calculated by adding the quantity of imported consumables to the amount produced in the system under study and subtracting the amount exported from the system. The remaining quantity is assumed to be consumed by the population (Chambers et al. 2000, Wackernagel and Rees 1996). The energy balance component considers both locally generated energy and, if known, energy embodied in traded goods (Chambers et al. 2000, Wackernagel and Rees 1996). Primary fuel consumption is adjusted for carbon content and used to derive the amount of forested land necessary to sequester the resulting CO_2 emissions (Chambers et al. 2000). Lastly, the area (in hectares) of each of the six land categories of biologically productive land is measured to calculate the biocapacity. Each of these components is used in one of three accounting type ledgers to determine the supply (biocapacity) and demand (ecological footprint) of the environmental system (Chambers et al. 2000, Wackernagel 1996).

Note that we deviate slightly from the naming convention commonly employed in an EFA (e.g., Chambers et al. 2000, Wackernagel 1996) in an attempt to make the text easier to follow. It is typical for the population's ecological footprint to be denoted with *EF* and the per capita ecological footprint identified with *ef*. To be consistent with this format, we have deviated from the convention by representing the population's biocapacity (typically denoted as BC_p) as *BC* and the per capita biocapacity as *bc* (compared to the frequently used BC_c).

The amount of land area appropriated per capita (aa_i) for each major consumption item (c_i) is estimated as:

$$aa_i = \frac{C_i}{N} \tag{3.1}$$

where *N* is the population of the region. The average demand or ecological footprint per capita (*ef*) is computed by summing all the ecosystem areas appropriated (aa_i) by all purchased items in the annual consumption of goods and services.

$$ef = \Sigma aa_i \tag{3.2}$$

Each item is converted into a footprint value, represented as hectares per capita (ha/ca). Often these areas are adjusted to express a world average and are converted to global hectares. An ecological footprint (*EF*) for the entire system or region is calculated by multiplying *ef* by the population size (*N*).

$$EF = N(ef) \tag{3.3}$$

The biocapacity for the population (*BC*) is the number of hectares of each of the six bioproductive land categories in the area under study.

$$BC = \Sigma L_i \tag{3.4}$$

where L_i indexes each of the six categories of land. A per capita biocapacity (*bc*) is calculated by dividing the region's *BC* by the population of the region.

$$bc = \frac{\Sigma L_i}{N} \tag{3.5}$$

An ecological balance is calculated by subtracting *ef* from *bc* to determine if there is an ecological deficit or reserve. If *ef* exceeds *bc*, the system is considered unsustainable at the individual level, and if *EF* exceeds *BC,* an ecological deficit exists and the system is considered unsustainable regionally. Conversely, the system is considered sustainable if there is an ecological reserve ($ef < bc$ or $EF < BC$). However, because we question the accuracy of identifying a system as sustainable (see Chapter 1), we identify a system's movement toward or away from sustainability by examining the ecological balance. A system is considered moving away from sustainability if the ecological reserve is decreasing or, if there is an ecological deficit, the deficit is increasing through time.

3.2 Methods

The data needs of traditional EFA accounting are relatively straightforward, although they can be intensive. EFA requires food consumables such as meat, dairy, fish, fruits and vegetables, animal feed, roots and tubers, and pulses (i.e., legumes), and per capita energy consumption. This level of detail creates difficulty when analyzing sub-national regions because it is often difficult to obtain data for local areas, especially parts of states. To overcome this quandary, researchers often approximate values for many of the variables or use values from disparate years (e.g., Bagliani et al. 2008). This occurs because data on consumption patterns are more likely to be collected for national and even state level rather than for smaller political units. Thus, depending on the data required, we were limited by the availability of data sources due to the regional nature of our study and the requirement for 26 consecutive yearly (1980-2005) values. Rather than calculating a national EFA and scaling it to the region by multiplying by the population of the region, we decided to reduce the number of variables to those that were necessary to calculate the EFA for the region. Because our goal was to calculate a simplified ecological footprint for the region and not necessarily a more detailed ecological footprint as calculated in Wackernagel et al. (2005), we attempted to restrict our variables to data specific to the region (i.e., county-level data). However, because data for some essential components of a footprint analysis were not available at the individual or county level, we had to utilize data that were not specific to the region. When necessary, data that were available only at the state or national level were scaled to the region of study based on per capita rates in the larger systems (Table 3.1). Any data that were reported less frequently than annually were linearly interpolated in order to calculate EFA for all 26 years.

3.3 Data, Variables, and Sources

We selected variables easily obtained and freely available, thereby enabling a calculation that could be undertaken by virtually any entity interested in conducting its own EFA. Most variables were recorded as reported from the original data source (Table 3.1). However, biocapacity was calculated for some land categories. Specifically, arable land was reported for each county in the National Agricultural Statistics Service (NASS) report at 5-year intervals (NASS 1984, 1989, 1994, 2009a, 2009b). Pasture was estimated using the NASS reports by subtracting the hectares of arable land from total farmland. Forest land was estimated from United States Department of Agriculture (USDA) Forest Service data and subtracting the amount of harvested forest for each county. Built land was obtained from the US Census Bureau from the land area reported for each Census-designated place in each county. Because the region is land-locked, there was no bioproductive area for the sea category. Lastly, energy land is the amount of forested land required to sequester CO_2 produced from energy consumption. This value was zero hectares (ha) on the supply side of the equation because it is not a supply, per se. Energy land is obtained by subtracting from forest land the area necessary to sequester CO_2 and, therefore, does not exist before CO_2 is produced.

Energy consumption data for the State of Colorado were obtained from the Department of Energy's Energy Information Administration (EIA; EIA 2006). We assumed that EIA data calculated on a per capita usage and multiplied by the population of the SLB was sufficient to estimate the energy consumption. We justified this assumption by comparing coal, natural gas, and propane consumption in the SLB to their consumptive use for the State of Colorado. We decided the more readily available EIA data adequately represented consumption for these sources (see Appendix 3-A). Using EIA data for Colorado, consumption was calculated as per capita for the state and included coal, natural gas, petroleum, nuclear, hydroelectric, and wood and waste categories. An added benefit of using EIA data, the petroleum category includes motor fuel, thereby capturing energy consumption for transportation in the SLB. Energy consumption was converted to area of forest and the corresponding energy land required for CO_2 absorption, following Chambers et al. (2000).

Per capita food consumption for the US, from USDA Economic Research Service (USDA-ERS 2009), was used to estimate food consumption for the region under study. Because data were already in quantity consumed, it was not necessary to subtract exports from imports and production to estimate consumption. Each food item was assigned to an appropriate land category and a per capita footprint was calculated for each food item by dividing the kg consumed by the global yield for that kind of land and dividing the result by the population of the region. The footprint for each land category was summed to produce the amount of land required to support levels of consumption of the population of the region.

Global yields were used because it is unlikely that most items consumed in the region were produced in the region. Global yields were taken from Chambers et al. (2000: 70-73) and were constant for all years. Ideally, global yields and conversion factors (see below) would be calculated for each year and would result in a better estimate of the EFA for a region. However, more accurate annual values are unlikely to have a large influence on the results. Another compromise in our analysis is that many items are not included in this EFA because every consumable is not reported or tracked at the regional level and, thus, it is not currently possible to include every item consumed.

Many studies suggest converting footprints into global hectares (gha) in order to allow comparison of EFAs between systems (e.g., Wackernagel et al. 2004b, Wiedmann and Lenzen 2007). A global hectare is "normalized to the area-weighted average productivity of biologically productive land and water in a given year" (Global Footprint Network 2008). In other words, a global hectare is the global average productivity (i.e., kg produced) per one hectare of land or water and facilitates comparison between EFAs for different nations. Equivalence factors and yield factors are necessary to convert actual ha into gha and they can be obtained from the literature for certain years (e.g., Chambers et al. 2000, Wackernagel and Yount 1998), but a complete set is difficult to obtain without additional expense. To overcome this lack of factors, we recorded values from Chambers et al. (2000) and McIntyre et al. (2007) for alternative calculations using gha. However, our goal was not to produce a mechanism by which regions can be compared but rather to enable a region to analyze their movement toward or away from sustainability and manage accordingly. Moreover, because the purpose of our study was practical, rather than academic in nature, we decided to use local hectares as the working unit.

3.4 Results

We were able to assemble 26 years (1980-2005) of data consisting of 35 variables of consumption (Table 3.1). We also obtained data for agricultural production of the eight major products in the region but these values were not necessary to estimate consumption because national consumption values were used. Appendix 3-B contains a sample accounting ledger used in EFA and Appendix 3-C contains the complete data worksheet.

Biocapacity shows a decreasing trend for the 26-year period, peaking at nearly 36 hectares per capita (ha/ca) in 1980 and decreasing to less than 28 ha/ca in 2005 (Fig. 3.1a; Table 3.2). Ecological footprint was relatively flat, with a low of 5.1 ha/ca in 1997 to a high of 5.5 ha/ca in 1985 (Fig. 3.1a; Table 3.2). Subtracting *ef* from *bc* provides the ecological balance and reveals the SLB had an ecological reserve, although it was declining, during the period examined. The reserve was at a period high of 30.54 ha/ca in 1980 and declined steadily though year 2005 when the ecological remainder was 22.34 ha/ca (Table 3.2).

3.5 Discussion

3.5.1 Biocapacity (supply)

Although the SLB appears to have an abundance of biocapacity, this is a result of low population density and large area of pasture and arable lands. These two land types typically increase the human carrying capacity of a system and are heavily weighted in EFA as is evident in the value the methodology places on these (human-centric) biologically productive land categories. Moreover, an abundance of forest is available to sequester CO_2 and provide renewable wood products. However, it must be remembered the SLB is part of a larger system and resources produced in the region help support that larger system, including the rest of the US and world.

The decrease in *bc* seems to be due, primarily, to population growth in the region. An increasing population draws on a relatively fixed supply of bioproductive land in the SLB, resulting in a decreasing amount of bioproductive land per person. Specifically, biocapacity of forest declined from 22.93 ha/ca to 18.56 ha/ca and pasture declined from 12.13 ha/ca to 7.17 ha/ca (Fig. 3.2). Arable land was variable during the 26-year period, starting at 5.67 ha/ca in 1980, peaking in 1990 at 5.96 ha/ca, declining to 5.13 ha/ca in 2000, and rising to 5.33 ha/ca in 2005 (Fig. 3.2). During this period, built land increased slightly during the 26 years (from 0.12 ha/ca to 0.15 ha/ca; Fig. 3.2). In absolute terms, the number of hectares of arable land increased, the hectares of forest remained constant, and the hectares of pasture decreased in the SLB region during the 26 years. The results suggest the overall decline in *BC* for the region was minimal, especially when compared to the decline in *bc* (Fig. 3.1a and b). Hence, as the population size increased, more people were drawing on the same number of hectares of resources, resulting in fewer resources available per person. This indicates the decrease in biocapacity of forest and pasture land categories were due to population growth and the *bc* available from these land categories. Conversely, although biocapacity of arable land was variable, there was an overall decrease (Fig. 3.2), indicating an increase in the supply of total hectares of arable land in the region that did not quite keep pace with population growth. Lastly, the amount of built land increased from 4572 ha in 1980 to an estimated 7350 ha in 2005. This is an increase of more than 60% and represents land that typically, according to EFA accounting, was agricultural land. In summary, the overall decrease in biocapacity in the SLB in these calculations is largely due to population increase. If the region were a self-reliant, closed system, the carrying capacity of the system would be far from reached and many more individuals could be supported. However, because the SLB provides resources to support the larger system, and draws on resources from outside the region (i.e., it is not a closed system), the excess biocapacity should be evaluated with that in mind.

3.5.2 Ecological Footprint (demand)

Unlike the US (e.g., Wackernagel and Yount 1998, WWF 2008), the average ecological footprint of individuals in the SLB decreased slightly (with some variation) during the time analyzed (Fig 3.1a). Ecological footprint (*ef)* was 5.41 ha/ca in 1980 and finished the period at 5.13 ha/ca in 2005 (Fig 3.1a). However, the high of 5.5 ha/ca was in 1985 and the low of 5.10 ha/ca occurred in 1997 (Fig 3.1a). Although *ef* showed a general decrease, the *EF* for the SLB increased slightly (Fig. 3.1b), likely due to an increase in population in the SLB.

Examining the individual land categories and the energy footprint can help identify components responsible for trends (Fig. 3.3). Overall, demand placed on each of the land categories remained relatively constant during the 26-year period, except for forest (Fig. 3.3). Per capita demand on pasture, arable, built, sea, and energy lands have remained stable, as consumption did not increase dramatically during the period. However, during the same period the area of forest remained constant while forest harvest increased from 23973 million board feet (MBF) in 1980 to 35251 MBF in 1989 and has been declining since to 4444 MBF in 2005. This coupled with the increase in population resulted in a decrease in area of forest available per capita in the region.

Focusing on energy land, there was a general increase in total energy consumption from fossil fuels for the region. However, although there was some variability, per capita energy footprint revealed a slight decline for coal, natural gas, and petroleum consumption (slope = -0.0021, -0.002, and -0.004, respectively) in the 26-year period. Energy consumption from nuclear and hydroelectric was nonexistent and is a source that could be expanded to benefit the region. Wood and waste usage, however, increased during the first 6 years of the period analyzed and has been decreasing both per capita and for the population since 1986 (Fig. 3.4). The US Census Bureau provides a category of number of homes using wood for heating and this value for the SLB decreased from 1990 to 2000 census from 3750 to 2327 homes (US Census Bureau 1990, 2000), suggesting that such a reduction was realistic.

3.5.3 Global Hectares

Converting ha into gha increased *ef* by less than 10%, or about 0.5 ha and available *bc* nearly doubled. For example, in 1980 the *ef* was 5.41 ha (5.94 gha) and *bc* (minus 12% for biodiversity) was 35.95 ha (64.39 gha). The ecological reserve was 30.54 ha (58.46 gha). In 2005 *EF* was 5.13 ha (5.51 gha), *bc* was 27.47 ha (49.31 gha), and the remainder was 22.34 ha (43.80 gha). Of course, the conversion from ha to gha would be better using year specific yield and equivalence factors, but the difference likely would be minor. For example, Lammers et al. (2008) report an equivalence factor for energy land of 1.36 in 1980 and 1.38 in 2003 in their time-series analysis of Ireland. However, our interest was in trends (i.e., was the system moving toward or away from sustainability), not necessarily the actual value and may not be worth the added expense or difficulty. However, we think using ha is acceptable if one is not comparing between different regions.

3.5.4 Examination of Sustainability

Whether using ha or gha, our analysis suggests the SLB was moving away from sustainability, on both a per capita basis (Fig. 3.1a) and a population basis (Fig. 3.1b). Although the *ef* remained relatively flat during the 26 years (which by itself would suggest the SLB was not moving away from sustainability), available *bc* decreased because of increasing population size. These trends reveal a decreasing ecological reserve (the space between the two lines is decreasing; Fig. 3.1 and Table 3.2). The decrease in the ecological reserve over the 26 years was amplified on a population level examination. The *EF* was increasing and *BC* was decreasing through time (Figs. 3.1 and 3.5). This was evident in the individual land categories as well. For example, per capita food consumption (e.g., meat, cereal, fruit and vegetable, and fish) increased during the period, requiring more bioproductive land to satisfy the consumption and the amount of available arable and pasture land per capita decreased. The overall result was a decreasing surplus of bioproductive land (Fig. 3.1a) that was available to support the population in the SLB. If the trend continues, *ef* will eventually overshoot *bc*, resulting in an ecological deficit.

Although our analysis suggests the *ef* is relatively low, one potential flaw was the large number of missing variables that represent embodied energy in goods and services. For example, Utah Vital Signs reported over 2 gha/ca were required to meet the consumptive levels for Utah in 1990 and about 1.5 gha/ca in 2003 (McIntyre et al. 2007). When compared to the food and energy consumption for Utah in 1990 (5.2631 gha/ca) and 2003 (5.8239 gha/ca), it is not an inconsequential quantity. However, these variables do not represent such a large part of EFA that they alter the trends captured by food and energy consumption. It is important to note that a portion of data in that report came from both US and Utah consumption rates and may or may not accurately represent consumptive levels for the Utah population.

The trends in the SLB were not unexpected. Because of the economic, environmental, and social characteristics of the SLB, we did not expect a substantial amount of change to occur during the 26 years examined. The SLB is an agricultural-based region and has many traits that accompany this type of society (e.g., San Luis Valley Development Resources Group 2007). Moreover, the SLB functions as a resource exporting region, providing much of its bioproductive land and resources to support larger systems, which include those of Colorado, the US, and the world.

3.5.5 Strengths and Weaknesses of Methodology

The simplified EFA we conducted has captured a trend indicating the SLB was moving away from sustainability. There are a number of strengths and weaknesses to the methodology we employed. The greatest strength of our methodology is the use of readily available data that makes the methodology available to any entity interested in computing their ecological footprint to determine if their system is moving toward or away from sustainability. The greatest weakness of our methodology may be the exclusion of potentially important variables. The lack of data at sub-national scales resulted in the exclusion of well over 100 variables that are typically included in a traditional footprint account. All of the variables usually included in the embodied energy component, as well as some other variables, were excluded. In addition, the footprint methodology in general does not take into account exports of natural resources that may lower the biocapacity. Another limitation is the lack of data for each year of our study. For example, we had data at five year intervals for agricultural production from the Census of Agriculture and ten year intervals for population and housing variables from the Decennial Census of Population and the census years did not align (i.e., decennial censuses were 1980, 1990, and 2000 whereas the agricultural censuses were 1978, 1982, 1987, 1992, 1997, and 2002). We used linear interpolation to estimate the values for missing years. Because of these imputations, we were limited in performing statistical analysis on trends in the results (e.g., a Mann-Kendall test for trends or time-series analysis). Such interpolation would bias the trend especially if a measure of uncertainty was available and we could statistically test the trend. Nonetheless, after calculating the ecological footprint for the US using the same variables employed in our study, we are confident the methodology does an acceptable job capturing trends in an EFA for a region, which was a central goal of this project (see Appendix 3-D for comparison with US). Although not unimportant, the embodied energy component of a typical ecological footprint account generally accounts for less than the food and energy consumption components. For instance, Lammers et al. (2008) found that less than 1 ha per capita was from the embodied energy component. These weaknesses, then, need to be balanced with the availability of the method and its relative ease of use. However, there is enough detail in the account that stakeholders can identify areas of the system on which to focus attention to improve sustainability of the system.

Although there were several methodologies used early on in EFA accounting, recently there has been a push to standardize the methods (e.g., Wackernagel 2009). Specifically, a couple of groups have proposed their methodology as a standard (e.g., Venetoulis and Talberth 2008 - Redefining Progress; Kitzes et al. 2009 - Global Footprint Network, Best Foot Forward). Unfortunately, these groups do not publish their complete methodologies or data, in part because they provide a commercial EFA calculating service. Because the groups do not provide the information free of charge or make it readily available, it is difficult to conduct an EFA with limited budgets which is one of our goals for our methodology. Moreover, this standardization has some drawbacks that make the calculation more difficult than it need be. First, the standard recommends starting with national level data. However, a subsystem or region may not reflect a national average, or levels of consumption may not be typical and this could be concealed using national data. Thus, scaling these variables to the population of the subsystem may not adequately represent the subsystem. Second, these groups do not make the factors that are necessary for conversion to a common normalized unit (global hectare, gha) readily available. Our goal in this project was not to create a "better" or more accurate EFA; rather it was to make the methodology more accessible and usable for the end user while still being adequate for sustainability analysis.

3.6 References

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Table 3.1 – Scale and source of data for the variables used to calculate ecological footprint for the SLB.

Scale	Variable	Purpose/Notes	Source	Website	Specific data link
National					
	Consumption of Animal Products (lbs / capita)	Includes bovine, buffalo, sheep, goat, non-bovine, milk, cheese, butter, eggs, and fish categories	USDA Economic Research Service	www.ers.usda.gov	www.ers.usda.gov/Data/FoodConsumption/FoodAvailQueriable.aspx
	Cereal Consumption (lbs / capita)	Includes cereals, wheat, and maize categories	USDA Economic Research Service	www.ers.usda.gov	www.ers.usda.gov/Data/FoodConsumption/FoodAvailQueriable.aspx
	Fruit & Vegetable Consumption (lbs / capita)	Includes vegetables, fruit, animal feed, roots, tubers, and pulses consumption	USDA Economic Research Service	www.ers.usda.gov	www.ers.usda.gov/Data/FoodConsumption/FoodAvailQueriable.aspx
State					
	Fossil Fuel (Gj / year)	Includes coal, natural gas, and petroleum consumption	Energy Information Administration	www.eia.doe.gov	www.eia.doe.gov/emeu/states/state.html?q_state_a=co&q_state=COLORADO
	Nuclear Electric Consumption (million kWh)		Energy Information Administration	www.eia.doe.gov	www.eia.doe.gov/emeu/states/state.html?q_state_a=co&q_state=COLORADO
	Hydro-electric Consumption (million kWh)		Energy Information Administration	www.eia.doe.gov	www.eia.doe.gov/emeu/states/state.html?q_state_a=co&q_state=COLORADO
	Wood and waste Consumption (trillion BTU)		Energy Information Administration	www.eia.doe.gov	www.eia.doe.gov/emeu/states/state.html?q_state_a=co&q_state=COLORADO
County					
	Population (persons)		Bureau of Economic Analysis	www.bea.gov	www.bea.gov/regional/reis/default.cfm?selTable=CA1-3&section=2
	Land Area (ha)		US Census Bureau	www.census.gov	quickfacts.census.gov/qfd/states/08000.html and for US
	Built land (ha)	Census designated places based on 1990 and 2000 data	US Census Bureau	www.census.gov	www.census.gov/geo/cob/bdy/pl/pl90e00/pl08_d90_e00.zip
	Arable land (ha)	1982, 1987, 1992, 1997, 2002, 2007	USDA Agricultural Statistics	www.agcensus.usda.gov	http://www.agcensus.usda.gov
	Forest including deforestation (ha)	1987, 1997, 2002 and treated as a constant	USDA Forest Service	www.fia.fs.fed.us	www.fia.fs.fed.us/tools-data/spatial

Scale	Variable	Purpose/Notes	Source	Website	Specific data link
Calculated					
	Pasture (ha)	total farmland minus arable land; values reported as “D” in report are listed as values from adjacent survey	USDA Agricultural Statistics	www.agcensus.usda.gov	
	Sea (ha)	No sea category in biocapacity in SLB			No sea category in biocapacity in SLB
	Forest harvest (MBF)		1. USDA Forest Service 2. USDA Natural Resources and Conservation Service	1. Data generated by Bruce F. Short, Biological Resources Staff Officer, San Luis Valley Public Lands Center 2. National Resources Inventory 2001 Annual NRI, Urbanization and Development of Rural Land, July 2003 (and see www.nrcs.usda.gov/technical/land)	1. Bruce F. Short, Biological Resources Staff Officer, San Luis Valley Public Lands Center, 1803 West Highway 160, Monte Vista, CO 81144, bshort@fs.fed.us, phone (719) 852-6225 2. USDA, Natural Resources and Conservation Service, National Resources Inventory 2001 Annual NRI, Urbanization and Development of Rural Land, July 2003 (and see www.nrcs.usda.gov/technical/land)
	Energy land (ha)				Based on CO_2 production and subtracted from forest land. Thus, biocapacity is zero.
	Non-productive land (ha)	Total land area minus the sum of EF land area			Total land area minus the sum of EF land area

Table 3.2 – Ecological footprint and biocapacity in the San Luis Basin, Colorado, 1980-2005. Twelve percent of the biocapacity area was subtracted from the total biocapacity to protect biodiversity.

Year	Ecological Footprint (hectares per capita)	Biocapacity (hectares per capita)	Ecological Balance (hectares per capita)
1980	5.41	35.95	30.54
1981	5.39	34.91	29.52
1982	5.39	33.84	28.45
1983	5.31	33.23	27.92
1984	5.45	32.85	27.39
1985	5.50	32.88	27.37
1986	5.49	32.46	26.97
1987	5.37	32.15	26.78
1988	5.45	32.06	26.61
1989	5.37	32.42	27.04
1990	5.42	32.65	27.23
1991	5.31	32.23	26.92
1992	5.30	32.41	27.11
1993	5.31	32.10	26.78
1994	5.30	31.22	25.92
1995	5.20	30.30	25.10
1996	5.22	29.73	24.51
1997	5.10	29.21	24.11
1998	5.14	28.77	23.64
1999	5.15	28.43	23.29
2000	5.26	27.97	22.71
2001	5.26	28.04	22.78
2002	5.14	27.74	22.60
2003	5.15	27.65	22.50
2004	5.22	27.34	22.12
2005	5.13	27.47	22.34

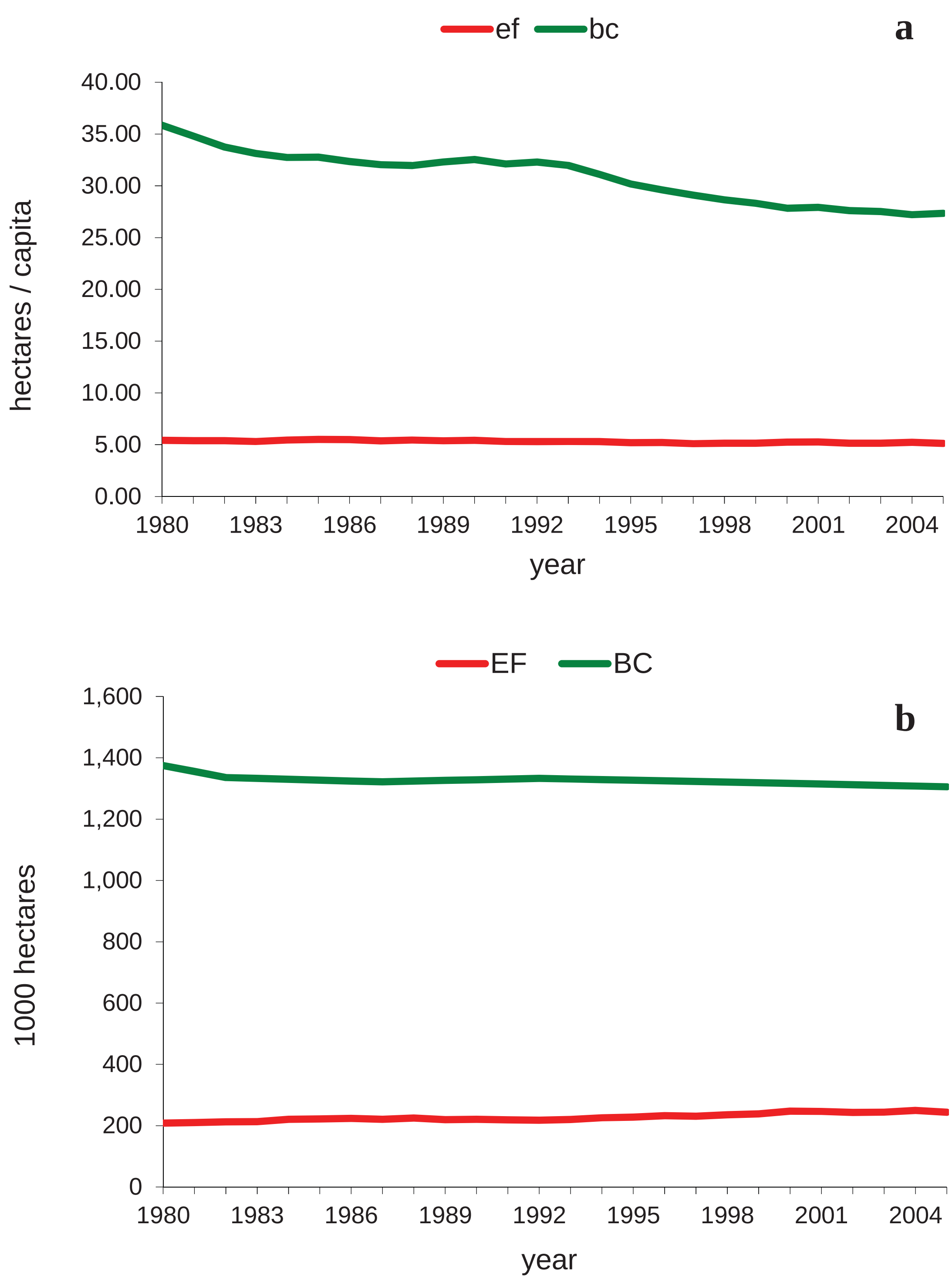

Figure 3.1 – Biocapacity compared to ecological footprint for 26 years in the San Luis Basin. Twelve percent of the biocapacity area was subtracted from the total *BC* and *bc* to protect biodiversity. a – Per capita biocapacity (*bc*) compared to per capita ecological footprint (*ef*). b - Biocapacity for the population (*BC*) compared to total ecological footprint (*EF*).

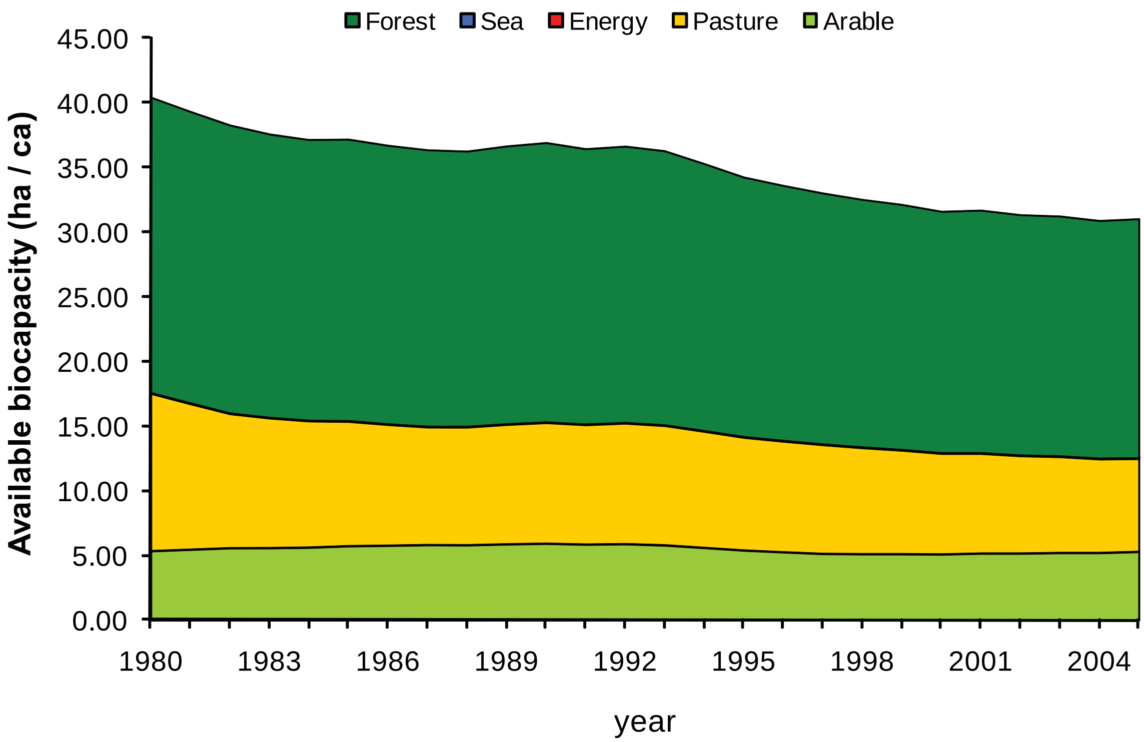

Figure 3.2 – Available biocapacity (*bc*) for the five footprint land categories over a 26-year period in the San Luis Basin, Colorado. Twelve percent of the biocapacity area was subtracted from the total *bc* to protect biodiversity. Note that built-up land has no biocapacity and is not included in the figure.

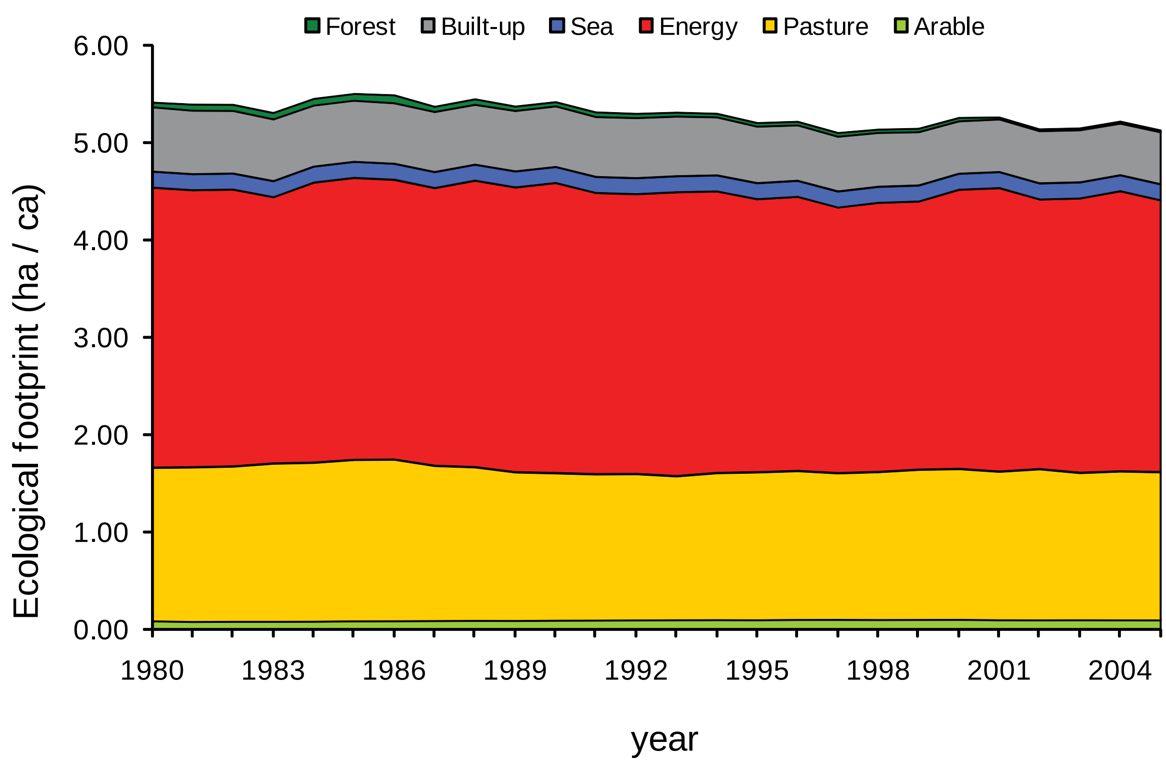

Figure 3.3 – Ecological footprint (ef) and the demand placed on each of the six land categories over a 26-year period in the San Luis Basin, Colorado.

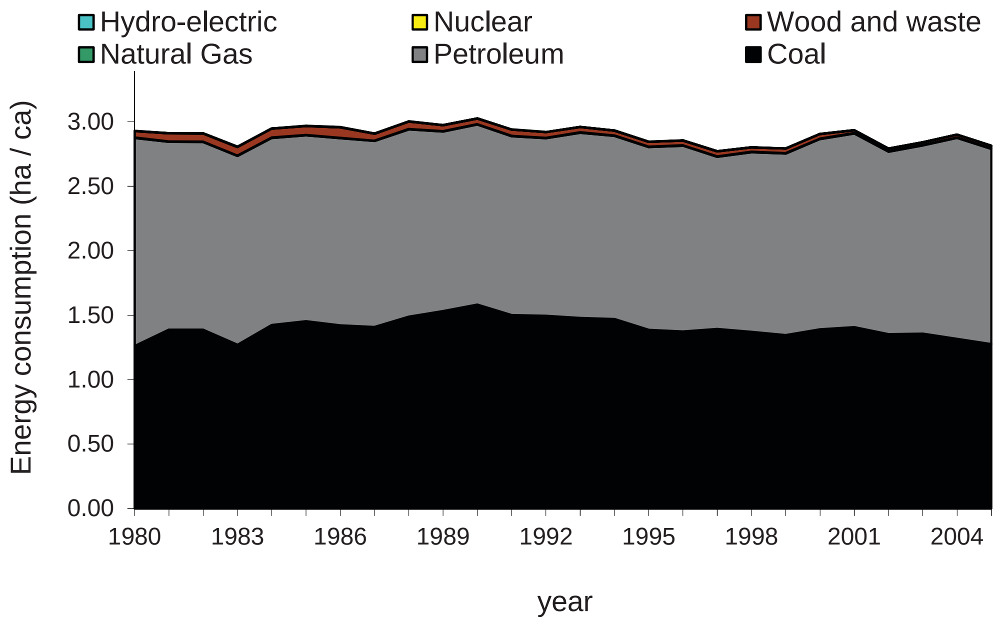

Figure 3.4 – Energy consumption (hectares per person) by major energy source over a 26-year period in the San Luis Basin, Colorado.

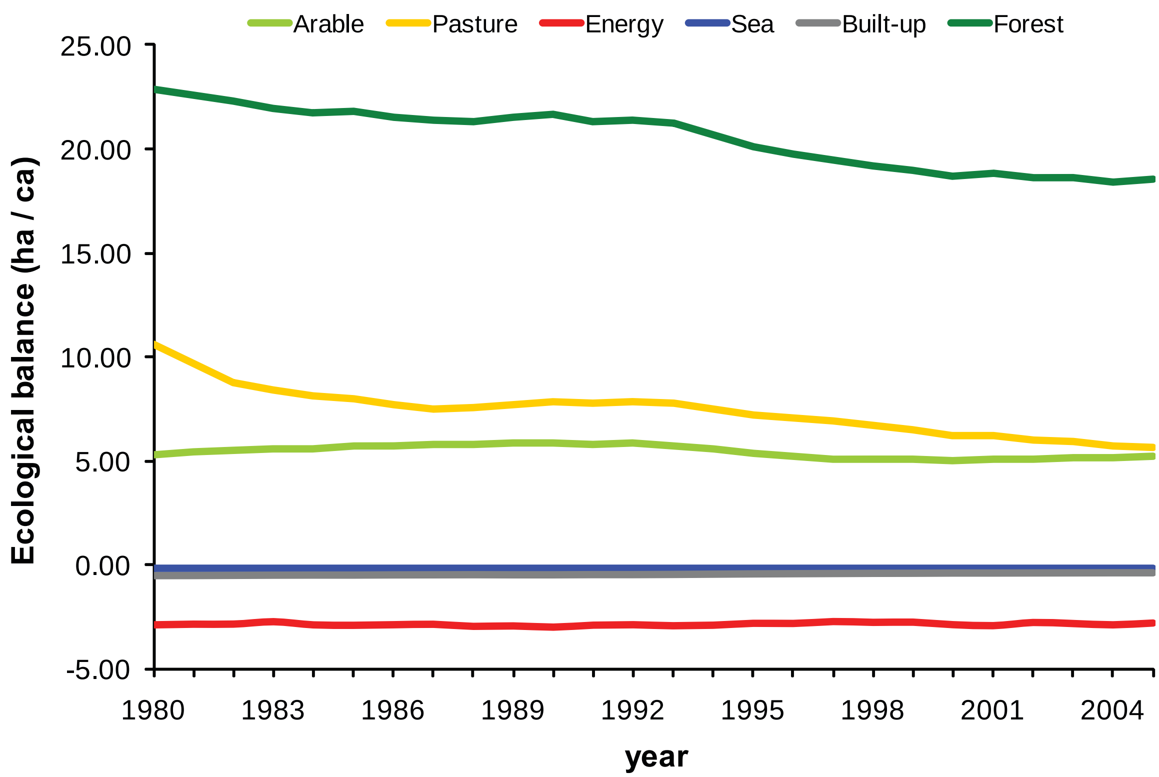

Figure 3.5 – Ecological balance (ha/ca) of the different land categories in the SLB. Remainder equals biocapacity per capita minus the ecological footprint for the SLB region. Positive values represent a surplus or remainder of biocapacity and negative values represent a deficit of biocapacity. Twelve percent of the biocapacity area was subtracted from the total *bc* to protect biodiversity.

Appendix 3-A: Estimation of Energy Use and Determination to Use EIA State Level Data

For exposition purposes, this appendix demonstrates the applicability of using state level data as an estimate of individual energy consumption in the San Luis Basin. State level data are easier to obtain, but may not accurately represent regional level energy consumption.

Energy consumption data for the State of Colorado were obtained from the Department of Energy's Energy Information Administration (EIA; EIA 2006). We assumed that EIA data calculated on a per capita usage and multiplied by the population of the SLB was sufficient to estimate the energy consumption. We justified this assumption by comparing coal, natural gas, and propane consumption in the SLB to their consumptive use for the State of Colorado.

Xcel Energy and San Luis Valley Rural Electric Co-Op, the primary energy suppliers in the SLB, provided usage rates for their customers. We estimated coal consumption by starting with actual electricity consumption for 2006. The amount of electricity produced from coal is highly dependent on the type of coal used (EIA 2009). We assumed it takes 0.521 short tons (472.56 kg) of coal to produce 1 MWh of electricity (Heede 2005), which works out to approximately 1.024 lbs per kWh. In 2006, the population of the SLB was nearly 1% of Colorado's population. Therefore, the SLB would use about 1% of the energy in the state. Using data provided by the energy suppliers indicates that residents in the SLB used 236895 short tons (1.18% of 2006 state estimates) of coal and 1.5 billion cubic feet (0.33% of 2006 state estimates) of natural gas.

We attempted to use the same strategy for propane consumption, but were unable to get consumption rates of propane in the SLB from suppliers. Therefore, a crude estimate of propane use was generated by examining the relationship between heating degree days (HDD) and quantity of propane used in a household. We averaged the number of HDD from 20 weather stations located in and around the SLB (NOAA Western Regional Climate Center, http://www.wrcc.dri.edu/). Based on an estimate of 1200 gallons of propane used per year for a 2600 ft^2 home in Montrose, CO (USDA 2006) and 6360 mean number of HDD reported at the Montrose 2 weather station, we estimated 0.189 gallons per HDD. However, the majority (US Census Bureau 2000) of homes in the SLB were built before 1979 and the median house size of new construction in the US in 1972 was around 1,400 ft^2 (US Bureau of the Census 1976). Therefore, we used the mean of 0.102 gallons per HDD (consumption levels are dependent on numerous factors including house size, lifestyle, energy efficiency of appliances, how well a structure is insulated, etc.). The mean annual number of HDD in the SLB was 9006. The result, based on HDD, is an estimated average of 914.98 gallons (21.78 barrels) of propane used per household (approximately 29%, or 5200, of the 17,687 households are heated with propane; US Census Bureau 2000).

Next, we estimated the per household propane consumption for Colorado. According to EIA data, around 40.6% (2632.504 K barrels) of propane was used by the residential sector in Colorado (EIA 2006) in 2000. There were 1,808,037 households in the state in 2000 and 6.2% (112098 households) of them used propane to heat their home (US Census Bureau 2000). Of the 6484 thousand barrels of propane consumed in the state, 40.6% (2632.504 thousand barrels) were used by the residential sector (EIA 2006). Thus, the average propane use for Colorado was 986.32 gallons per household.

Based on HDD (0.102 gallons / HDD / household), the SLB would consume 113,283 barrels of propane in a typical year. This is 4.30% of Colorado's total residential propane use. If we use state level data (986.3 gallons / household), the SLB would consume 122,116 barrels of propane in a typical year. This is 4.64% of Colorado's total for residential propane use. Propane consumption is relatively similar for either method and would not adversely affect the energy consumption in the SLB. Of course, this only accounts for residential consumption, but may adequately represent total consumption as well.

A summary of these calculations is below:

Data sources (based on 2000 census data, US Census Bureau)
EIA data for Colorado,
1,808,037 households
112,098 use propane (≈6.2%)
6,484,000 barrels of propane consumed
40.6% of propane consumed for residential use
San Luis Basin data from energy suppliers:
17,687 households
5200 use propane
9006 average heating degree days (HDD)
1400 sq ft average house size
Montrose, CO (in SLB) special study data:
2600 sq ft house
1200 gallons propane per year
6360 HDD (at Montrose 2 weather station)
SLB propane energy use proportioned from state **EIA** data:
0.406 residential proportion * 6,484,000 barrels =
2632504 barrels of propane for residential use in CO
2,632,504 barrels / 112,098 households =
23.48395 barrels of propane per household in CO
23.48395 barrels/household * 5200 households in SLB =
122,116 barrels consumed in SLB per year = 4.64% of CO's propane use (122,116 barrels / 2,632,504 barrels * 100)
SLB propane energy use based on SLB **HDD** data:
1200 gallons / 42 gallons per barrel = 28.57143 barrels used in Montrose
1400 sq ft SLB / 2600 sq ft Montrose = 0.5384615 SLB proportion of Montrose use
9006 HDD SLB / 6360 HDD Montrose = 1.416038 SLB fraction of Montrose HDD
28.57143 * 0.5384615 * 1.416038 = 21.78520 barrels per household in SLB
21.78520 barrels/household * 5200 households in SLB =
113,283 barrels consumed in SLB per year = 4.30% of CO's propane use (121,375 barrels / 2,632,504 barrels * 100)
Percent difference: (EIA – HDD) / HDD = 7.8%

Because of the ease of getting energy consumption from EIA and because state level data are a consistent source of energy consumption values, we think they are an adequate surrogate for actual consumption energy data in the region. Using EIA data for Colorado, consumption was calculated as per capita for the state and included coal, natural gas, petroleum, nuclear, hydroelectric, and wood and waste categories.

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Appendix 3-B: Ecological Footprint Accounting Ledger for 1980 in the San Luis Basin

This appendix contains the basic tables used in ecological footprint accounting. Tables list the main resources produced and consumed and the supply (biocapacity) and demand (ecological footprint) of land area in the San Luis Basin region.

Table 3-B.1 – Ecological footprint accounting ledger for food consumption for 1980 in the San Luis Basin. Local Yield and Production are italicized because they were not needed to compute apparent consumption. Global yields are from Chambers et al. (2000).

Resource	**Global yield**	**Local yield**	**Production**	**Apparent consumption**	**Footprint component**	**Land category**
Unit	*(kg / ha)*	*(kg / ha)*	*(kg)*	*(kg)*	*(ha / capita)*	
MEAT						
.meat (fresh)		*199.243*	*92,990,880*	2,919,258		
..bovine, buffalo	32	*188.715*	*88,077,314*	1,280,774	1.0404	pasture
..sheep, goat	72	*7.379*	*3,443,739*	17,449	0.0063	pasture
..non-bovine, goat, mutton, buffalo	764	*3.149*	*1,469,828*	1,621,035	0.0552	pasture
DAIRY						
..milk	458	*0.000*		4,140,803	0.2350	
..cheese	46	*0.000*		305,362	0.1726	
..butter	22	*0.000*			0.0000	
..eggs	573	*0.000*		1,364,454	0.0619	
FISH						sea
.marine, inland fish	35	*0.000*		218,465	0.1623	sea
GRAINS	2752	*1229.170*	*268,326,225*	4,590,896	0.0434	arable
.cereals	2752	*879.013*	*191,887,425*	579,315	0.0055	arable
..wheat		*350.157*	*76,438,800*	3,964,468		
..maize		*0.000*		225,095		
FRUITS & VEGETABLES	8136	*0.000*		10,617,864	0.0339	arable
.vegetable & fruit		*0.000*		10,617,864		
..vegetable etc.		*0.000*		5,896,099		
..fresh fruit		*0.000*		4,721,765		
ANIMAL FEED		*0.000*				
..animal feed	2752	*1847.935*	*403,401,978*		0.0000	arable
ROOTS & TUBERS		*0.000*				
.roots & tubers	12814	*2278.070*	*497,299,806*	1,280,984	0.0026	arable
PULSES		*0.000*				
.pulses	802	*0.000*		93,642	0.0030	arable

Table 3-B.2 – Ecological footprint accounting ledger for energy consumption for 1980 in the San Luis Basin. Global average energy to land ratio was used to convert joules to hectares (Chambers et al. 2000).

Primary energy use *	**Global average energy to land ratio**	**Energy use**	**Footprint component**	**Land type**
Unit	*(Gj / ha/ yr)*	*(Gj / SLB / yr)*	*(ha / capita / yr)*	
Coal consumption (short tons = 2000 lbs)	55	3880385.04	0.5468	energy land
Natural Gas Consumption (billion cubic feet)	93	12625.97	168.0439	energy land
Petroleum Consumption (thousand barrels)	71	4965333.44	0.4273	energy land
Total fossil fuel consumption		340771652986		
Nuclear energy consumption	71	31755.94	66.8133	energy land
Hydro-electric consumption	1000	81746.54	25.9548	energy land

Table 3-B.3 – Ecological footprint accounting ledger for supply and demand of bioproductive land for 1980 in the San Luis Basin. Equivalence factors are from McIntyre et al. (2007) and Chambers et al. (2000) and were treated as constants for the 26 years.

Demand - Footprint (per capita)

Category	**Total**	**Equivalence factor**	**Equivalence total**
Unit	*(ha / capita)*		*(gha / capita)*
Fossil energy	2.88	1.17	3.37
Built-up land	0.67	2.22	1.48
Arable land	0.09	2.22	0.20
Pasture	1.57	0.49	0.77
Forest including deforestation	0.05	1.35	0.07
Sea	0.16	0.36	0.06
Total used	**5.41**		**5.94**

Supply - Existing regional capital (per capita)

Category	**Yield factor**	**Regional area**	**Yield adjusted equivalent area**
Unit		*(ha / capita)*	*(gha / capita)*
Fossil energy			
Built-up land	1.42	0.12	0.17
Arable land	1.42	5. 39	7.65
Pasture	1.63	12.18	19.85
Forest including deforestation	1.97	22.93	45.17
Sea	1.28	0.00	0.00
Other		14.30	
Total existing		**40.61**	**72.84**
Total available (minus 12% for biodiversity)		**35.74**	**64.10**
ECOLOGICAL REMAINDER		**30.32**	**58.16**

Appendix 3-C: Twenty-six Years (1980-2005) of Data for the San Luis Basin, Colorado.

Table 3-C.1 – Twenty-six years (1980-2005) of data for the San Luis Basin, Colorado. Italicized values were estimated using linear interpolation

Variable name	1980	1981	1982	1983
Population (persons)	38469	*38980*	*39467*	*40112*
Coal consumption (short tons)	158449.0558	176724.9259	178864.4571	166457.3616
Natural Gas Consumption (billion cubic feet)	3.385607069	2.775030315	2.90050471	2.739301399
Petroleum Consumption (thousand barrels)	811.3289941	742.0195447	750.66351	767.7980211
Nuclear Electric Consumption (million kWh)	8.821093419	9.804234462	7.335054132	9.574754423
Hydro-electric Consumption (million kWh)	22.70737241	18.31258213	21.27036787	23.94968653
Wood and waste Consumption (trillion BTU)	0.141507795	0.184565695	0.188210528	0.200967439
Land Area (hectares)	2121718.26	2121718.26	2121718.26	2121718.26
Population density (individuals per hectare)	0.018131059	0.018371902	0.018601433	0.018905432
Built-up land (ha)	4572.30285	*4646.10285*	*4719.90285*	*4793.70285*
Arable land (ha)	*207209.4897*	*214383.1902*	221556.8907	*225385.0547*
Pasture (ha)	*468443.1367*	*438884.2499*	409325.3631	*402236.8031*
Forest including deforestation (ha)	882085.2711	882085.2711	882085.2711	882085.2711
everything else (ha)	559408.0596	581719.4459	604030.8322	607217.4282
mean precipitation (cm)	50.8	52.2	54.4	55.5
Meat Consumption (lbs/capita)	179.82	179.69	174.6	175.5
meat (fresh; lbs/capita)	167.3	167	162.1	162.1
bovine, buffalo (lbs/capita)	73.4	74.1	73.9	75.5
sheep, goat (lbs/capita)	1	1	1.1	1.1
non-bovine (lbs/capita)	92.9	91.9	87.1	90.1
milk (gal/capita)	27.6	27.1	26.4	26.3
cheese (lbs/capita)	17.5	18.2	19.9	20.6
eggs (lbs/capita)	271.1	264.4	264.1	260.2
fish (lbs/capita)	12.52	12.69	12.5	13.4
Cereal Consumption (lbs/capita)	263.1	262.3	262.8	264
cereals (lbs/capita)	33.2	33.98	32.32	32.17
wheat (lbs/capita)	227.2	225.7	227.7	229
maize (lbs/capita)	12.9	13.3	13.8	14.7
Fruit & Vegetable Consumption (lbs/capita)	608.5	587.3	615.1	603.4
vegetables & fruits (lbs/capita)	608.5	587.3	615.1	603.4
vegetables (lbs/capita)	337.9	333.9	336	339.3
fruit (lbs/capita)	270.6	253.4	279.1	264.1
roots and tubers (lbs/capita)	73.41199886	71.47119517	71.35533997	74.32447044
pulses (lbs/capita)	5.366536979	5.419061948	6.488707427	6.526480216
coffee and tea (lbs/capita)	11.08	10.77	10.64	10.84
cocoa (lbs/capita)	3.4	3.6	3.7	4
oil seed (lbs/capita)	1.506196043	1.391510049	1.610763691	1.557785299
fats (lbs/capita)	60.1	60.2	60.8	62.8
sweetener consumption (lbs/capita)	120.2	119.8	117.7	119.3
forest harvest (MBF)	23,973.14	14,124.07	24,001.56	25,115.40
meat production (fresh; kg)	92,990,880	99,130,808	96,894,691	102,167,967
bovine, buffalo production (kg)	88,077,314	94,061,842	92,394,147	99,536,388
sheep, goat (kg)	3,443,739	3,353,902	3,000,000	2,631,579
non-bovine, goat, mutton, buffalo (pork; kg)	1,469,828	1,715,064	1,500,544	-
grain production (kg)	268,326,225	306,234,575	312,838,180	347,138,625
cereal production (kg)	191,887,425	208,865,375	227,228,900	221,039,425
wheat production (kg)	76,438,800	97,369,200	85,609,280	126,099,200
animal feed production (kg)	403,401,978	299,723,304	295,581,960	304,422,567
roots and tubers production (kg)	497,299,806	524,182,716	581,850,528	631,668,984

Variable name	1984	1985	1986	1987
Population (persons)	*40490*	*40369*	*40804*	*41104*
Coal consumption (short tons)	188272.4105	191747.1074	189421.8273	189189.4125
Natural Gas Consumption (billion cubic feet)	2.937764886	2.755240242	2.495543403	2.647416314
Petroleum Consumption (thousand barrels)	767.9700599	759.9430665	774.1604165	774.6466201
Nuclear Electric Consumption (million kWh)	0.702508994	0.402592181	0.655395237	2.193573517
Hydro-electric Consumption (million kWh)	27.70440016	29.65343036	28.53490033	22.91906123
Wood and waste Consumption (trillion BTU)	0.210752698	0.212618996	0.252075091	0.166409025
Land Area (hectares)	2121718.26	2121718.26	2121718.26	2121718.26
Population density (individuals per hectare)	0.019083589	0.01902656	0.019231583	0.019372977
Built-up land (ha)	*4867.50285*	*4941.30285*	*5015.10285*	*5088.90285*
Arable land (ha)	*229213.2187*	*233041.3827*	*236869.5467*	240697.7122
Pasture (ha)	*395148.2431*	*388059.6831*	*380971.1231*	373882.5899
Forest land (ha)	882085.2711	882085.2711	882085.2711	882085.2711
everything else (ha)	610404.0242	613590.6202	616777.2162	619963.7839
mean precipitation (cm)	56.4	59.9	58.4	47.4
Meat Consumption (lbs/capita)	180.9	185	184.8	184.58
meat (fresh; lbs/capita)	166.7	169.9	169.3	168.38
bovine, buffalo (lbs/capita)	75.3	76.1	76	70.8
sheep, goat (lbs/capita)	1.1	1.1	1	0.98
non-bovine (lbs/capita)	91.2	93.2	92.3	96.6
milk (gal/capita)	26.4	26.7	26.5	26.1
cheese (lbs/capita)	21.5	22.5	23.1	24.1
eggs (lbs/capita)	260.1	255.2	253.5	253.8
fish (lbs/capita)	14.2	15.1	15.5	16.2
Cereal Consumption (lbs/capita)	268.7	283.6	289.5	301.2
cereals (lbs/capita)	34.45	39.34	43.83	48.77
wheat (lbs/capita)	231.1	241.1	242.3	249
maize (lbs/capita)	16	17.2	19.4	21.7
Fruit & Vegetable Consumption (lbs/capita)	626.5	631.6	637.4	641.1
vegetables & fruits (lbs/capita)	626.5	631.6	637.4	641.1
vegetables (lbs/capita)	356.5	359.6	360	366
fruit (lbs/capita)	270	272	277.4	275.1
roots and tubers (lbs/capita)	75.20384805	74.2373237	77.13000354	76.89765767
pulses (lbs/capita)	5.101417896	7.117753361	6.600845207	5.157145681
coffee and tea (lbs/capita)	10.96	11.25	11.26	10.94
cocoa (lbs/capita)	4.3	4.6	4.8	4.8
oil seed (lbs/capita)	1.709343849	1.572551223	1.678779644	1.301461261
fats (lbs/capita)	64.6	68.2	68.6	66.9
sweetener consumption (lbs/capita)	121.8	126.2	124.3	128.8
forest harvest (MBF)	30,777.54	30,784.99	34,714.50	32,798.34
meat production (fresh; kg)	106,428,675	-	-	*104790311.1*
bovine, buffalo production (kg)	103,965,880	102,649,819	104,776,134	*104582695.1*
sheep, goat (kg)	2,462,795	100,652,087	102,909,528	*207616.0228*
non-bovine, goat, mutton, buffalo (pork; kg)	-	1,997,731	1,866,606	-
grain production (kg)	356,523,415	483,574,415	449,167,880	313,170,000
cereal production (kg)	247,711,175	240,060,065	211,729,155	161,090,200
wheat production (kg)	108,812,240	243,514,350	237,438,725	152,079,800
animal feed production (kg)	342,193,593	114,993,440	84,188,080	84,673,600
roots and tubers production (kg)	781,827,618	441,830,724	437,380,938	511,067,769

Variable name	1988	1989	1990	1991
Population (persons)	*41289*	*40903*	40682	*41283*
Coal consumption (short tons)	200731.8624	204688.8725	210345.8029	202397.8189
Natural Gas Consumption (billion cubic feet)	2.885678728	3.084130514	3.037972946	3.266446794
Petroleum Consumption (thousand barrels)	784.1199118	743.9996627	741.978769	748.0894453
Nuclear Electric Consumption (million kWh)	8.353280528	6.605283571	0	0
Hydro-electric Consumption (million kWh)	22.08556746	21.87609984	17.46526957	21.86569235
Wood and waste Consumption (trillion BTU)	0.178456448	0.141095849	0.134064393	0.151134105
Land Area (hectares)	2121718.26	2121718.26	2121718.26	2121718.26
Population density (individuals per hectare)	0.019460171	0.019278243	0.019174082	0.019457343
Built-up land (ha)	*5162.70285*	*5236.50285*	5310	*5446*
Arable land (ha)	*241324.6522*	*241951.5922*	*242578.5322*	*243205.4722*
Pasture (ha)	*375721.2299*	*377559.8699*	*379398.5099*	*381237.1499*
Forest land (ha)	882085.2711	882085.2711	882085.2711	882085.2711
everything else (ha)	617424.4039	614885.0239	612345.9467	609744.3667
mean precipitation (cm)	47.5	37.3	63.8	51.0
Meat Consumption (lbs/capita)	186.7	184.69	183.39	184.51
meat (fresh; lbs/capita)	171.5	169.09	168.39	169.62
bovine, buffalo (lbs/capita)	69.7	66.09	64.79	63.72
sheep, goat (lbs/capita)	1	1	1	1
non-bovine (lbs/capita)	100.8	102	102.6	104.9
milk (gal/capita)	26.1	26	25.7	25.5
cheese (lbs/capita)	23.7	23.8	24.6	25
eggs (lbs/capita)	246.6	237	234.1	232.9
fish (lbs/capita)	15.2	15.6	15	14.89
Cereal Consumption (lbs/capita)	307.5	304.7	316.9	318.8
cereals (lbs/capita)	50.12	51.35	53.5	53.93
wheat (lbs/capita)	254.2	250.3	260.4	262
maize (lbs/capita)	21.7	21.8	21.4	21.7
Fruit & Vegetable Consumption (lbs/capita)	644.3	641.8	659.3	651.2
vegetables & fruits (lbs/capita)	644.3	641.8	659.3	651.2
vegetables (lbs/capita)	365.2	380.1	385.1	395.2
fruit (lbs/capita)	279.1	261.6	274.2	256
roots and tubers (lbs/capita)	76.16900377	78.46913146	74.99830509	80.97654572
pulses (lbs/capita)	6.935747548	5.710816178	6.716221499	7.347342826
coffee and tea (lbs/capita)	10.54	10.83	11.03	11.09
cocoa (lbs/capita)	4.8	4.9	5.4	5.7
oil seed (lbs/capita)	1.29784794	1.26545431	1.163385732	1.266307156
fats (lbs/capita)	67.7	64.7	64.9	67.1
sweetener consumption (lbs/capita)	130.2	128.5	132.4	132.9
forest harvest (MBF)	33,139.45	35,251.90	23,871.55	23,286.68
meat production (fresh; kg)	*104531691.7*	*104273072.3*	*104014452.9*	*103808938.3*
bovine, buffalo production (kg)	*104389255.9*	*104195816.7*	*104002377.5*	*103808938.3*
sheep, goat (kg)	*142435.831*	*77255.6391*	*12075.44724*	
non-bovine, goat, mutton, buffalo (pork; kg)	-	-	-	-
grain production (kg)	308,737,340	378,839,230	370,231,930	356,537,105
cereal production (kg)	163,127,120	206,442,855	185,472,205	175,487,080
wheat production (kg)	145,610,220	172,396,375	184,759,725	181,050,025
animal feed production (kg)	88,291,200	121,690,080	65,962,720	61,183,680
roots and tubers production (kg)	513,245,030	400,367,411	452,367,770	444,429,827

Variable name	1992	1993	1994	1995
Population (persons)	*41120*	*41466*	*42564*	*43793*
Coal consumption (short tons)	200910.4621	200253.9844	204375.7016	198328.0663
Natural Gas Consumption (billion cubic feet)	3.05817693	3.350570905	3.188727254	3.318819344
Petroleum Consumption (thousand barrels)	740.125866	778.5602277	790.3129064	811.3139992
Nuclear Electric Consumption (million kWh)	0	0	0	0
Hydro-electric Consumption (million kWh)	17.63156623	21.9393547	17.64657663	24.38760008
Wood and waste Consumption (trillion BTU)	0.135265518	0.127367593	0.121148777	0.12245299
Land Area (hectares)	2121718.26	2121718.26	2121718.26	2121718.26
Population density (individuals per hectare)	0.019380519	0.019543594	0.020061099	0.020640346
Built-up land (ha)	*5582*	*5718*	*5854*	*5990*
Arable land (ha)	243832.4072	*241884.4072*	*239936.4072*	*237988.4072*
Pasture (ha)	383075.8336	*382653.3536*	*382230.8736*	*381808.3936*
Forest land (ha)	882085.2711	882085.2711	882085.2711	882085.2711
everything else (ha)	607142.748	609377.228	611611.708	613846.188
mean precipitation (cm)	49.2	53.8	53.7	52.6
Meat Consumption (lbs/capita)	188.31	188.01	190.99	190.05
meat (fresh; lbs/capita)	173.72	173.21	176.11	175.67
bovine, buffalo (lbs/capita)	63.23	61.75	63.65	64.32
sheep, goat (lbs/capita)	0.99	0.96	0.86	0.85
non-bovine (lbs/capita)	109.5	110.5	111.6	110.5
milk (gal/capita)	25.1	24.4	24.3	23.9
cheese (lbs/capita)	25.8	26	26.6	26.9
eggs (lbs/capita)	233.6	233.7	235.1	232.3
fish (lbs/capita)	14.59	14.8	14.88	14.38
Cereal Consumption (lbs/capita)	322.1	331.5	333.7	329.3
cereals (lbs/capita)	56.61	57.63	57.99	58.38
wheat (lbs/capita)	262.9	270.8	272.2	266.9
maize (lbs/capita)	22.1	23.1	24	24.9
Fruit & Vegetable Consumption (lbs/capita)	677.5	688	694.8	690.9
vegetables & fruits (lbs/capita)	677.5	688	694.8	690.9
vegetables (lbs/capita)	394.2	406.7	412.3	406.2
fruit (lbs/capita)	283.4	281.2	282.6	284.7
roots and tubers (lbs/capita)	78.46850247	82.22013295	82.47743694	82.41809971
pulses (lbs/capita)	7.816088605	7.230088179	7.707390748	7.507275821
coffee and tea (lbs/capita)	10.86	9.89	8.97	8.74
cocoa (lbs/capita)	5.7	5.3	4.8	4.5
oil seed (lbs/capita)	1.428604794	1.732915794	1.617091058	1.627044122
fats (lbs/capita)	69.2	71.6	69.4	67.2
sweetener consumption (lbs/capita)	136.1	139.1	141.6	144.1
forest harvest (MBF)	25,041.38	26,320.28	36,621.15	21,581.56
meat production (fresh; kg)	*103615499.1*	*103422059.9*	*103228620.7*	*103035181.5*
bovine, buffalo production (kg)	*103615499.1*	*103422059.9*	*103228620.7*	*103035181.5*
sheep, goat (kg)	-	-	-	-
non-bovine, goat, mutton, buffalo (pork; kg)	-	-	-	-
grain production (kg)	312,335,335	263,941,090	270,419,775	339,636,530
cereal production (kg)	158,970,960	132,075,390	136,866,050	165,980,305
wheat production (kg)	153,364,375	131,865,700	133,553,725	173,656,225
animal feed production (kg)	79,350,560	59,811,440	74,820,400	55,621,280
roots and tubers production (kg)	479,678,842	529,211,650	556,813,021	523,813,843

Variable name	**1996**	**1997**	**1998**	**1999**
Population (persons)	*44566*	*45289*	*45902*	*46377*
Coal consumption (short tons)	199934.5087	206220.1121	205489.9538	203823.0838
Natural Gas Consumption (billion cubic feet)	3.581222009	3.550272466	3.679618252	3.654395462
Petroleum Consumption (thousand barrels)	839.2337976	789.8510935	835.9981164	853.5482589
Nuclear Electric Consumption (million kWh)	0	0	0	0
Hydro-electric Consumption (million kWh)	20.69150494	22.90207509	16.30182389	17.14163877
Wood and waste Consumption (trillion BTU)	0.12392165	0.132994334	0.118193798	0.124008014
Land Area (hectares)	2121718.26	2121718.26	2121718.26	2121718.26
Population density (individuals per hectare)	0.021004674	0.021345435	0.021634352	0.021858227
Built-up land (ha)	*6126*	*6262*	*6398*	*6534*
Arable land (ha)	*236040.4072*	*234092.0285*	*236491.2485*	*238890.4685*
Pasture (ha)	*381385.9136*	*380963.3746*	*375949.7946*	*370936.2146*
Forest land (ha)	882085.2711	882085.2711	882085.2711	882085.2711
everything else (ha)	616080.668	618315.5858	620793.9458	623272.3058
mean precipitation (cm)	46.2	60.3	50.7	51.9
Meat Consumption (lbs/capita)	188.56	186.81	192.19	197.17
meat (fresh; lbs/capita)	174.07	172.54	177.62	182.42
bovine, buffalo (lbs/capita)	64.96	63.44	64.26	64.88
sheep, goat (lbs/capita)	0.81	0.8	0.86	0.84
non-bovine (lbs/capita)	108.3	108.3	112.5	116.7
milk (gal/capita)	23.8	23.4	23	22.9
cheese (lbs/capita)	27.3	27.5	27.8	29
eggs (lbs/capita)	233.4	234.3	239.2	249.7
fish (lbs/capita)	14.49	14.27	14.57	14.75
Cereal Consumption (lbs/capita)	342.9	343.5	337.4	339.9
cereals (lbs/capita)	59	57.25	57.39	56.93
wheat (lbs/capita)	279.3	281.3	274.6	277.3
maize (lbs/capita)	25.9	26.5	27.2	27.8
Fruit & Vegetable Consumption (lbs/capita)	703.3	709.7	696.2	705.2
vegetables & fruits (lbs/capita)	703.3	709.7	696.2	705.2
vegetables (lbs/capita)	416.9	415.1	411	414.3
fruit (lbs/capita)	286.4	294.6	285.2	291
roots and tubers (lbs/capita)	85.54335133	81.4107545	80.90923623	81.77681111
pulses (lbs/capita)	7.432451946	7.394777992	7.261340726	7.805818174
coffee and tea (lbs/capita)	9.51	9.87	10.18	10.64
cocoa (lbs/capita)	5.2	5	5.4	5.6
oil seed (lbs/capita)	1.337575603	1.089728557	1.320826467	1.544245332
fats (lbs/capita)	65.6	65.1	65.5	68.2
sweetener consumption (lbs/capita)	144.4	147.7	148.9	151.2
forest harvest (MBF)	11,056.57	3,871.70	4,352.81	6,737.07
meat production (fresh; kg)	*102841742.3*	*102648303.1*	*102454863.9*	*102261424.7*
bovine, buffalo production (kg)	*102841742.3*	*102648303.1*	*102454863.9*	*102261424.7*
sheep, goat (kg)	-	-	-	-
non-bovine, goat, mutton, buffalo (pork; kg)	-	-	-	-
grain production (kg)	375,290,000	383,370,840	367,873,510	354,264,550
cereal production (kg)	200,765,300	204,269,240	191,675,035	186,655,875
wheat production (kg)	174,524,700	179,101,600	176,198,475	167,608,675
animal feed production (kg)	119,122,400	97,997,520	81,382,400	96,247,200
roots and tubers production (kg)	461,094,984	668,035,017	641,613,001	680,508,942

Variable name	**2000**	**2001**	**2002**	**2003**
Population (persons)	47074	*46863*	*47304*	*47376*
Coal consumption (short tons)	213776.4764	215523.3959	208941.3594	210025.8599
Natural Gas Consumption (billion cubic feet)	4.003141834	4.910043486	4.824877192	4.543803648
Petroleum Consumption (thousand barrels)	908.0605101	919.4162247	875.4892085	903.9772299
Nuclear Electric Consumption (million kWh)	0	0	0	0
Hydro-electric Consumption (million kWh)	15.81676148	15.82007546	12.70866345	13.15201882
Wood and waste Consumption (trillion BTU)	0.125098182	0.071957534	0.067274976	0.069824506
Land Area (hectares)	2121718.26	2121718.26	2121718.26	2121718.26
Population density (individuals per hectare)	0.022186735	0.022087287	0.022295137	0.022329072
Built-up land (ha)	6670	*6806*	*6942*	*7078*
Arable land (ha)	*241289.6885*	*243688.9085*	246088.125	*248487.345*
Pasture (ha)	*365922.6346*	*360909.0546*	355895.5272	*350881.9472*
Forest land (ha)	882085.2711	882085.2711	882085.2711	882085.2711
everything else (ha)	625750.6658	628229.0258	630707.3367	633185.6967
mean precipitation (cm)	46.7	46.9	30.6	43.6
Meat Consumption (lbs/capita)	196.79	193.94	200.49	199.04
meat (fresh; lbs/capita)	181.58	179.14	184.85	182.81
bovine, buffalo (lbs/capita)	65.05	63.59	64.98	62.38
sheep, goat (lbs/capita)	0.83	0.85	0.87	0.83
non-bovine (lbs/capita)	115.7	114.7	119	119.6
milk (gal/capita)	22.5	22	21.9	21.6
cheese (lbs/capita)	29.8	30	30.5	30.5
eggs (lbs/capita)	251	252.4	254.6	254.3
fish (lbs/capita)	15.21	14.8	15.64	16.23
Cereal Consumption (lbs/capita)	345.8	336	328.8	329.9
cereals (lbs/capita)	59.61	60.29	61.18	61.09
wheat (lbs/capita)	280	269	260.6	261.4
maize (lbs/capita)	28.4	29	29.7	30.3
Fruit & Vegetable Consumption (lbs/capita)	711.2	684.2	684.9	702
vegetables & fruits (lbs/capita)	711.2	684.2	684.9	702
vegetables (lbs/capita)	422	411.9	411.1	420.1
fruit (lbs/capita)	289.2	272.3	273.8	281.8
roots and tubers (lbs/capita)	81.17866908	81.14909138	77.07850497	80.8407184
pulses (lbs/capita)	7.641999969	6.939987162	6.744101795	6.639901043
coffee and tea (lbs/capita)	11.14	10.37	10.03	10.3
cocoa (lbs/capita)	5.9	5.6	4.8	5.3
oil seed (lbs/capita)	1.499920327	1.49992465	1.499942751	1.499793877
fats (lbs/capita)	84.3	85.3	90.1	89.2
sweetener consumption (lbs/capita)	148.8	147	146.1	141.3
forest harvest (MBF)	5,506.58	3,223.76	2,679.38	3,897.25
meat production (fresh; kg)	*102067985.5*	-	-	-
bovine, buffalo production (kg)	*102067985.5*	90,209,619	79,211,661	64,341,425
sheep, goat (kg)	-	90,209,619	79,211,661	64,341,425
non-bovine, goat, mutton, buffalo (pork; kg)	-	-	-	-
grain production (kg)	468,344,800	340,367,365	254,515,900	259,156,120
cereal production (kg)	236,823,800	178,770,515	121,562,200	118,279,070
wheat production (kg)	231,521,000	161,596,850	132,953,700	140,877,050
animal feed production (kg)	87,971,600	75,844,480	49,007,600	31,955,920
roots and tubers production (kg)	679,397,630	789,961,911	561,666,515	567,427,189

Variable name	2004	2005
Population (persons)	*47831*	*47530*
Coal consumption (short tons)	205594.4562	198190.5176
Natural Gas Consumption (billion cubic feet)	4.576624544	4.790411072
Petroleum Consumption (thousand barrels)	974.5921966	940.204808
Nuclear Electric Consumption (million kWh)	0	0
Hydro-electric Consumption (million kWh)	12.4296962	14.42219504
Wood and waste Consumption (trillion BTU)	0.076970504	0.070327311
Land Area (hectares)	2121718.26	2121718.26
Population density (individuals per hectare)	0.022543521	0.022401655
Built-up land (ha)	*7214*	*7350*
Arable land (ha)	*250886.565*	*253285.785*
Pasture (ha)	*345868.3672*	*340854.7872*
Forest land (ha)	882085.2711	882085.2711
everything else (ha)	635664.0567	638142.4167
mean precipitation (cm)	49.1	47.0
Meat Consumption (lbs/capita)	201.45	199.76
meat (fresh; lbs/capita)	184.85	183.56
bovine, buffalo (lbs/capita)	63.31	62.78
sheep, goat (lbs/capita)	0.83	0.78
non-bovine (lbs/capita)	120.4	120
milk (gal/capita)	21.2	21
cheese (lbs/capita)	31.2	31.4
eggs (lbs/capita)	256	253.9
fish (lbs/capita)	16.6	16.2
Cereal Consumption (lbs/capita)	326.6	326.3
cereals (lbs/capita)	60.58	61.89
wheat (lbs/capita)	258.1	256.4
maize (lbs/capita)	30.9	31.4
Fruit & Vegetable Consumption (lbs/capita)	693.8	688.6
vegetables & fruits (lbs/capita)	693.8	688.6
vegetables (lbs/capita)	421.7	415.4
fruit (lbs/capita)	272.1	273.2
roots and tubers (lbs/capita)	79.35153158	74.98827017
pulses (lbs/capita)	5.966688317	6.148759756
coffee and tea (lbs/capita)	10.45	10.35
cocoa (lbs/capita)	6	6.5
oil seed (lbs/capita)	1.488811125	1.478475521
fats (lbs/capita)	88.4	87.2
sweetener consumption (lbs/capita)	141.6	141.6
forest harvest (MBF)	6,280.86	4,444.48
meat production (fresh; kg)	-	-
bovine, buffalo production (kg)	69,523,593	68,018,376
sheep, goat (kg)	69,523,593	68,018,376
non-bovine, goat, mutton, buffalo (pork; kg)	-	-
grain production (kg)	265,175,950	241,908,150
cereal production (kg)	114,660,030	110,377,850
wheat production (kg)	150,515,920	131,530,300
animal feed production (kg)	27,140,160	31,252,800
roots and tubers production (kg)	569,717,854	655,502,132

Appendix 3-D: Ecological Footprint Analysis for the United States, 1980-2005

This appendix provides results of an Ecological Footprint Analysis (EFA) for the United States from 1980 to 2005 for comparative purposes with the San Luis Basin EFA.

Because EFAs usually reveal patterns for the US where ecological deficit (*ef* > *bc* or *EF* > *BC*) is the rule, as demonstrated by the analysis on Utah (McIntyre et al. 2007), and the analysis for the SLB reveals an ecological reserve, we decided to conduct an EFA for the US to test the methodology employed for SLB, using the same variables and data sources (see Table 3.1). For comparison purposes, the Global Footprint Network (2009) graph for the US shows a general increase in *ef* for the US from 1980 (~6 gha) to 2005 (~5 gha) and a general decrease in *bc* from 1980 (~7.5 gha) to 2005 (~9 gha). These results indicate the ecological balance for the US is a deficit and US was moving away from sustainability for the period (an increasing ecological deficit from ~1.5 to 4 gha). Our methodology reveals similar trends for the US, revealing the US had an ecological deficit because *EF* had already exceeded *BC* by 1980 (whether reported ha or gha or per capita or for the entire population; Figs. 3-C.1 and 3-C.2). EFAs for the US usually identify an ecological deficit occurring around 1970 (e.g., Global Footprint Network 2009). The differences in the results between US and SLB increased our confidence that our methodology captured trends in the SLB, rather than merely duplicating that of the larger system.

References

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McIntyre, S., Peters, H.M., Christensen, M.H., Emmi, P.C., Martinson, W., Mielke, M., Senbel, M., Stark, D.O. 2007. The ecological footprint of Utah: a sustainability indicators project of the Utah Population and Environment Coalition. Utah Vital Signs, 26 June. 59 pp. Available online at http://www.utahpop.org/vitalsigns/research/report_2007.htm. Last accessed July 13, 2009.

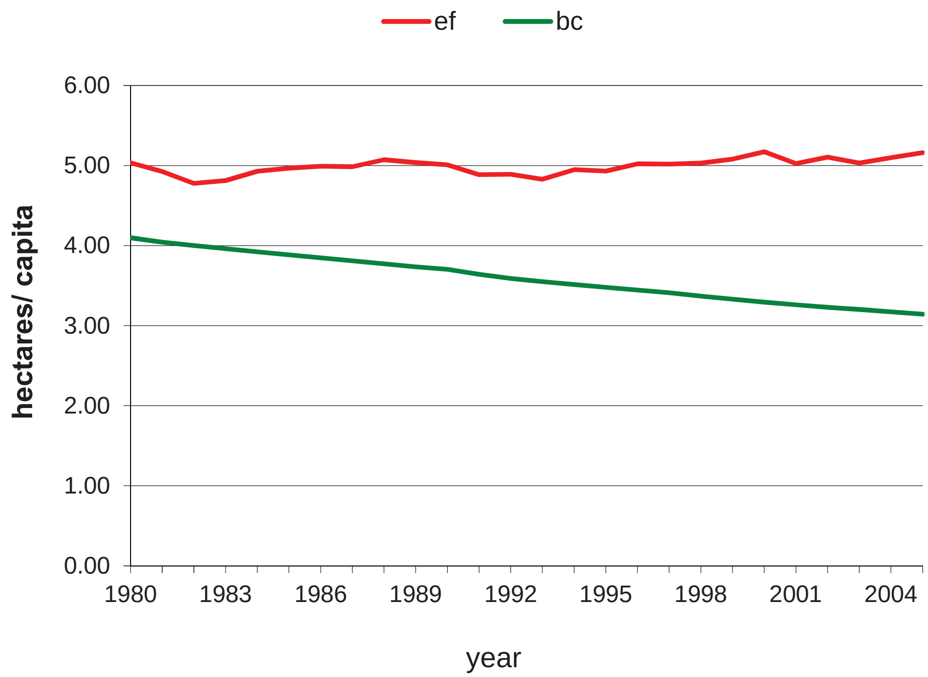

Figure 3-D.1 – Biocapacity (*bc*) compared to ecological footprint (*ef*) per capita for 26 years in the US. Twelve percent of the biocapacity area was subtracted from the total *bc* to protect biodiversity.

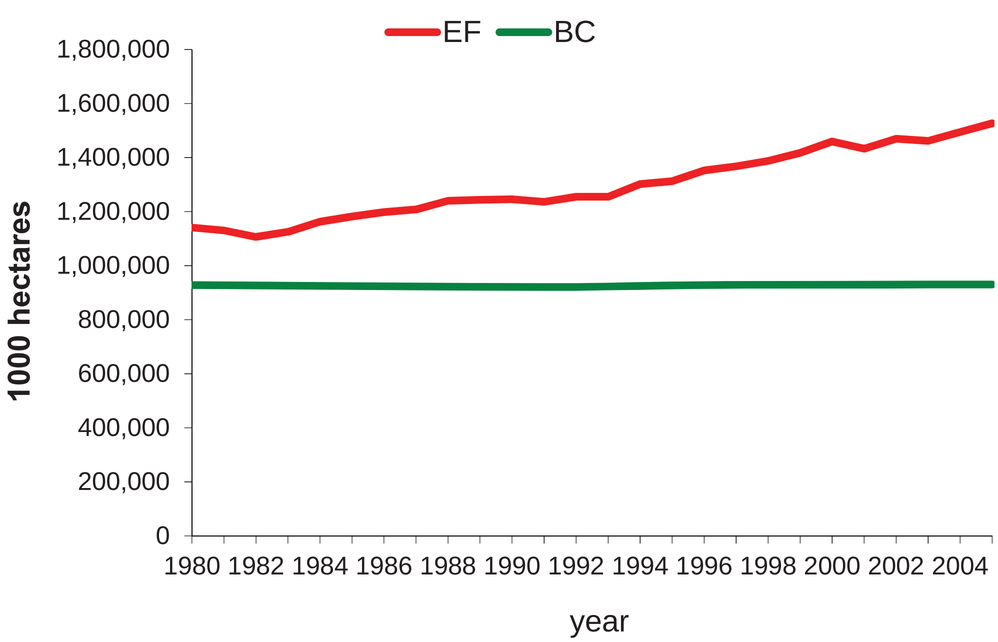

Figure 3-D.2 – Total ecological footprint (*EF*) and biocapacity (*BC*) for the US population. Twelve percent of the biocapacity area was subtracted from the total *BC* to protect biodiversity.

4.0
Green Net Regional Product

4.1 Introduction

This chapter describes the data sources and methodology used to estimate Green Net Regional Product (GNRP) for the San Luis Basin (SLB). GNRP is similar to Green Net Domestic Product (GNDP; defined in Chapter 2), but applied to a region on a smaller spatial scale. The boundary of this metric was delineated by the seven counties that we define as the SLB (Fig. 1.1). The chapter is outlined as follows. First, we describe the basic model of estimating GNRP and the components of the depreciation of natural capital. Next, we highlight the public data sources used to estimate Net Regional Product (NRP), and the three components of natural capital depreciation. Then we present the methodology used to estimate GNRP, followed by the estimates themselves. Finally, we point out some of our assumptions when calculating GNRP with public data sources and our conclusion.

4.2 Model

Using the information describing GNDP in Section 2.2.2, the model for the SLB GNRP is

$$GNRP(t) = NRP(t) + \lambda_n(t)\dot{K}^n(t) \tag{4.1}$$

Net Regional Product (NRP) is equal to Gross Regional Product (GRP) minus the depreciation of human-made capital. It does not include the depreciation of natural capital, which is represented by the second term on the right of Equation 4.1, where $\lambda_n(t)$ is the shadow price of natural capital $\dot{K}^n(t)$ and is the change in natural capital over time, t. This component still has to be estimated in order to estimate GNRP.

Natural capital, when incorporated in NRP calculations, is typically included as the extraction of natural resource stocks. For example, a resource stock that might be important is forests. Although timber is considered a valued output, GNRP captures the depreciation of natural capital through the value of decreases in the forest stock (Seroa da Motta and Ferraz do Amaral 2000). Given the contribution of agribusiness to the SLB, we included the depletion of both groundwater and soil as components in the depreciation of natural capital. In addition, we captured the effect of the consumption of energy on future generations through carbon dioxide emissions (CO_2). When stocks of capital are not changing over time or the change is minimal, an advantage of using the change in GNRP is that those stocks of capital can be dropped as explained in Chapter 2. Based on our assumptions, mining activities and forestry were considered constant. The assumption for forestry was consistent with Ecological Footprint Analysis. The decision to consider mining constant could be debated given the export data used in Emergy Analysis (Chapter 5; e.g., sand and gravel was decreasing, broken stone or rip rap was marginally decreasing). We did not explicitly include the depreciation of human capital in our estimate of GNRP. Aggregate consumption in NRP (Eq. 4.1) already incorporates education expenditures. If these expenditures are the best proxy for investment in human capital, the expenditures are already included in the equation (see Pezzey et al. 2006 for discussion). We are aware, however, that education expenditures are typically considered a poor measurement of the depreciation of human capital (e.g., Ferreira and Vincent 2005). Because sustainability relates to the potential for future increases or decreases in welfare rather than any absolute level of welfare, the absolute estimates of GNRP do not relate to sustainability. Sustainability is measured by changes in GNRP over time.

4.3 Data and Sources

One approach to calculate NRP, Equation 4.1, would begin with collecting data to estimate GRP and then adjust GRP by the depreciation of man-made capital stock (i.e., top-down approach). This nominal estimate is then converted into real NRP using the Gross Domestic Product (GDP) deflator (Banzhaf and Smith 2002, Landefeld et al. 2008). Unfortunately, the lack of economic data for the counties in the SLB hampers the implementation of this approach.

The data we used to estimate real NRP, described in the next section, are available from the Bureau of Economic Analysis (BEA) in the US Department of Commerce. The BEA is responsible for calculating the economic accounts in order to understand how the economy is performing (BEA 2006a). This Agency provides economic accounts data for the US, states, and regions, including counties (BEA 2006a). Our approach for estimating NRP included data from all three scales. The economic measures required include GDP and Consumption of Fixed Capital (CFC) for the US. Personal Income and GDP for Colorado and New Mexico were needed and available from the BEA. For the seven counties in the SLB, we used Personal Income from the BEA (Table 4.1).

For each component of the depreciation of natural capital, we needed an estimate of the change in the stock of the capital and a "price." Goods and services provided by the environment and not traded in markets are not considered in the definition of natural capital depreciation above. A number of articles, however, have been published on how to proceed with calculating GNRP when some of the goods and services cannot be valued with existing prices (e.g., Banzhaf and Smith 2002, Cairns 2001). Banzhaf and Smith (2002) stated that incorporating the depreciation of nonmarket goods and services is difficult because of the lack of data and because these goods and services are not measured in standard, well-defined units like market goods.

Cairns (2001) suggested using shadow prices of the local amenities that do not have market prices. For environmental spillovers or externalities that extend beyond the local economy (e.g., reducing CO_2 emissions), he recognized the global shadow value overstates the benefits to the local economy. However, he pointed out the inadequacy (for green accounting purposes) of imposing local value (as measured by willingness to pay) as the price of benefits that extend globally. His proposed solution was to count the difference between the shadow value and the domestic willingness to pay for mitigation of the spillover pollution as an export from the pollution emitter to the recipient of pollution. He provided a theoretical approach for incorporating these nonmarket values, but did not implement his approach.

In the case of carbon emissions, we have opted to follow the example of Hamilton and Clemens (1999) who assumed the property right to a clean environment lies with the victim of pollution and thus charge global damages to emitting countries.[8] Carbon emissions are counted as an environmental cost equal to the global social cost of carbon.

Next, we describe the data needed to calculate the change in the stock of groundwater, soil erosion, and CO_2 emissions and the sources of these data. Additional details of the methodology are described in Section 4.4. The Colorado Water Conservation Board and the Colorado Division of Water Resources have created Colorado's Decision Support Systems that provide information about the water balance of many of its river basins (CWCB and CDWR 2008). Its purpose is to help water managers make better decisions related to water use. The Upper Rio Grande is one of the basins that is available. Colorado Division of Water Resources provided the updated calculations for the groundwater basin in the Upper Rio Grande and data required to include the years 1970-2005 (personal communication with R. Bennett, February 2008).

Wind erosion is the main cause of soil erosion in the SLB (personal communication, R. Sparks, USDA, May 2008). Finding reliable, county-level soil-erosion data is challenging. No estimates have been attempted for the SLB. The National Resource Information (NRI) data on wind erosion at first appeared to be a promising data source (e.g., NRCS 2007); however, NRI data are not reliable at the county level (personal communication, R. Sparks, USDA, May 2008). Following the recommended approach described by Richard Sparks, an agronomist in the USDA Natural Resources Conservation Service (NRCS) stationed in the region (see Appendix 4-A), a number of data sets were required. First, the Agricultural Statistics for Colorado provides annual estimates of planted acres of different crops by county. The US Census of Agriculture (NASS 1984, 1989, 1994, 2009a, 2009b) provides data on total crop land and total harvested land. We used reports beginning in 1982 and continuing every five years until 2002. Through numerous communications, R. Sparks provided information about crop rotations, soil type, and residue management by year (personal communication, May-November 2008). The Wind Erosion Equation Technology from 1980-2005 (Woodruff and Siddoway 1965) was then applied to this calculation of acreage by crop rotation, soil type, and residue management.

Carbon dioxide emission estimates do not exist at the county level. Therefore, we needed to find an alternative approach. Required data included state-level data for Colorado and New Mexico and the population of each state for the same years (1980-2005). State-level emissions can be found at the Energy Information Agency (EIA 2007). In addition, we needed the SLB population for the same years. Population data were acquired through the Bureau of Economic Analysis (BEA 2007). We used the average per capita CO_2 emissions for Colorado and New Mexico (EIA 2008) and applied this to the SLB population estimates. Table 4.1 presents the sources and the Websites where these data can be accessed.

[8] Although we focus on determining whether the region is moving towards or away from sustainability, another possibility would have been to assess the region's contribution towards global sustainability. If this would have been our objective, global emissions of carbon would have been the correct estimate. The approach used in this report is similar to that of Pezzey et al. (2006).

4.4 Calculation Methodology

Due to the lack of data for the top-down approach, the alternative, bottom-up approach adjusts Personal Income, which is available for all counties in the SLB (e.g., BEA [2008] presents the relationship between Personal Income and GDP). Personal Income is defined as (BEA 2007: XI-6):

> income received by persons from participation in production, plus transfer receipts from government and business, plus government interest (which is treated like a transfer receipt).

Personal Income for the region was converted to Net Regional Product as follows. We estimated Net Domestic Product by state (NDP_{state}) using Gross Domestic Product by state (GDP_{state}) and the ratio of Consumption of Fixed Capital (CFC_{US}) to GDP for the US (GDP_{US}) (4.2). This was proposed because BEA does not estimate CFC for states (personal communication C. Woodruff, 25 January 2008). It is somewhat similar to the approach used by Pezzey et al. (2006) where United Kingdom estimates were used to convert Scottish data. Once NDP_{state} was calculated, we estimated the ratio of NDP_{state} to Personal Income by state. We used this process for both Colorado and New Mexico (i.e., represented by subscript state in Equations 4.2 and 4.3) across time and multiplied by the Personal Income for the counties in the SLB, as presented in Equation 4.3. The estimate of NRP for the SLB was the average of both the Colorado and New Mexico calculations because we believed the GDP_{state} and Personal Income for Colorado and New Mexico bound the calculations for the SLB.

$$NDP_{state} \approx GDP_{state} - \left(\frac{CFC_{US}}{GDP_{US}}\right) GDP_{state} \tag{4.2}$$

$$NRP \approx \left(\frac{NDP_{state}}{PI_{state}}\right) \times PI_{SLB} \tag{4.3}$$

Without data to support this approach, the alternative would have been to use the ratio of Net Domestic Product for the US to Personal Income for the US, but we do not believe the Net Domestic Product is representative of the economy of the SLB. We are aware of another complication described by BEA related to GDP by state time series. Because BEA switched from Standard Industrial Classification (SIC) to North American Industry Classification System (NAICS)-based GDP in 1997, the time series results in a discontinuity. A SIC-based GDP is closer to Gross Domestic Income (GDI) and a NAICS-based GDP is closer to US GDP (BEA 2006b). Although BEA strongly cautions against combining these two series to have a complete time series, we appended the two by adjusting the SIC-based GDP by state (prior to 1997) using the ratio GDP_{US}/GDI_{US} to make years relatively consistent with post-1997. The estimate for real NRP, which has been adjusted using the GDP deflator, is in the second column of Table 4.2.

As stated in the previous section, we used data to estimate the change in the stock of natural capital and existing studies to estimate the shadow price. The previous section described the change in the stock of natural capital and data needed to estimate NRP. We provide more detail here on how we combined shadow price and the change in natural capital stock. In order to estimate the value of the change in the natural capital, we used benefit transfer, an economic valuation approach.

An alternative to collecting primary economic value data via observation or survey is to use benefit transfer based on secondary data. Benefit transfer applies economic value (e.g., willingness to pay for a change in environmental quality) from one study to another location or context (Desvousges et al. 1992). The accuracy of benefit transfer depends on the existence and quality of applicable studies. The advantages of benefit transfer approaches include saving the time and cost of developing and implementing new studies. This is a standard approach for the USEPA because of limitations on primary data collection using surveys (see The Paper Reduction Act of 1995). Of course, the disadvantages are obvious. Benefit transfer is not usually as accurate as analysis done with primary data. This means the values estimated for the policy site will depend on differences in the resources being valued and the relevant populations.

According to Wilson and Hoehn (2006: 336), "few benefit transfer practitioners seem fully satisfied with the state of the science." However, certain steps need to be taken to ensure a high quality transfer. A few authors have listed these steps. For example, the USEPA (2000: 86-87) describes the steps as: 1) understanding the characteristics and consequences of the policy case along with the effected population; 2) identifying existing studies or values that are relevant for the policy case through a literature search; 3) reviewing available studies for quality and applicability and to determine their transferability; 4) transferring the benefit estimates; and 5) addressing uncertainty because judgments and assumptions are involved.

We used a water balance model from the Colorado's Decision Support Systems for the depletion of groundwater. This model was used to estimate the water balance for many of Colorado's basins, including the Rio Grande River Basin (CWCB and CDWR 2008). Over the 26 years of this study, the model showed, on average, that groundwater storage has been declining in the region (outflow has been greater than inflow; Table 4.2, column 3). We used the shadow price of water for agriculture from Hurd and Coonrod (2007), which was based on a hydro-economic model for the Rio Grande watershed. The purpose of their study was to examine the impact of climate change on water supplies in the arid southwest. We used $76/acre-foot (2005$) from their baseline estimate in 2000. It is not reflective of the market price of water, but rather the marginal value of an additional acre-foot of water for agricultural purposes. The authors pointed out that this estimate was relatively high compared to the estimate for New Mexico because of the Rio Grande Compact (CWCB 2000), which requires Colorado to deliver a certain amount of water to New Mexico and Texas, and because of the high marginal value of agricultural production in the SLB (Hurd and Coonrod 2007). The depreciation of groundwater is presented in column 4 of Table 4.2.

Soil erosion in the SLB is primarily from wind, and it had not been estimated over time prior to this study. To produce a credible estimate, we needed data on soil erodibility, crop rotations, tillage management, crop growth stages, and winterkill. Because agriculture is not a major activity in all of the SLB, we focus on Alamosa, Conejos, Costilla, Rio Grande, and Saguache counties. We collaborated with R. Sparks, who is familiar with the farming practices in the SLB (more details of this effort are described in Appendix 4-A). The estimate for wind erosion, in tons/year, is in column 5 of Table 4.2. The damage estimate was based on Huszar and Piper (1986) who calculated off-site damages due to wind erosion in New Mexico. Ringquist et al. (1995) revised the Huszar and Piper estimate to focus on agricultural sources only. The value we used was $2.42/ton (2005$) and the total estimate is in column 6 of Table 4.2. Therefore, rather than capturing the quality-adjusted stock of agricultural land as described by Hrubovcak et al. (2000), we present the off-site damages caused by wind erosion. Other papers have derived estimates from Huszar and Piper (1986). For example, Bunn (1998) used one particular Major Land Resource Area (MLRA) that is part of the study area and determined the off-site cost per ton of eroded soil per acre was approximately $10.12 (2005$). Williams and Young (1999) used Huszar and Piper to estimate off-site costs in South Australia. Additional studies, such as a hedonic analysis, would be necessary in order to determine the foregone production rents due to the soil erosion on farmland values (Hrubovcak et al. 2000). We are currently attempting to determine the feasibility of such a study in the SLB.

Per capita CO_2 emissions for the SLB were calculated as the average of the EIA estimates for Colorado and New Mexico. This per capita emission estimate was multiplied by the population of the SLB to calculate total emissions (Table 4.2, column 7). Although we estimated carbon flows (i.e. emissions) to estimate the annual social cost of carbon emissions, global temperature is influenced by the absolute concentration of CO_2 in the atmosphere. CO_2 emissions remain in the atmosphere for many years. Pezzey et al. (2006) noted the social cost of carbon emission estimates should incorporate the atmospheric lifetime of emissions. Following Tol (2007) who calculated the social cost of carbon based on a meta-analysis of 125 peer-reviewed estimates, we used a value approximately equal to $24/ton CO_2 (2005$). The damage cost caused by these emissions is presented in column 8 of Table 4.2. Lifetime costs of emissions were included in this estimate.

Because we did not know the right prices and incorrectly estimating the prices could lead to a misinterpretation of the results, we conducted a sensitivity analysis. We calculated low and high estimates of the prices and marginal damages of natural capital depreciation. For the depreciation of groundwater, the low value was $66.05/acre-foot and the high value was approximately $85/acre-foot. These values were based on the variability of the 30 years of simulation (personal communication B. Hurd, May 2010). The low and high estimates of damages caused by wind erosion were $0.27/ton and $9.57/ton, respectively (Huszar and Piper 1986). These costs were based on specific regions (MLRA 48/51 and 77) rather than for the entire state. The social cost of carbon ranged from $0/ton CO_2 to $77.29/ton CO_2. Tol (2007) calculated the 95-percentile for peer-reviewed studies. The estimate means the author is 95% confident the expected social cost of carbon is equal to or less than $77.29/ton CO_2. Tol (2007) did not provide a lower bound estimate, so we chose $0.

4.5 Results

Following the methodology presented in the previous section and using the 26 years of data consisting of the variables described in Table 4.1, we estimated the SLB GNRP. Aggregating the results from NRP, Groundwater Storage Depreciation, Soil Erosion Damage, and CO_2 Damage Costs, we estimated GNRP in column 9 of Table 4.2. The final column shows the change in GNRP from one year to the next in between the rows. The

NRP, GNRP, and the change in GNRP are all presented in Figure 4.1; components of natural capital depreciation are presented in Figure 4.2.

Although there were peaks and troughs, NRP and GNRP both had upward trends suggesting the components of natural capital depreciation have a minimal effect. Natural capital depreciation ranges from -8.6 to 0.11 percent of NRP. However, caution should be taken in interpreting the actual values in those two columns because we dropped the components that do not vary. Through the 26 years of data, CO_2 damages and soil erosion changes have remained fairly constant; however, groundwater storage fluctuated over this time (Fig. 4.2). Overall, it appears that natural capital stocks have declined.

If we strictly follow Pezzey et al. (2006) and Hanley et al. (2002), originally summarized in Chapter 2, who suggested the change in GNRP is a one-sided test of weak sustainability (e.g., when man-made capital can be substituted for natural capital), the calculation revealed the SLB was moving away from sustainability during the time period 1985-86 to 1987-88. This appears to be the longest negative range. Based on the results, there are other periods of negative change, but not since 1999-2000. As we discuss below, this strict interpretation, based on the theoretical literature, may have some problems.

The sensitivity analysis, when using the lower bound estimates, revealed that GNRP is about 3% to 6% higher than our GNRP estimate in Table 4.2 (see Fig. 4.3). When we calculated GNRP with the high values, our estimates ranged from 7% to 14% lower than GNRP in Table 4.2.

4.6 Discussion

The previous section presented the results of estimating GNRP for the SLB over a 26-year period. The methodology satisfies the objective of estimating GNRP using an approach that others can follow using publicly available data. With that said, the data were not perfect. This section discusses the assumptions needed in order to estimate GNRP of the SLB and some of the limitations we found while developing the GNRP methodology.

Before we present some of the specific assumptions for our calculations, we want to state that there is uncertainty surrounding the application of this method. Although the calculation is theoretically founded, the approach requires many assumptions (e.g., Stern 1997). Although these assumptions are very important, we briefly mention them because they can be found in the literature (e.g., Dasgupta 2001, Neumayer 2010, Stern 1997). Assumptions related to weak sustainability and using the right prices (i.e., shadow prices) are important and do lead to uncertainty in the calculations. It is not our intent to minimize this first group of assumptions underlying the theory, but this section focuses on those assumptions related to our specific calculations and interpretation.

Calculating the NRP of the SLB required a number of simplifying assumptions. We already stated the type of data necessary to use a top-down approach would have been prohibitive; therefore, we used US and state data to convert Personal Income in the SLB to NRP. To do so, we assumed the ratio of US GDP to US CFC was similar to that in both Colorado and New Mexico. Taking the Net Domestic Product by state and estimating the ratio to Personal Income to the state required another assumption of similarity. If neither of these are sound assumptions, we may have over or underestimated NRP in the SLB.

Because of a change in the BEA approach to estimating state GDP, we assumed the ratio of US GDI to US GDP is similar to that of Colorado and New Mexico prior to 1997. This is necessary because of the switch from the SIC to the NAICS-based GDP. The BEA cautions against completing the time series by combining the two; it is not clear that adjusting the SIC-based GDP with the US ratio is acceptable either. For studies that may follow this methodology, estimating GNRP after 1997 avoids the need for this assumption and transformation.

Based on existing literature, preliminary examination of data, and the methodology for the other metrics, human capital and certain components of natural capital depreciation were assumed constant (e.g., forestry). The decision to do this removed the need to include those data in the calculations. Although we were interested in the change in GNRP, no additional information can be gleaned from the calculations because the annual calculations do not capture these particular components.

Business cycles complicate the use of GNRP to analyze sustainability. Sustainability is concerned with the long-term and thus short-term business cycles may obscure the interpretation of the metric. The theoretical literature on GNRP assumes the economy is achieving its potential output. GNRP calculated with actual data reflects recessions that prevent GNRP from reaching its potential output. Temporary dips in GNRP due to the business cycle may not represent movement away from sustainability if potential GNRP is steadily increasing. BEA (2003) determined that recessions occurred in the area from 1981-82 (most severe), 1990-91, and in 2001. GNRP follows the decline in 1981-82, but not 1990-91 (although it slows). There was a fall from 1999 to 2001 in Real NRP, but not GNRP. This introduced some doubt as to whether the decline in GNRP 1981-1982 indicates movement away from sustainability or simply reflects the temporary economic downturn. There is no generally accepted method of controlling for the business cycle in sustainability analysis, but Pezzey et al. (2006: 71) attempted "an ad hoc allowance for the Scottish business cycle during 1992-1999."

There is another reason to be cautious of concluding the region was moving away from sustainability based on periodic decreases in GNRP interspersed throughout the overall growth in GNRP during the study period. GNRP does not explicitly consider technological progress, but the overall growth or decline in GNRP is largely determined by a competition between technological progress that allows GNRP to rise and natural capital depreciation that pulls down GNRP (Weitzman and Löfgren 1997). Technological progress does not proceed smoothly, but rather comes in fits and starts. Because consumers typically wish to smooth their consumption, consuming capital (resulting in negative growth in GNRP) during years of little technology growth is rational behavior.

Over the 26-year period, it appears that technological progress was greater than net depreciation for the region, since GNRP rose over the entire period.[9] The years of declining GNRP when GNRP was moving away from sustainability should provoke legitimate concern the region might have been consuming its capital at too rapid a rate and technology was not keeping up. However, the ultimate growth in GNRP suggests that isolated declines in GNRP were only signs the region was moving away from sustainability, rather than a definitive judgment as the theoretical literature would suggest.

We used a number of approaches to estimate the change in natural capital stock for CO_2 emissions, soil erosion, and groundwater. Colorado's Decision Support Systems, which is used to estimate the change in groundwater stock, has its own set of assumptions, but given their approach, we feel the calculation was accurate (e.g., CWCB and CDWR 2008). Soil erosion was developed with R. Sparks and required a number of simplifying assumptions in order to calculate crop rotations by soil type and wind erosion based on the Wind Erosion Equation. More details on the approach can be found in Appendix 4-A. Finally, we assumed that Colorado and New Mexico per capita CO_2 emissions bound the SLB per capita CO_2 emissions. If the residents of the SLB had different habits in terms of energy consumption that differs from the two states, the results may not be accurate. However, the research for ecological footprint determined that per capita energy consumption in the SLB was not significantly different than per capita state consumption (see Appendix 3-A).

We did not know the right prices for the different capital stocks and we used existing literature for those estimates. Because we used benefit transfer to estimate the shadow price and marginal damage costs for natural capital depreciation, we need to consider the quality of the studies, the relevant populations, and the uncertainty of the results. We have the most confidence in estimating the depreciation of water because the study of Hurd and Coonrod (2005) included the Upper Rio Grande River Basin, which is part of the SLB. They discussed the value of agriculture and the Rio Grande Compact, which both play an important role in the shadow price of groundwater in the SLB. We were fairly confident in the marginal damage cost of carbon emissions that was based on Tol (2005, 2007). This confidence was based on their use of 125 peer-reviewed studies. Nonetheless, there were many different statistical distributions that could have been used and many studies in the gray literature that were not included. The studies used in the meta-analysis may not be representative, but we believe it is the best information available. We had the least confidence in our estimate of damages due to wind erosion. The study we used was for New Mexico, but it had a very low response rate for the survey suggesting that it may not even be representative of New Mexico, let alone the SLB. We only used off-site costs of wind erosion and not on-site agricultural damages. In addition, the results were presented in total dollars and we revised the estimates to dollars per ton. The assumptions required to use the value from the Huszar and Piper study (1986) were quite simplifying.

Natural capital was mostly declining (Fig. 4.2) and, if the weak sustainability assumption was incorrect or if we underestimated the prices for natural capital, the results could reveal a movement away from sustainability. Based on the sensitivity analysis, we believe other components, such as NRP, are relatively more important than the shadow prices and damage costs (see Fig. 4.3). Because the trends in GNRP did not differ substantially throughout the range of the sensitivity analysis, the interpretation remains consistent with the results in Table 4.2. That is, given the results of the weak sustainability metric, the system appears not to be moving away from sustainability.

[9] Error in our estimate of human capital may lead to a misleading result, but we think that our interpretation regarding technological progress was likely correct.

4.7 Conclusion

We estimated GNRP, a metric based on the concept of weak sustainability, from 1980-2005 for the SLB. The results show that GNRP had an increasing trend over the 26-year study period with a few negative periods. Given this fairly short time horizon, we conclude that there was no definitive evidence of movement away from sustainability. However, if the assumptions behind GNRP, like weak sustainability, are wrong, along with the decline in natural capital stocks, then the results could indicate problems in the longer term.

4.8 References

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Table 4.1 – Green Net Regional Product (GNRP): Variables, Purpose, and Data Sources.

Scale	Variable name	Purpose	Source*	Home Website	Specific Data Link
US					
	Gross Domestic Product (GDP)		BEA	http://www.bea.gov/	http://www.bea.gov/national/nipaweb/TableView.asp?SelectedTable=43&ViewSeries=NO&Java=no&Request3Place=N&3Place=N&FromView=YES&Freq=Year&FirstYear=1980&LastYear=2005&3Place=N&Update=Update&JavaBox=no
	Consumption of Fixed Capital (CFC)		BEA	http://www.bea.gov/	http://www.bea.gov/national/nipaweb/TableView.asp?SelectedTable=43&ViewSeries=NO&Java=no&Request3Place=N&3Place=N&FromView=YES&Freq=Year&FirstYear=1980&LastYear=2005&3Place=N&Update=Update&JavaBox=no
	Ratio: CFC/GDP	Ratio needed to convert GDP by state to NDP by state	EBT		
	Gross Domestic Income (GDI)		BEA	http://www.bea.gov/	http://www.bea.gov/national/nipaweb/TableView.asp?SelectedTable=43&ViewSeries=NO&Java=no&Request3Place=N&3Place=N&FromView=YES&Freq=Year&FirstYear=1980&LastYear=2005&3Place=N&Update=Update&JavaBox=no
	Ratio: GDP/GDI	For years prior to 1997, GDP by state was calculated differently. This ratio makes GDP by state relatively consistent.	EBT		

Scale	Variable name	Purpose	Source*	Home Website	Specific Data Link
State					
	Personal Income (PI) for Colorado (thousands of dollars)		BEA	http://www.bea.gov/	http://www.bea.gov/regional/spi/default.cfm?selTable=summary
	GDP for CO (thousands of dollars)		BEA	http://www.bea.gov/	http://www.bea.gov/regional/gsp
	Net Domestic Product (NDP) for CO (thousands of dollars)		EBT		
	Ratio: NDP/PI for CO	Ratio multiplied by PI for SLB provides estimate of Net Regional Product (NRP)	EBT		
	CO_2 emissions for Colorado		EIA	http://www.eia.doe.gov/	http://www.eia.doe.gov/oiaf/1605/state/state_emissions.html
	Population for Colorado	Used to estimate per capita CO_2 emissions for CO and total emissions for SLB	BEA	http://www.bea.gov/	http://www.bea.gov/regional/spi/default.cfm?selTable=summary
	Personal Income (PI) for New Mexico (thousands of dollars)		BEA	http://www.bea.gov/	http://www.bea.gov/regional/spi/default.cfm?selTable=summary
	GDP for NM (thousands of dollars)		BEA	http://www.bea.gov/	http://www.bea.gov/regional/gsp
	Net Domestic Product (NDP) for NM (thousands of dollars)		EBT		
	Ratio: NDP/PI for NM	Ratio multiplied by PI for SLB provides estimate of Net Regional Product (NRP)	EBT		
	CO_2 emissions for New Mexico		EIA	http://www.eia.doe.gov/	http://www.eia.doe.gov/oiaf/1605/state/state_emissions.html
	Population for New Mexico	Used to estimate per capita CO_2 emissions for NM and total emissions for SLB	BEA	http://www.bea.gov/	http://www.bea.gov/regional/spi/default.cfm?selTable=summary

Scale	Variable name	Purpose	Source*	Home Website	Specific Data Link
SLB					
	Personal Income (PI) for Colorado counties	Used to estimate SLB Net Regional Product	BEA	http://www.bea.gov/	http://www.bea.gov/regional/reis/default.cfm?selTable=CA1-3&section=2
	Water Budget for the Upper Rio Grande River	Change in groundwater levels	CDSS	http://cdss.state.co.us/DNN/default.aspx	http://cdss.state.co.us/DNN/RioGrande/tabid/57/Default.aspx
	Crop acres planted	Used to estimate total crop rotation acres and tillage/residue management practices needed for wind erosion	NASS	http://www.nass.usda.gov/index.asp	http://www.nass.usda.gov/Statistics_by_State/Colorado/index.asp
	Total crop land, Total harvested land	Used to estimate total crop rotation acres and tillage/residue management practices needed for wind erosion	NASS	http://www.agcensus.usda.gov/	http://www.agcensus.usda.gov/Publications/2007/Full_Report/Census_by_State/Colorado/index.asp
	Crop rotation acres, Soil type, Tillage/residue management	Used to estimate total crop rotation acres and tillage/residue management practices needed for wind erosion	EBT		
	Wind Erosion (tons/year)		WEQ, EBT	http://www.weru.ksu.edu/nrcs/weq.html	
	Population	Used for CO_2 emissions	BEA	http://www.bea.gov/	http://www.bea.gov/regional/reis/default.cfm?selTable=CA1-3&section=2

*BEA-Bureau of Economic Analysis

EBT-Estimated by Team

EIA-Energy Information Agency

CDSS-Colorado's Decision Support Systems

NASS-National Agricultural Statistics Service

WEQ-Wind Erosion Equation

Table 4.2 – Estimates of all components of Green Net Regional Product (GNRP).

	NRP*	Ground-water Storage (acre-feet)	Ground-water Storage Dep.*	Total Erosion (tons/year)	Soil Erosion Damage*	CO_2 Emissions (metric tons/year)	Damage Cost*	GNRP*	Change in GNRP*
1980	$775,613	81,972	$6,190	4506372	$10,913	1045868	$24,845	$746,045	
1981	$727,258	-287,123	-$21,681	4858200	$11,765	1016955	$24,158	$669,655	-$76,390
1982	$661,019	222,041	$16,766	4703520	$11,390	1028255	$24,426	$641,969	-$27,686
1983	$761,240	250,925	$18,947	4739397	$11,477	1060526	$25,193	$743,518	$101,549
1984	$759,773	157,077	$11,861	4838600	$11,717	1057820	$25,128	$734,789	-$8,729
1985	$771,614	306,292	$23,128	4480889	$10,851	1034373	$24,571	$759,320	$24,531
1986	$737,433	258,278	$19,503	4114138	$9,963	976931	$23,207	$723,766	-$35,554
1987	$719,223	63,079	$4,763	3443462	$8,339	1023873	$24,322	$691,326	-$32,440
1988	$702,787	-300,027	-$22,655	3402277	$8,239	1062133	$25,231	$646,662	-$44,664
1989	$754,919	-278,902	-$21,060	3457701	$8,373	1087591	$25,836	$699,650	$52,988
1990	$793,954	-39,154	-$2,957	3254087	$7,880	1117838	$26,554	$756,563	$56,913
1991	$786,673	42,696	$3,224	3216740	$7,790	1062657	$25,243	$756,864	$301
1992	$794,303	50,215	$3,792	3082521	$7,465	1067248	$25,352	$765,278	$8,414
1993	$894,289	256,157	$19,342	3047803	$7,381	1080506	$25,667	$880,583	$115,305
1994	$953,794	-28,618	-$2,161	2965568	$7,182	1079803	$25,651	$918,801	$38,218
1995	$969,925	445,193	$33,616	2984107	$7,226	1066590	$25,337	$970,978	$52,177
1996	$1,001,422	-435,869	-$32,912	3239852	$7,846	1109930	$26,366	$934,298	-$36,680
1997	$1,057,552	210,103	$15,865	3228373	$7,818	1153430	$27,400	$1,038,199	$103,902
1998	$1,061,384	-110,554	-$8,348	3498540	$8,472	1157612	$27,499	$1,017,065	-$21,134
1999	$1,135,535	252,837	$19,092	3236475	$7,838	1173798	$27,884	$1,118,905	$101,840
2000	$1,106,954	-504,537	-$38,098	3091684	$7,487	1227015	$29,148	$1,032,222	-$86,683
2001	$1,086,389	24,917	$1,881	2869825	$6,950	1242678	$29,520	$1,051,801	$19,579
2002	$1,168,512	-860,888	-$65,006	2907283	$7,040	1194397	$28,373	$1,068,093	$16,292
2003	$1,186,687	-302,288	-$22,826	3037519	$7,356	1199228	$28,488	$1,128,018	$59,925
2004	$1,176,482	-21,781	-$1,645	3051094	$7,389	1230885	$29,240	$1,138,209	$10,191
2005	$1,190,061	125,141	$9,449	3028607	$7,334	1228372	$29,180	$1,162,997	$24,787

*In thousands of 2005 dollars

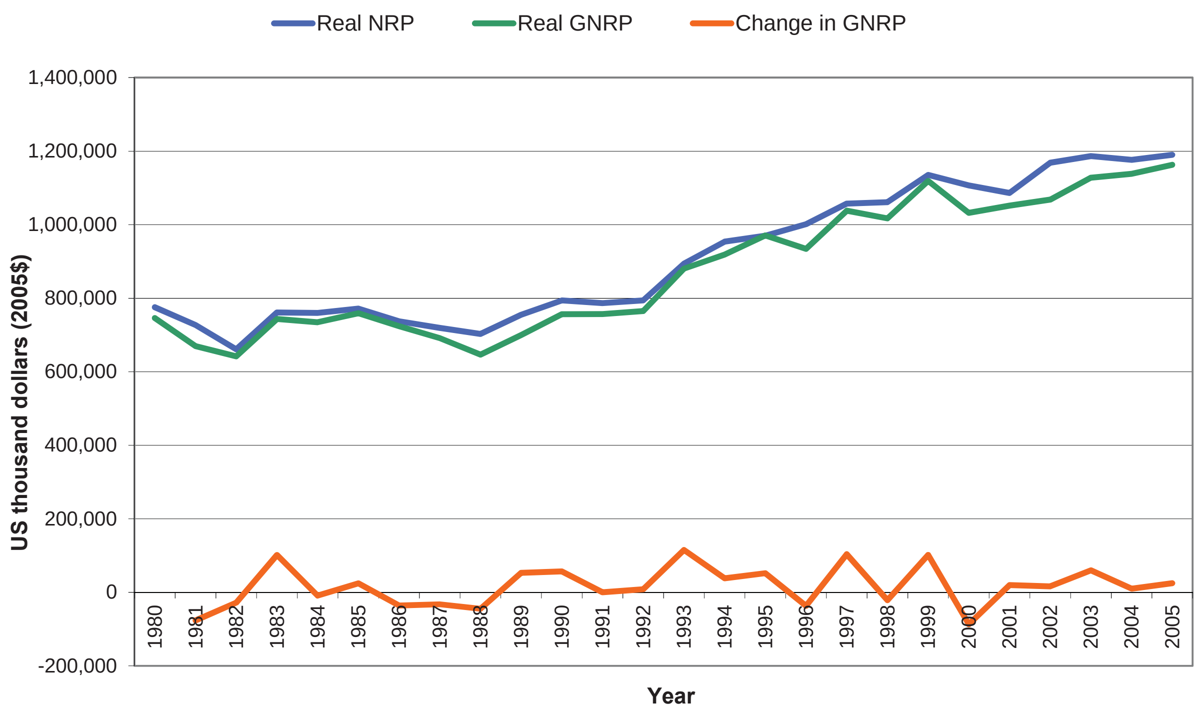

Figure 4.1 – Net Regional Product, Green Net Regional Product, and the change in Green Net Regional Product.

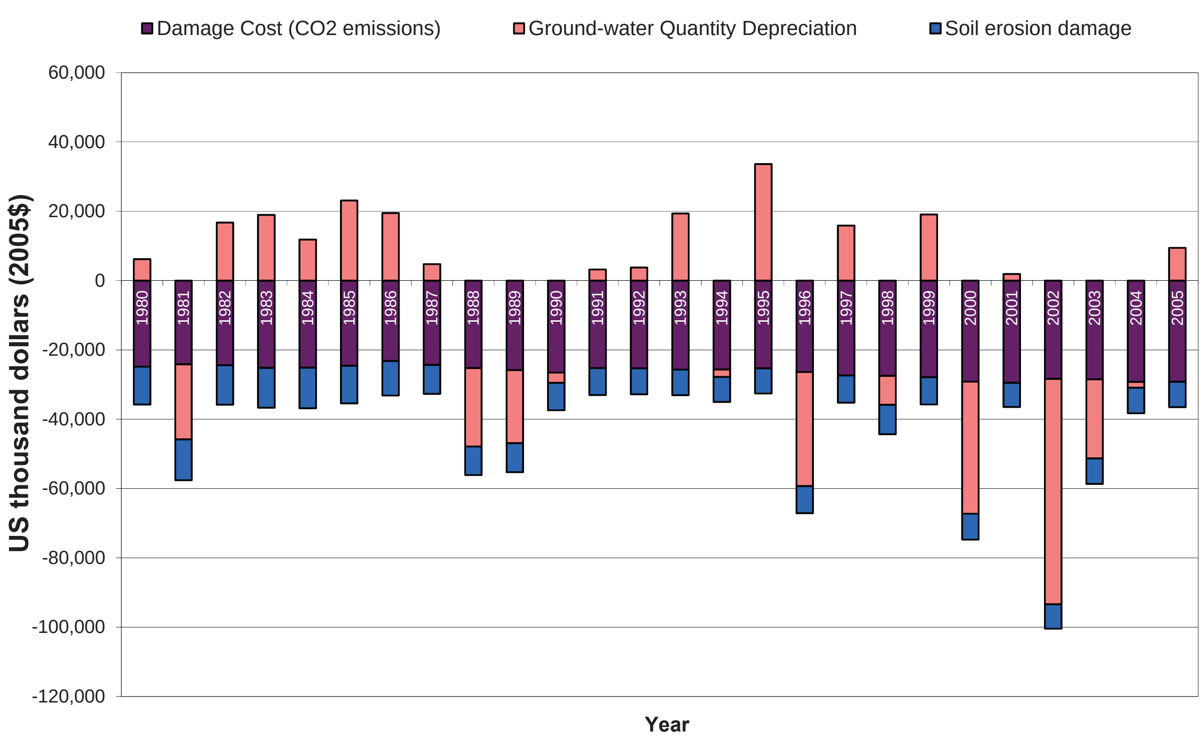

Figure 4.2 – Components of the Depreciation of Natural Capital.

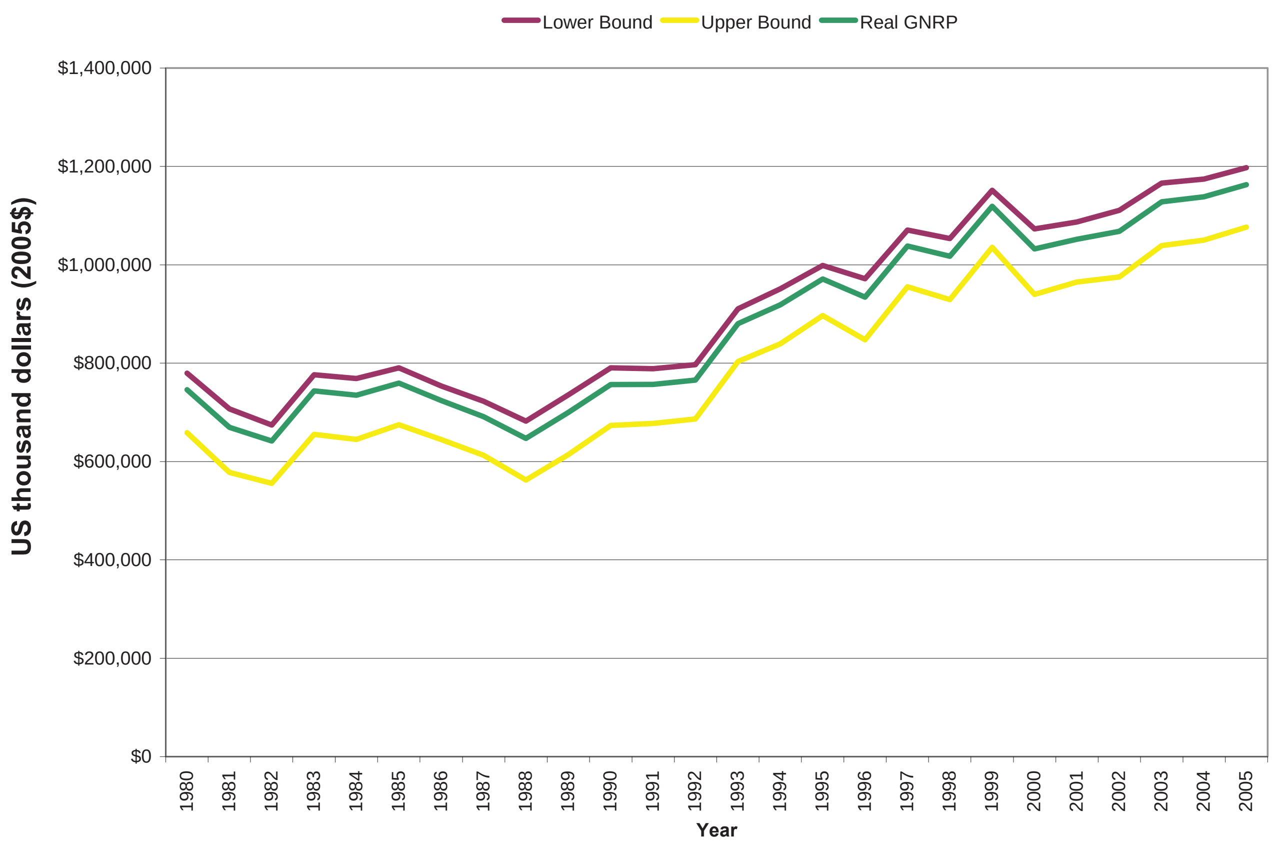

Figure 4.3 – Sensitivity Analysis Using Upper and Lower Bounds on the Prices for Natural Capital Depreciation.

Appendix 4-A: Wind Erosion Calculations

Green Net Regional Product, Emergy Analysis, and Fisher information all included wind erosion in the calculations. This appendix describes details of the approach for estimating wind erosion in the San Luis Basin (SLB). Agriculture was not a major activity in all SLB counties, so we only focused on Alamosa, Conejos, Costilla, Rio Grande, and Saguache counties. The estimates were based primarily on the following data: 1) National Agricultural Statistics Service (Colorado profile and Census of Agriculture); 2) farming practices and trends in the SLB based on the knowledge, experience, and expert opinion of Richard Sparks, an agronomist and irrigation specialist in the US Department of Agriculture (USDA), Natural Resource Conservation Service (NRCS), Center, CO; and 3) Wind Erosion Equation (Woodruff and Siddoway 1965). Each plays an important role in the general approach described below. This work had never been attempted for the SLB over the 26-year study period. Figure 4-A.1 identifies the basic steps we used in the process.

The general approach for collecting initial data and estimating wind erosion was as follows:

1. We first needed the individual county acreages of spring barley, spring wheat, winter wheat, potatoes, alfalfa, oats, and other hay (only for Conejos, Costilla, and Saguache counties). The National Agricultural Statistics Service (NASS) provides annual estimates of planted acres of different crops by county and data on total crop land and total harvested land beginning in 1982 and continuing every five years until 2002 through the Census of Agriculture (NASS 1984, 1989, 1994, 2009a, 2009b).
2. The soil erodibility index was estimated for county acreage for two major soil types (soil erodibility index I=134 tons per acre per year and I=86 tons per acre per year) based on expert opinion and Web Soil Survey (Soil Survey Staff 2009). Index I represents potential for soil loss measured in tons per acre per year. It assumes the field is isolated, level, smooth, unsheltered, bare, wide, and loose (NRCS 2002). Table 4-A.1 presents the approximate distribution of crops between the two soil types.
3. We estimated the acres of different crop rotations by the two soil types (based on the soil erodibility index) for each county. Seven crop rotations for the counties were included in the calculation (Table 4-A.2). A crop rotation is a series of different crops in the same field in succeeding seasons. It could occur over a couple of years to a much longer period. There are many benefits of rotating crops including preventing diseases, reducing soil erosion, controlling pests, and improving the soil fertility (NRCS 2002).

Some rotations were included to factor in the drought and aquifer decline years (2001 - 2007). For example, cropland acreages were idled or planted to Sorghum /Sudan cover crops instead of spring grain. Other trends were included such as introducing Winter Rye cover crops between years of back-to-back potatoes from 1980 through 2000 and introducing Winter Wheat into the Potato - Grain rotations around the late 1990s depending on the county.

Total acres of irrigated cropland were based on Agricultural Statistics for Colorado and NASS. Because NASS reports census data every five years, the estimates for the other years were based on trends and expert opinion (total acres of planted crops gleaned from the agricultural statistics for the counties provided the initial minimum total acres of irrigated cropland). Total irrigated cropland acres minus the total crops planted (based on Agricultural Statistics for Colorado) equaled unreported crops (e.g., canola, sorghum, and vegetables) and unplanted acres. We assumed that vegetables and unplanted acres had similar wind erosion rates (therefore, we combined them into one rotation). Because of some large numbers of unaccounted acres, we included Colorado estimates for Other Hay in Conejos, Costilla, and Saguache counties.

The first step was to estimate continuous potatoes. Alamosa and Rio Grande counties planted about 20% of their total potatoes as continuous in the 1980's and grew to about 40% in the 1990's. The number of acres of continuous potatoes decreased around 2000 to about 20%, which corresponded to the decline of the aquifer and an increase in potato pathogens. Once we estimated continuous potatoes, we combined the remaining potatoes with small grains. The Potato-Small Grain rotation was a two-year rotation. We estimated the Alfalfa – Small Grain rotation next and the remaining small grains were assumed to be planted as continuous grains. We assumed the Alfalfa – Small Grain rotation was a 7-year rotation. For each county and every year, we compared total irrigated cropland acres based on Agricultural Statistics for Colorado and NASS to our estimate of total irrigated cropland acres based on crop rotation acres to make sure the data and the approach were consistent. We accounted for every acre of crops reported in the Agricultural Statistics for Colorado. Once this set approach was completed, each year was examined for accuracy and the time series was examined for trends. Minor revisions were made depending on the year and crop rotation based on known trends. For example, certain years had very high estimates of continuous small grains and the values were not realistic with known quantities; therefore, we adjusted that year to have more Potato - Small Grain acres in order to reduce continuous small grains. This required reducing the percent of continuous potato acres as well.

4. After all of the calculations for the individual counties were reviewed and determined to be accurate, a total estimate of crop acreage for each rotation in the SLB was then calculated. Table 4-A.3 displays total crop acreage for the SLB for 1980-2005. Rows 2-7 are based on the Agricultural Statistics for Colorado.

5. We accounted for the general trend of improving residue management and changes in tillage practices with the different crop rotations. The two practices were moldboard plow and noninversion tillage and we divided the rotation acreage between the two practices based on the trends for residue management. Using expert opinion, we assumed that 10% of continuous small grain acres were noninversion tillage in 1980 for soil type I=134. That percent grew to a high of 80% in 1997 and continued through 2005.

6. We used the Wind Erosion Equation (WEQ) to estimate average annual wind erosion for each of the different crop rotations and different tillage practices on the two soil types. WEQ is based on Woodruff and Siddoway (1965) where Erosion (tons/acre/year) is a function of soil erodibility index, soil ridge roughness factor, climatic factor, field length along the prevailing wind erosion direction, and equivalent quantity of vegetative cover. WEQ is used by the NRCS to estimate average wind erosion. The Wind Erosion Research Unit (WERU) of the NRCS has developed the "Excel Spreadsheet and Guidance Document" on which the wind erosion estimates are based (NRCS 2003). Table 4-A.4 presents the average annual wind erosion (tons/acre) for noninversion tillage and Table 4-A.5 presents the average annual wind erosion for conventional, moldboard plow. Continuous potatoes show no difference in average annual wind erosion, but other crop rotations reveal significant changes in the amount of erosion with the noninversion tillage.

7. Combining crop rotation acres and soil types with the WEQ average annual wind erosion, we estimated total erosion for the SLB in tons/year (Table 4-A.6). We divided this estimate by total acres of irrigated cropland to estimate tons/acre/year, which allows the NRCS to examine the trends of erosion management. From 1980 to 2005, there was a general trend of tons/acre/year decreasing, revealing an improvement in practices to reduce wind erosion (Table 4-A.6).

8. The final step was to have experts from the region review the results for wind erosion to assess if the results seem reasonable.

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Table 4-A.1 – Approximate distribution of crops between the two soil types (Based on Soil Erodibility Index, I).

County	I=134	I=86
Alamosa	50%	50%
Conejos	0%	100%
Costilla	80%	20%
Rio Grande	10%	90%
Saguache	30%	70%

Table 4-A.2 – Crop rotations included in soil erosion calculation.

Crop Rotation	Description
Continuous Potatoes, Vegetables, and Unplanted Acres	Potatoes planted every season, vegetables and unplanted acres assumed to have the same erosion rate as continuous potatoes
Potatoes-Winter Wheat	2-year rotation: one year potatoes, one year winter wheat
Potatoes-Winter Rye	1-year rotation with rye planted after potato harvest
Potatoes-Small Grain	2-year rotation: one year potatoes, one year small grain (e.g., barley, spring wheat)
Potatoes-Canola and/or Sorghum Cover	2-year rotation: one year potato, one year sorghum sudan
Alfalfa-Small Grain	7-year rotation: six years alfalfa, one year small grain (e.g., barley, spring wheat)
Continuous Small Grain	Small grain planted every season

Table 4-A.3 – Total acreage by crop rotation and Soil Erodibility Index.

Variable name	**1980**	**1981**	**1982**	**1983**	**1984**	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**
Potatoes All (Planted)	37000	40500	45500	47000	53500	56500	57000	61000	60000	62000	65500	71000
Wheat Other Spring (Planted)	36000	43000	38000	50000	49000	50500	40000	38000	41000	55000	29000	24900
Barley All (Planted)	107000	118000	114000	100000	117000	115000	120000	77000	65000	79000	84000	89500
Hay Alfalfa (Dry) (Harvested)	122900	99800	92800	89700	108600	129600	110000	118000	115000	105000	105000	105000
Wheat Winter All (Planted)	0	0	0	0	0	0	0	0	0	0	0	0
Oats	16000	17000	24000	39000	32000	26000	15000	14000	24000	15500	16700	11800
Unreported crops (Sorghum, carrots/lettuce/canola) + unplanted acres	56550	57150	61150	53537	39755	28055	47908	62208	70574	65910	82210	80999
Vegetables & unplanted acres (100% to 30% of unreported crops)	11842	13468	15468	14555	6700	800	4834	8123	10923	7450	11413	11688
Canola and sorghum cover (0% to 70% of unreported crops)	0	0	0	0	0	0	0	0	0	0	0	0
Other Hay (Wild dry hay, other haylage, etc.)	44708	43682	45682	38982	33055	27255	43074	54085	59651	58460	70797	69311
Total irrigated cropland acres	375450	375450	375450	379237	399855	405655	389908	370208	375574	382410	382410	383199
134: Potatoes	8090	9310	11530	11100	14100	14680	17440	18040	17660	17930	19685	20870
86: Potatoes	28910	31190	33970	35900	39400	41820	39560	42960	42340	44070	45815	50130
134: Continuous Potatoes + Vegetables and unplanted acres	5492	7796	5612	4946	4720	3298	5760	5246	6775	7563	7051	7411
86: Continuous Potatoes + Vegetables and unplanted acres	12630	15682	20646	20710	13880	9862	12314	16837	18168	14157	18329	16764
134: Potatoes-Winter Wheat	0	0	0	0	0	0	0	0	0	0	0	0
86: Potatoes-Winter Wheat	0	0	0	0	0	0	0	0	0	0	0	0
134: Potatoes-Winter Rye (only potato acreage)	0	0	0	0	0	0	0	0	0	0	669	3482
86: Potatoes-Winter Rye (only potato acreage)	0	0	0	0	0	0	0	0	0	0	669	3645
134: Potatoes-Small Grain (1:1 acreage)	13604	14318	18326	17520	22860	23864	26948	28220	27292	27826	30409	30771
86: Potatoes-Small Grain (1:1 acreage)	47836	46662	51094	54280	60340	64416	60572	65860	64668	67634	69981	71999
134: Potatoes-Canola and/or sorghum cover (1:1 acreage)	0	0	0	0	0	0	0	0	0	0	0	0
86: Potatoes-Canola and/or sorghum cover (1:1 acreage)	0	0	0	0	0	0	0	0	0	0	0	0
134: Alfalfa-small grain (7 year rotation)	24547	19460	18468	18597	21187	25737	21467	23217	22108	19833	19833	19717
86: Alfalfa-small grain (7 year rotation)	118837	96973	89798	86053	105513	125463	106867	114450	112058	102667	102667	102783
Remaining Small Grain	107797	130877	125823	138150	138300	125760	112907	62293	64853	84270	62005	57315
134: Continuous Small Grain	26735	31158	31795	34287	34990	32605	27876	14003	15342	18967	13722	12861
86: Continuous Small Grain	81062	99719	94028	103863	103310	93155	85031	48290	49511	65303	48283	44454

Variable name	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Potatoes All (Planted)	66500	72500	74000	77000	78000	77000	75800	77200	75800	68100	71600	66300	64083	58883
Wheat Other Spring (Planted)	32000	23500	30500	24000	43300	34500	25000	34000	32200	25000	14500	11000	15067	15067
Barley All (Planted)	77500	66000	58000	71000	61000	63500	60000	65000	77000	59000	49000	53000	52000	38000
Hay Alfalfa (Dry) (Harvested)	115000	129000	135000	140000	130000	130000	135000	160000	165000	167000	135000	130000	132833	147000
Wheat Winter All (Planted)	0	0	0	0	1500	5000	3000	3000	5000	5000	4000	4000	4150	4150
Oats	13200	17900	18000	24000	21000	21000	15000	17000	30000	18000	17000	20617	20617	20617
Unreported crops (Sorghum, carrots/lettuce/ canola) + unplanted acres	87166	78529	73929	64168	71101	101506	113768	80088	51688	75495	80293	99406	95573	100606
Vegetables & unplanted acres (100% to 30% of unreported crops)	13569	18186	13648	6105	11019	15191	31873	12918	1920	8282	13888	22924	22747	27462
Canola and sorghum cover (0% to 70% of unreported crops)	0	0	0	540	4824	6312	9276	7083	2343	6317	13735	12819	13387	16370
Other Hay (Wild dry hay, other haylage, etc.)	73597	60343	60281	57523	55258	80003	72619	60087	47425	60897	52670	63664	59439	56774
Total irrigated cropland acres	391366	387429	389429	400168	405901	432506	427568	436288	436688	417595	371393	384323	384323	384323
134: Potatoes	19680	22510	22860	23490	25140	24660	24740	24720	24010	21630	23110	20980	20310	18190
86: Potatoes	46820	49990	51140	53510	52860	52340	51060	52480	51790	46470	48490	45320	43773	40693
134: Continuous Potatoes + Vegetables and unplanted acres	5746	6280	4736	3202	4512	4749	10556	4981	1637	2840	4332	8060	8880	10216
86: Continuous Potatoes + Vegetables and unplanted acres	18084	16682	13616	7694	11289	15105	25863	12517	3807	8576	12359	17457	16368	19376
134: Potatoes-Winter Wheat	0	0	0	0	300	3760	2320	2300	4600	4040	3400	3120	3220	3220
86: Potatoes-Winter Wheat	0	0	0	0	2700	6240	3680	3700	5400	5960	4600	4880	5080	5080
134: Potatoes-Winter Rye (only potato acreage)	4019	6147	5905	5820	6287	6074	6089	5879	4505	4101	3391	3045	3215	2813
86: Potatoes-Winter Rye (only potato acreage)	5750	12656	12486	13083	12727	12245	11921	12093	9255	8369	7686	7126	7102	6512
134: Potatoes-Small Grain (1:1 acreage)	27680	29740	31018	32387	31251	26996	26094	27608	30715	24948	23481	21911	18945	13142
86: Potatoes-Small Grain (1:1 acreage)	65258	68104	70796	73147	64509	58415	55842	61525	71633	57409	56491	51522	48515	40675
134: Potatoes-Canola and/or sorghum cover (1:1 acreage)	0	0	0	156	3170	3483	5995	4960	1562	4189	11025	9452	10698	13397
86: Potatoes-Canola and/or sorghum cover (1:1 acreage)	0	0	0	924	6478	9141	12557	9205	3123	8444	16445	16186	16075	19342
134: Alfalfa-small grain (7 year rotation)	21058	23275	24267	26133	22750	23158	24150	30683	31033	31442	25608	21642	21039	22750
86: Alfalfa-small grain (7 year rotation)	113108	127225	133233	137200	128917	128508	133350	155983	161467	163392	131892	130025	133933	148750
Remaining Small Grain	57064	36978	33093	42900	55753	54627	36532	44767	60526	32988	18014	26233	31815	22275
134: Continuous Small Grain	12206	6193	6371	8476	10126	9271	4619	5675	8855	5435	2164	4906	6802	5693
86: Continuous Small Grain	44858	30785	26722	34423	45628	45357	31913	39092	51671	27553	15850	21327	25013	16582

Table 4-A.4 – Average annual wind erosion by crop rotation: practicing mulch or noninversion tillage.

Soil type: Crop rotation	Average Annual Wind Erosion (t/ac)
134: Continuous Potatoes + Vegetables and unplanted acres	39.8
86: Continuous Potatoes + Vegetables and unplanted acres	16.1
134: Potatoes-Winter Wheat	7.6
86: Potatoes-Winter Wheat	2.4
134: Potatoes-Winter Rye (only potato acreage)	10.7
86: Potatoes-Winter Rye (only potato acreage)	3.4
134: Potatoes-Small Grain	19.5
86: Potatoes-Small Grain	7.4
134: Potatoes-Canola and/or sorghum cover (1:1 acreage)	20.9
86: Potatoes-Canola and/or sorghum cover (1:1 acreage)	8.5
134: Alfalfa-small grain (7 year rotation)	5.7
86: Alfalfa-small grain (7 year rotation)	2.2
134: Continuous Small Grain	9.8
86: Continuous Small Grain	2.9

Table 4-A.5 – Average annual wind erosion by crop rotation: conventional, moldboard plow.

Soil type: Crop rotation	Average Annual Wind Erosion (t/ac)
134: Continuous Potatoes + Vegetables and unplanted acres	39.8
86: Continuous Potatoes + Vegetables and unplanted acres	16.1
134: Potatoes-Winter Wheat	24.9
86: Potatoes-Winter Wheat	10.1
134: Potatoes-Winter Rye (only potato acreage)	15.5
86: Potatoes-Winter Rye (only potato acreage)	5.2
134: Potatoes-Small Grain	33.2
86: Potatoes-Small Grain	13.3
134: Potatoes-Canola and/or sorghum cover (1:1 acreage)	44.2
86: Potatoes-Canola and/or sorghum cover (1:1 acreage)	18.9
134: Alfalfa-small grain (7 year rotation)	12.5
86: Alfalfa-small grain (7 year rotation)	5.4
134: Continuous Small Grain	35.6
86: Continuous Small Grain	14.6

Table 4-A.6 – Total Erosion (tons/year) for the SLB and Tons per Acre per Year.

Variable name	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
134: Continuous Potatoes + Vegetables and unplanted acres	218471	310112	223236	196724	187754	131189	229104	208670	269491	300858	280494	294794
86: Continuous Potatoes + Vegetables and unplanted acres	203640	252854	332892	333916	223798	159013	198550	271475	292941	228262	295533	270302
134: Potatoes-Winter Wheat	0	0	0	0	0	0	0	0	0	0	0	0
86: Potatoes-Winter Wheat	0	0	0	0	0	0	0	0	0	0	0	0
134: Potatoes-Winter Rye (only potato acreage)	0	0	0	0	0	0	0	0	0	0	7969	41480
86: Potatoes-Winter Rye (only potato acreage)	0	0	0	0	0	0	0	0	0	0	3193	17400
134: Potatoes-Small Grain (1:1 acreage)	442140	435858	520125	485222	617422	628156	672335	665325	624711	598729	654307	640972
86: Potatoes-Small Grain (1:1 acreage)	637745	622093	666132	691682	751132	782899	718340	761654	728822	742330	726867	747827
134: Potatoes-Canola and/or sorghum cover (1:1 acreage)	0	0	0	0	0	0	0	0	0	0	0	0
86: Potatoes-Canola and/or sorghum cover (1:1 acreage)	0	0	0	0	0	0	0	0	0	0	0	0
134: Alfalfa-small grain (7 year rotation)	297658	229443	205352	200536	221352	251610	195453	203592	193873	173923	167265	166281
86: Alfalfa-small grain (7 year rotation)	639097	521517	468873	435848	534410	615813	524535	543840	532475	471776	455704	440132
134: Continuous Small Grain	883472	1029634	968494	1000054	975332	824536	632875	281713	268980	332527	240576	208853
86: Continuous Small Grain	1184147	1456687	1318415	1395415	1327400	1087672	942946	507194	490984	609294	422178	388698
Total Erosion (tons/year)	4506372	4858200	4703520	4739397	4838600	4480889	4114138	3443462	3402277	3457701	3254087	3216740
Tons/Acre/Year	12.00	12.94	12.53	12.50	12.10	11.05	10.55	9.30	9.06	9.04	8.51	8.39

Variable name	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
134: Continuous Potatoes + Vegetables and unplanted acres	228583	249800	188374	127358	179485	188911	419905	198149	65099	112982	172315	320596	353231	406374
86: Continuous Potatoes + Vegetables and unplanted acres	291580	268972	219536	124050	182021	243547	417007	201815	61389	138273	199268	281477	263911	312412
134: Potatoes-Winter Wheat	0	0	0	0	3320	41613	25676	23465	46929	41216	31745	29131	30065	30065
86: Potatoes-Winter Wheat	0	0	0	0	16808	38846	22909	21614	29474	30245	21579	22893	21882	19934
134: Potatoes-Winter Rye (only potato acreage)	47876	73225	70334	69321	74894	72353	72526	70025	53658	48852	39590	35550	37535	32845
86: Potatoes-Winter Rye (only potato acreage)	26917	58076	56144	57625	54883	52806	51410	51035	39058	35321	31727	29418	29316	26884
134: Potatoes-Small Grain (1:1 acreage)	576581	619505	646113	674643	650968	562347	525628	556126	618725	502549	472996	441383	381617	264728
86: Potatoes-Small Grain (1:1 acreage)	658593	687309	693632	716660	613033	537920	497778	548432	638538	511741	503559	459270	432459	362580
134: Potatoes-Canola and/or sorghum cover (1:1 acreage)	0	0	0	5072	103054	113238	194903	161255	48967	126431	319921	263253	285510	341945
86: Potatoes-Canola and/or sorghum cover (1:1 acreage)	0	0	0	14561	102089	144052	197885	145068	49222	133074	250631	238298	228330	264704
134: Alfalfa-small grain (7 year rotation)	177596	196291	204654	211624	184226	187533	195563	238168	240885	244055	190179	160721	156244	168952
86: Alfalfa-small grain (7 year rotation)	484345	524878	549666	544552	511675	510055	529272	594686	615591	622930	502836	495720	510620	567109
134: Continuous Small Grain	198214	100567	103465	137649	164431	138560	69031	84821	132341	81233	32345	73332	101664	85087
86: Continuous Small Grain	392235	269180	233650	300992	398963	396594	279047	341815	451807	240923	138591	186477	218709	144989
Total Erosion (tons/year)	3082521	3047803	2965568	2984107	3239852	3228373	3498540	3236475	3091684	2869825	2907283	3037519	3051094	3028607
Tons/Acre/Year	7.88	7.87	7.62	7.46	7.98	7.46	8.18	7.42	7.08	6.87	7.83	7.90	7.94	7.88

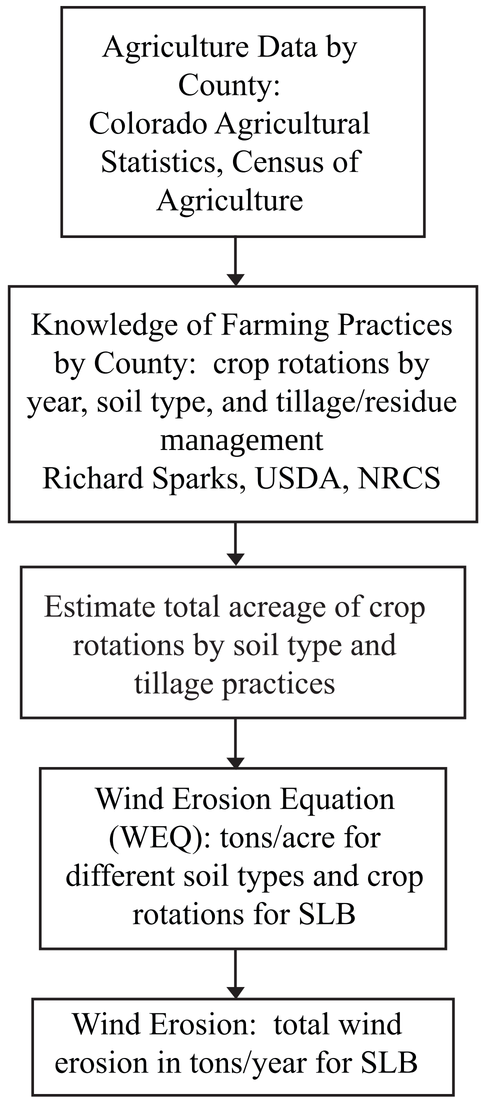

Figure 4-A.1 – General approach to estimating wind erosion in the San Luis Basin.

5.0 Emergy

5.1 Introduction

The effects of changes in system states on sustainability can be quantified using environmental accounting methods based on the transformations of available energy (Odum 1996). Environmental accounting using emergy and Emergy Analysis (EmA) provide an alternative to economic methods, which decision makers can use to assess the effects of their policies on their system.

When the available energy transformed from one form to another is traced through a network of interactions, the amount of energy required to create any item (e.g., an energy flow or storage) in the system can be determined. Tracing the energy flows required to support each network storage or flow and converting those flows to energy of a common unit (e.g., solar joules), enables the determination of the value of any item in the network (Campbell 2001) in terms of the resources required for that item to exist within the system. This value can then be expressed as the solar emjoules (sej) required for its production.

EmA is a method for assessing the available energy required for the production of a product or service in a system in units of equivalent quality (i.e., solar equivalent joules; Brown 2003, Campbell 2001; see Odum 1996 for a detailed description). The emergy evaluation of systems with its emphasis on the role of renewable and nonrenewable resources used in system support and its characterization of import and export exchange is a useful framework for the analysis of sustainable system operations (see Campbell et al. (2005) and Odum (1996) for detailed methods for conducting EmA).

Any quantity of energy can be converted into emergy by multiplying the original units (J or g) by an emergy per unit factor, the transformity (sej/J) or the specific emergy (sej/g), to obtain the emergy equivalent of the quantity in solar emjoules (sej). Other quantities (e.g., information or money) are converted into emergy using the appropriate emergy per unit factors. The emergy of environmental, economic, and social products and services is then directly comparable so the relative advantages and disadvantages of any changes can be readily determined by direct inspection of the values. Relative advantage is judged by movement toward greater emergy flow (empower) through a system network, because maximizing empower in a system network is the decision variable used to predict the outcome of evolutionary competition between alternative systems designs (Lotka 1922a, 1922b, Odum 1996).

Movement toward sustainability, from an energy systems perspective, is measured by the degree to which a system depends upon renewable resources for its operation. As a system decreases its use of non-renewable emergy and increases the fraction of renewable emergy in its total emergy use, the system moves toward a more sustainable state. The concept of sustainability requires that we specify what system state is to be sustained and over what time we expect to sustain it (Campbell 1998). The system structure and function maintained through greater use of renewable emergy must be equivalent to that supported by nonrenewable emergy on a per capita basis, for there to be no net degradation in the quality of life. Increasing empower, or the amount of emergy moving through the system may lead toward greater health and vitality; whereas, decreasing emergy flow may lead toward a less robust system with lower levels of overall function. Therefore, the evolution of networks toward higher empower designs is the overriding process governing the success of any condition or state of a system. This process may occur at the expense of other systems, depending on the emergy sources available to support its organization (Campbell et al. 1998). Ultimately, what is sustainable for a system and for how long depends on the available energy in the suite of external forcing functions. Often the operation of the maximum power principle appears to lead to pulsing designs, in which resources accumulate slowly over time and are then consumed rapidly once a threshold is exceeded (Odum 1996, Campbell 2001). Often under such scenarios, the only pattern that is truly sustainable is the pulsing cycle of change (Odum et al. 1995).

EmA provides managers with a comprehensive suite of indices to assess the ecological and economic well-being of their system (Odum 1996). It gives managers a comprehensive decision variable (emergy flow in the system network) against which they can judge the efficacy of their policies. From this comprehensive suite of indices and body of theory, we have abstracted a few indices (see below) that apply to system sustainability and used them to characterize conditions in the SLB.

EmA has been applied broadly to analyze nations (Brown 2003, Lefroy and Rydberg 2003, Ulgiati et al. 1994), states (Campbell 1998, Campbell et al.

2005, Campbell and Ohrt 2009, Tilley 1999) and counties (Lambert 1999), but the application of the method to regions has been less common (Tiezzi and Bastianoni 2008). The *San Luis Basin Sustainability Metrics Project* is a regional study that presented us with a unique set of challenges in data gathering and interpretation. The standard EmA method calculates a number of indices showing various aspects of system functions and the relationship of the system to its next larger system. However, because our focus was on regional sustainability, we thought it would be more straightforward, if we focused initially on a single index of emergy that relates strongly to sustainability. We identified the fraction of renewable emergy to total emergy used as the best index to assess, the condition of the regional system and to determine if the region was moving toward or away from sustainability. We report all the indices used in a standard EmA in this Chapter as well, and discuss aspects of system structure, function, and sustainability that are revealed by our analysis of these measures. Among these additional indices, we focused on the total emergy use as a measure of overall well-being of the region and the Emergy Sustainability Index, ESI, as a measure of the sustainability of the relationship between the SLB and its next larger system (i.e., the State of Colorado and the Nation). Before calculating the indices, we had to address several challenges, including setting the regional boundaries and assembling time-series data relevant to the region. In this study, we focused on developing emergy indices of sustainability over a period of 26 years from 1980 to 2005. However, data availability limited the complete emergy evaluation to the eleven-year period of 1995 to 2005.

5.2. Methods

The methods used in the emergy portion of this study needed to address two challenges. The first was a technical question of how to set boundaries for a regional study where more than one criterion could be logically used. The second challenge was to find and assemble relevant data on the region for a 26-year period. Both of these challenges have been seldom addressed in emergy analyses, where the considerable data requirements of the method often limit the analysis to systems with well-established boundaries (e.g., a nation, state, or county examined for one or two years). Detailed methods used to carry out an EmA are available in Campbell et al. (2005) and Campbell and Ohrt (2009). We will outline the methods in the following sections by discussing the aspects of the SLB regional study that were unique to this analysis. The seven steps for this emergy evaluation are described in Appendix 5-A.

5.2.1 Boundaries

The system boundaries of a region could be based with strong justification on two different sets of criteria (i.e., hydrologic or the political boundaries of counties). Both sets of boundaries were used for the study. Political boundaries were used to quantify all human activities (e.g., energy use, economic activity, etc.) and most natural inputs and storages (e.g., solar radiation and forest biomass). The hydrologic system boundary was used to determine the water flows that support human activities in the Upper Rio Grande River Basin of the San Luis Basin (SLB; see Chapter 1 for a description of the SLB). Ultimately, we chose a mixture of both because they better represent the actual flow of emergy through the system and they are similar in size and areal coverage.

5.2.2. Energy Systems Models

Information about a region is used to draw a detailed energy systems diagram using the Energy Systems Language (ESL) to represent the system under study (for a detailed description of this process, see Campbell et al. 2005). The resulting diagram should capture the essence of the system and its operation. The detailed model is simplified by aggregating components of similar function, characterizing the inputs and outputs and reducing the complexity of internal components and flows to basic measures of economic activity, resource supply, and total emergy flow. Energy Systems Models aggregated in this manner provide indices of system operation related to sustainability and self-sufficiency, as well as other system properties.

We reexamined the indices used to evaluate two aspects of the relationship between a system and the associated larger system. First, the emergy yield ratio (EYR) for a local system, often characterized for a nation, state, or region as U/F (where U is total emergy flow in the system and F is feedback from the next larger system), is redefined as Y/F, where Y or yield is equivalent to exports. This definition more closely matches the original definition of EYR formulated for production processes (Odum 1996). Second, the ratio formed by the total emergy flow in the system (U) and the feedback (F) from the larger system is defined as the local effect of emergy investment because it shows the effect of feedback from the larger system on the local system's empower (see Appendix 5-B).

5.2.3 Emergy Analysis

EmA tables provide a template for the creation of the accounts needed to construct an emergy income statement and balance sheet. The tables provide a simple way to demonstrate and record the calculation of the emergy values for annual flows of mass, energy, and information. In the emergy tables, data on the mass of flows are converted to energy and then to emergy to aid in comparisons and to provide information for the analysis of public policies (Table 5.1). Note that for many items, transformities are available in the literature or they can be calculated (Campbell et al. 2005, Odum 1996; see Appendix 5-C for values used in this study and the other appendices 5-D through 5-G for other results and discussion, e.g., Table 5-G.1 provides sources used to obtain data for the EmA of the SLB system). Figure 5.1 shows a detailed Energy Systems Language diagram of the SLB region and Table 5.2 lists the energy, material, and information flows, which are linked to the diagram through the k coefficient values shown in the table and the diagram.

The energy content of many items has been widely tabulated, but a similar compendium of transformities and other emergy per unit factors does not exist at present. If the production process is unknown or not easily documented, transformities may be determined using one of the ten methods given in Odum (1996) and Campbell and Ohrt (2009). The emergy per unit factors used in this study are given in Appendix 5-C.

We estimated the transformity for each commodity class to determine the emergy per ton of each commodity imported. These transformities were approximated by averaging known transformities of items within the class (without services); however, not all items in a class were included in the determination of the transformity. In some cases, when a transformity was not known for any item in the class, the parent material was used as a surrogate for the item's transformity. The use of parent materials resulted in a minimum estimate of the emergy imported and exported in these commodity classes. The information needed for EmA is most often reported as annual flows of energy and/or mass. Usually mass can be easily converted to energy as the energy content of many objects has been widely tabulated (e.g., USDA 2009). The transformity (sej/J) and specific emergy (sej/g) have been calculated for many items and can be used to convert energy and mass flows to emergy (Appendix 5-C). In this study, emergy accounts for renewable and nonrenewable local inflows, renewable production, imports, and exports were calculated for the seven counties comprising the SLB.

Initially, we assumed all imports were used in the system. However, we discovered a situation in the SLB where Antonito, Colorado (Conejos County) is a railhead and trans-shipment point for heavy materials, such as unexpanded perlite and volcanic scoria (San Luis Valley Development Resources Group 2007). To account for the movement of these materials through the system, we removed processed nonmetallic minerals from the import-export balance, to avoid falsely attributing the emergy of these materials to use by the SLB system. In addition, the actual amount of local nonrenewable resources (e.g., crushed stone, sand and gravel) used in the SLB was unknown. Export vastly exceeded import of these materials, so we assumed the difference was "apparent production" and assumed that 10% of the "apparent production" was used in the system.

5.2.4. Data and Sources

Data on the human system, and much of the "natural" system, of the SLB were collected based on political boundaries, whereas, hydrologic data were collected using the basin boundary (Fig. 1.1). Water resource data conformed to the boundaries of our system. Data on economic and social activities were collected at the county level (Table 5-G.1). When only the state or national level data were available, we used average per capita data from the state or national level to estimate variables (Table 5-G.1). All data were yearly averages.

Data needed to construct an emergy income statement of a region can be categorized as follows: (1) renewable energy inputs to the system and information on renewable production carried out in the system; (2) nonrenewable energy inputs, production and consumption (including any renewable energy sources used in a nonrenewable manner; i.e., rate of use exceeds rate of replenishment); (3) imports to the system (including raw and finished materials and services); (4) exports from the system (including raw and finished materials and services). Data on the SLB were gathered via literature surveys, interviews with experts, the purchase of a dataset, and meetings with knowledgeable people from the region (Table 5-G.1).

The need for data on SLB imports and exports was the limiting factor in determining the period investigated using EmA. Commodity Flow Surveys produced by the US Census Bureau every five years provide such data at the state level, but these data did not provide annual estimates and they were not available to us at the county level. Thus, we identified a private company, IHS Global Insight, Inc. (GI; Global Insight 2009) that used data from a network of shippers, publicly available sources, and US Census Bureau to compile freight movements by US county. GI data for the seven counties in the SLB, from 1995 to 2005, were purchased for approximately $20,000. We report less detailed EmA results using variables for the period 1980-2005.

5.2.5 Summary Tables and Indices

A summary of the variables with their definitions are given in Table 5.3. Summary variables were used to define total emergy used and fraction of renewable emergy (Fig. 5.2; Table 5.3). Fraction of renewable emergy used to total emergy used was the primary evaluation criterion used to assess local system condition and movement toward or away from sustainability. A number of additional indices were computed (Table 5.4), but these were not necessary for estimating the fraction of renewable emergy to total emergy that we used in this study (Appendix 5-B presents the definitions of other indices important for a complete EmA, including the Emergy Yield Ratio, the Environmental Loading Ratio, and the Emergy Sustainability Index).

5.3 Results

In this section, we present the major results of EmA for the SLB. Other results and associated discussion are located in the appendices.

5.3.1 The Detailed Energy Systems Model of the San Luis Basin

We produced a detailed diagram of an Energy Systems Model of the SLB environmental system (Fig. 5.1; see Chapter 1 and Appendix 5-D for a detailed description of SLB). The large rectangular box represents the boundaries of the SLB. External forcing functions or energy, material, or information sources entering from outside the system are shown as circles. They enter the system through pathway lines crossing the boundaries. They are arranged in order of increasing transformity from left to right around the system boundary. Flows of energy and matter leave the system as shown by arrows crossing the boundary. All the flows on pathways crossing the system boundaries as well as flows of energy and materials moving within the system are defined (Table 5.2). Surface and groundwater flow out of the region into New Mexico. Unused solar energy (albedo) is reflected into space and wind blows over the region and passes on to the surrounding systems. A fully specified energy source (circles) always contains all the necessary parameters needed to define the source over the simulation time planned for the models created from the detailed diagram. For example, wind speed and direction over many annual cycles would be important variables to model the development and maintenance of the dunes in Great Sand Dunes National Park and Preserve. Although this detailed information about the wind is implied by the wind source symbol, it is not included in this highly aggregated depiction of the SLB.

Used energy leaves the lower boundary of the box delineating the SLB system. No other flows exit from the lower boundary and the heat sink symbol, which receives the energy dissipated by all components and flows in the system, including the background temperature of the environment. The inclusion of temperature as part of the specification of energy systems models allows entropy calculations to be performed.

The major physiographic systems within the SLB are aggregated into three classes: 1) mountains which are to a large extent forested, 2) the valley floor, which is divided into an area covered by the natural shrub vegetation of the region including phreatophytes and xerophytes (e.g., sagebrush), and 3) agricultural land, which is generally irrigated with surface or groundwater (Emery 1996). The primary economic systems of the region are centered around its natural resources (e.g., food processing and shipment, mining and processing ores and building materials, and recreation are important activities tied to natural resources). In addition, power companies recently have recognized the high solar power potential of the region (SLVDRG 2007). For example, a solar power plant that was under construction during the course of our study is now operational. However, during the time of this study, all the electricity used in the SLB was imported.

5.3.2 Aggregate Diagram

Aggregated ESL diagrams of the SLB were used to evaluate the SLB each year under study. They show how emergy from renewable resources and local nonrenewable resources (including renewable resources like soil and ground water that were being used in a nonrenewable manner) interacted with imported goods and services to support regional economic activity and produce exports (Fig. 5.2, Table 5.3). Although the major social, economic, and environmental flows were evaluated, there were several gaps in the data. For example, we were not able to find data needed to document internal mineral resources (i.e., primarily sand and gravel and crushed stone) used in the system, thus this value was estimated by assuming 10% of the total resources remained in the region. In addition, we were not able to apply the method utilized by Campbell et al. (2005) to determine the import and export of pure services to and from the SLB. Thus, there is a “?” in the places designated by P_2I_3, P_2E_3, and E_4 on the diagram (Fig. 5.2).

5.3.3 Total Emergy and Percent Renewable Use

Data used to compute total emergy used and the renewable emergy used were available from 1995 to 2005. These data are the main components of our sustainability metric based on EmA. During this 11-year period, the overall trend indicates little change in total emergy use and a slight decrease in the renewable emergy used (Fig. 5.3). Total emergy use per person rose 8% from 1995 to 2000 and then fell 14.7% from its peak in 2000 to 2005 with the largest year to year decrease (9.8%) occurring from 2002 to 2003 (Fig. 5.4). Total outflows exceeded inflows until 2001, when the two were almost equal (Fig. 5.5). In 2000, outflows began to decline more rapidly than inflows and as a result, inflows slightly exceeded outflows in 2003; however, in 2004 and 2005 outflows increased rapidly to more than 2.5 times the inflows (Fig 5.5). The components of total emergy inflow determine the total emergy used, which is defined as the total emergy inflow plus the emergy from local sources (Fig. 5.6). The increase in emergy use by the system seen from 2003 to 2005 followed similarly timed increases in the emergy of renewable sources and imports.

Both the emergy used from local renewable sources and the fraction of total emergy used from home sources (those within the SLB region) were in a slight declining trend from 1997 to 2001, but the fraction of the local renewable sources was more variable (Fig. 5.7). Renewable emergy available per capita declined from 1980 to 2005 such that the renewable emergy per person in 2005 was only around 75% of that available in 1980 (Fig. 5.8). Further, there was up to a 22% year-to-year (2001-2002) decrease in the renewable emergy per capita along its declining trend due to variations in rain and snowfall.

5.3.4 Summary of Renewable and Non-renewable Emergy

The geopotential energy of snow was the largest emergy inflow into the system over the 26-years examined (Figs. 5.9 and 5.10). Agricultural production is considered to be fundamentally renewable in most emergy analyses (i.e., renewable inputs of rain, wind and soil fertility can support agriculture without large subsides of nonrenewable emergy). We recognize that nonrenewable emergy is a major input to most agriculture in the US, but this study does not include a detailed analysis of the agricultural subsystems of the SLB. Emergy in livestock, primarily cattle, was the largest agricultural product of the SLB from 1980 until 1997 (Fig. 5.11). Wheat accounted for the largest emergy of crop production from 1980 to 1985 (Fig. 5.11). Hay accounted for the largest emergy from crop production from 1986 until the conclusion of the study period, except in 1989, when wheat once again was briefly dominant (Fig. 5.11).

Data on nonrenewable emergy production in the SLB (crude oil, metallic ores, broken stone or riprap, sand and gravel, and non-metallic minerals) were taken from the GI dataset, which was for the years 1995 to 2005. The use of nonrenewable emergy in fuels and electricity in the SLB remained constant over the study period (Fig. 5.12). However, nonrenewable emergy production fluctuated, with emergy of sand and gravel and broken stone/riprap in a declining trend from 1995 to 2005, but showing intermittent spikes in production (Fig. 5.12).

5.3.5 Summary of Import-Export Exchange

From 1995-2005, exported emergy exceeded imported emergy, with the most dramatic increase in the difference from 2003 to 2005 (Fig. 5.13). In addition, there was a dramatic spike in net immigration in 1988, 1989 and 1990, and a smaller surge of people into the SLB in 2004 and 2005 (Fig. 5-E.2).

5.3.6 Imported Emergy

Data on petroleum, coal, natural gas and electricity imported, and the services required to deliver these energy inputs were collected for 1980 to 2005 (Fig. 5.14). Data were available from 1995 to 2005 for material imports other than fuels, services in materials (other than fuels), and tourism (Fig. 5.14, see Appendix 5-E for detailed data on Imports). "Materials other than Fuels" carried the largest amount of emergy into the SLB over the period for which we had data. The emergy in these materials was more than twice as large as the next largest input, which was the service required to deliver the material inputs. From 1995 to 2005, emergy of "Agricultural Goods," principally fertilizers and agricultural chemicals, increased from about 18% to 38% of material imports, whereas "Construction Goods" were around 22% of imports from 1995 to 1999, but then declined to 13% of total imports in 2005 (Fig. 5.15). Emergy of "Industrial and Mining Goods" was about 35% of inputs from 1995 to 1998 and then declined to 24% in 1999, after which it rapidly rose to a peak of around 44% of inflows from 2000 to 2001, led by emergy of industrial gases and electrometallurgical products, respectively (Fig. 5.15). After 2001, emergy of "Industrial and Mining Goods" fell to 27.2% of inflows in 2005. Over the 11-year period, emergy of "Consumer Goods" remained around 25% of the emergy of material imports until 2000 when it fell to around 17% of inflows in 2001 and 2002. After 2002, the import of the emergy of "Consumer Goods" recovered to its former level before declining to 22% of the input in 2005.

5.3.7 Exported Emergy

Data on agricultural crops and livestock were available from 1980-2005 and data on emigration were available from 1985-2005. Remaining export data were obtained from the GI dataset and were only available from 1995 to 2005. If we assume that almost all agricultural production was exported, livestock was the major agricultural export of emergy from the region until 1996 when hay (Table 5-E.2) became the dominant export of emergy (Fig. 5.16). From 1995 until 2003, “Gravel or Sand” was the largest emergy export from the region (Table 5-E.5).

The overall pattern of major exports of emergy showed a declining trend from 1995 to 2003, after which there was a dramatic resurgence of the annual empower exported (Fig. 5.16). The resurgence of emergy exports was lead by total materials and by “All Other Materials” (i.e., materials without agricultural crops, livestock, and mineral and forest products; Fig. 5.17). The emergy in services in material exports that were required to make them followed the trend of materials, but was of smaller magnitude, except for the services in “All Other Materials,” which exceeded the emergy of the materials during the export resurgence from 2003-2005 (Fig. 5.17). From 2003 to 2004, there was a steep increase in the emergy exported in the “All Other Materials” category, such that it was three times greater than the emergy exported in sand and gravel in 2004 and 2005 (Fig. 5.17). For the period from 1995 to 2000, “Miscellaneous (Misc.) Food Preparations, nec (not elsewhere classified)” was the largest export of emergy from the SLB, but in 2001 “Misc. Printed Matter” was the largest component briefly until in 2002 when “Misc. Agricultural Chemicals” became the dominant export (Fig. 5.18). After falling to its lowest point in 2003, emergy of “All Other Materials” exported had a sharp jump upward in 2004 lead by emergy of “Miscellaneous Agricultural Chemicals.” “Miscellaneous Agricultural Chemicals” includes such products as insecticides, herbicides, soda ash and sulfur, soil conditioners, and mulch. While all “other” materials exported increased from 2003 to 2005 (Fig. 5.18), the increase in “Miscellaneous Agricultural Chemicals” exported was six times greater than that of the next largest export (“Misc. Printed Matter”; Fig. 5.18).

5.3.8 Population and per Capita Indices

The population of the SLB grew steadily from 1980 to 2005, increasing nearly 15% during the period and there was a corresponding increase in the emergy of electricity and fuel use per capita during the same period (Fig. 5.19). The rate of growth in the use of both fuel and electricity use increased after 1992 (Fig. 5-G.3). Per capita use of emergy from fuels and electricity declined from 1980 to 1983 and then began to increase in two stages (1983-1997 and 1997-2005) with some variation (±3%) within a stage (Fig. 5.19). The most rapid growth in per capita energy use occurred between 1999 and 2001, when it increased by approximately 10%.

5.4 Discussion

Emergy analyses that consider how a system changes over many years are becoming more common. Historical studies of nations have been performed (e.g., Abel 2007, Rydberg and Jansen 2002, Sundberg et al. 1994, Tilley 2006) and nations have been evaluated over decades (e.g., Cialani et al. 2005, Ferreyra and Brown 2007, Hagstrom and Nilsson 2005, Huang et al. 2006). Also, Pulselli et al. (2008) studied the sustainability of two regional systems in Italy over 32 years using the Index of Sustainable Economic Welfare and emergy analysis; however, studies of the sustainability of regional environmental systems with nonstandard boundaries (i.e., boundaries that were not based on standard political or administrative reporting units) carried over many years appear to be rare. The SLB, as defined for this study, is such a nonstandard region.

5.4.1 Spatial Boundaries

This study is unique in that the major organizing renewable energy flows for the region are the available geopotential and chemical potential energy in rain and snow. Although the transformity of snow was determined by Campbell and Ohrt (2009), this is the first EmA where snow was shown to account for the largest renewable emergy input to a system. The variation in the geopotential energy of snow is the primary driver behind the fluctuations in total geopotential energy inflow and the renewable emergy base of the SLB system over the 26-year period of the study (Fig. 5.8). The present human system in the SLB is largely organized around agriculture, which is dependent on the surface and ground water flows that originate in the high mountain snowpack (Emery 1996). Thus, as mentioned above, the boundaries for the analysis of this nonstandard region might be logically set to conform to those of the Upper Rio Grande River Basin, or to conform to the political economic reporting units based on the county boundaries. We chose to deal with the initial boundary problem by choosing those boundaries that were appropriate for the process under consideration (i.e., economic and social data were collected for counties, whereas water flows were determined by the Upper Rio Grande River Basin).

5.4.2 Data Availability

Another major obstacle was finding a complete set of data for the local region that we could use. Technical problems related to determining the inflow and outflow of commodities to and from the region that had been solved at the state level (Campbell et al. 2005, Campbell and Ohrt 2009) had to be revisited in the context of the SLB. Of all the data needed to perform an EmA for the region, information on the import and export of commodities was the most difficult to obtain over the entire period of interest. Once we found a source from which these data could be purchased for a subset of years, we found that it contained inconsistencies and uncertainty greater than data from the U.S. Census Bureau Commodity Flow Survey.

5.4.3 Renewable Inputs to the SLB

Ordinarily, the renewable emergy base of a system is determined by averaging the independent inputs of emergy to the system over many years. This rule is applied because societal structures have many years to adjust to the emergy signature of a location (i.e., economic activities adjust to take advantage of the amounts of available energy of various kinds in the region and their expected availability). This study departs from this custom by looking at the year-to-year variability in the availability of renewable resources. For our study of the SLB, where agriculture and the region's unique natural systems are highly dependent on the year-to-year availability of water resources, we think the inclusion of this level of detail is justifiable. Evapotranspiration (ET) appears nearly constant because we had only one composite annual estimate for the ET of each vegetation class and thus its variability depends on the change in land use over the 26-year period (Appendix 5-E). If we had annual estimates of ET, we would expect it to vary with the hydrological cycle in a manner similar to precipitation.

5.4.4 Temporal Patterns of Development and the Water Cycle

Until 2002, emergy of production from renewable sources (e.g., crops, livestock, and forests) was more than twice the emergy of total fossil fuel and electricity use including services. After 2002, this ratio fell due to a marked decline in the total emergy of agricultural production and the steady increase in the emergy supporting society. The salient characteristic of the renewable emergy base for the SLB is the geopotential energy expended due to snowmelt and its subsequent runoff, which is the largest renewable emergy input to the region. However, the work done by the snow occurs after a period of storage; thus, there is a lag between the time the work is delivered from the time the input enters the system. Snowmelt delivers high quality energy in a pulse that carries twice the emergy of the next largest input, ET. This pulse is essential to maintaining rare geological features like the sand dunes and for recharging groundwater. If climate change results in drier winters or in warmer winter temperatures as indicated by climate change predictions for the region, as evidenced by State of New Mexico (2005), the formation and duration of the snow pack may be affected. Changes in the long-term snowfall or winter temperatures could result in significant changes in the hydrological and geological features of this unique system and have effects on agricultural production.

5.4.5 Nonrenewable Resources

The use of nonrenewable resources, such as, fossil fuels and electricity in the SLB showed a steady growth trend over the period examined that was proportional to population growth. The construction material (sand and gravel and broken stone) produced in the SLB declined by about 40% from 1995 to 2005. Miscellaneous nonmetallic minerals in unprocessed form were mined in the SLB but apparently were not used there. Exports in this category precipitously increased from 2003 to 2005, and were part of a general economic resurgence that occurred in the region during this time. Soil erosion from wind steadily declined over the period (Fig. 5.20 and Appendix 4-A), likely due to improvement in cultivation methods. The use of groundwater for irrigation was episodic and it corresponds with periods of decreased precipitation in the region. Peak groundwater withdrawals exceeding the recharge rate occurred with increasing frequency over the 26-year period with the greatest decline occurring in 2002. During times of peak withdrawal, the emergy supplied by groundwater use was a significant contribution to the annual emergy used in the region, and this emergy source approached that supplied by fuels and electricity in 2002 (Fig. 5.12). Over-withdrawals of groundwater (i.e., faster than it can recharge), could threaten the water resource base for agriculture in the region and the sustainability of this activity in the SLB.

5.4.6 Patterns of Import and the Emergy Budget of the SLB

Material goods other than energy account for the largest part of total imports from 1995 to 2005. Processed nonmetallic minerals accounted for most of the emergy in imported material goods excluding fuels and electricity. However, imports in this category fell 45% over the 11-year period examined (Appendix 5-E). Perlite is classified as a processed nonmetallic mineral used for construction and agricultural purposes. Because large quantities of perlite entered the SLB (San Luis Valley Development Resources Group 2007) and there is a defunct perlite mine in Conejos County, we assumed that materials moving in the nonmetallic minerals category would be largely perlite. Perlite is both imported into and exported from the SLB, however, according to the GI data, much more is imported than exported. We were puzzled by this difference and what might have happened to the missing mass or, alternatively, if the GI data were incorrect.

If the difference was consumed in the SLB, it would greatly increase the emergy used there. The apparent consumption of perlite declined about 40% from 1995 to 2005. Further investigation revealed that perlite was trucked into the SLB from mines in northern New Mexico to the railhead at Antonito, where it was mixed to order and placed on rail cars for shipment out of the region (San Luis Valley Development Resources Group 2007). Furthermore, the mines in northern New Mexico supplied 80-85% of the perlite from US sources during the late 1990s (Barker et al. 2002), so these material flows pertain to the larger system and not to the SLB. A similar condition applies to scoria, another processed nonmetallic mineral, and thus, the emergy of processed nonmetallic minerals was removed from the emergy import–export balance for the SLB.

The emergy of "Agricultural Goods" increased 269% from 1995 to 2005 suggesting increased use of fertilizer and agricultural chemicals in the region and by extension increased cultivation of certain crops. During this period, BEA (2009) reports the total expenses for fertilizer and lime increased. "Industrial and Mining Goods" imported increased two times from 1999 to 2002 and then declined to the 1995 level by 2005, which may be indicative of increased industrial activity in the region during this time. The rapid increase in imports in this category was due to industrial gases (2000-2002) and electrometallurgical products (2002). The import of "Consumer Goods" (i.e., imported commodities classified as primarily for use by consumers) remained constant from 1995 to 2000 and then declined to 67% of this level in 2001 and 2002 and recovered to 86% of the 1995-2000 plateaus by 2005. This decrease in the imported consumer goods occurred in spite of population growth, which was 10% for this period, indicating that consumers in the SLB may have decreased their per capita utilization of imported consumer goods during this time.

5.4.7 Patterns of Export

Exports of most materials were in a declining trend from 1995 to 2003, when total materials exported was at a minimum for the 11-year period. From 2003 to 2005, the emergy exported in materials increased markedly due to a general resurgence of the export economy as indicated by the fact that exports of "All Other Materials" increased in all categories during this time. These data show the category "Miscellaneous Agricultural Chemicals" led this resurgence (Fig. 5.18). However, we do not know the exact commodity or industrial activity that accounts for these exports. The miscellaneous agricultural chemicals commodity class includes commodities such as pesticides, herbicides, fungicides, defoliates, soil conditioners, mulch, sulfur and soda ash. From 1995 to 1998, exports had a slightly increasing trend in emergy due to the manufacture of "Misc. Food Preparations," (i.e., processed agricultural products such as french fries from potatoes) which was the largest category of all other exports until 2003. We assumed that almost all the agricultural production in the SLB was exported so the discussion above pertaining to the patterns of renewable production applies to exports.

5.4.8 Export-Import Exchange

The fact that exports exceeded imports by a considerable margin over the entire study period indicates the SLB is a hinterland supplying raw materials and primary products to other areas in North America as shown by the GI data. Exports and imports have different temporal patterns prior to 2003 (Fig. 5.13), but both reach a low point at this time. From 2000 to 2003, both decline together, suggesting the import-export sectors of the economy of the SLB were contracting during that time. From 2003 to 2005, exports increased precipitously to the highest level obtained during the 11-year period, while imports increased very slightly.

5.4.9 Patterns of Population Growth and Consumption

Fuel use in and fuel import to the SLB increased 16% over the 26-year period and electricity use increased by 80% compared to a 25% increase in population. Thus, we must look for factors other than population growth to explain the increase in energy use. From 1980 to 2005, the consumption of electricity per capita increased by 44%, which accounts for the additional growth in electricity consumption. Because of its high transformity, the use of more electricity by people may be indicative of an increase in their quality of life over this time. Per capita fuel consumption declined 7% over the period but the concomitant population increase resulted in a 16% rise in fuel consumption. From 1995 to 2005, the population increased 9.8% as the emergy of the fuels and electricity used increased 20.7% or 28.8% (services included). Without considering services, the emergy of fuel consumption increased 19.2% as the emergy of electricity use increased 23.4% from 1995 to 2005 (Fig. 5.19). Increased consumption of fuels (+8%) and electricity (+12%), along with population growth, may contribute to the observed increases in consumption.

The SLB has a very high proportion of renewable emergy (31-51% of total emergy use) supporting the system and its people compared to renewable contributions of around 3% for many developed areas in the US (Campbell et al. 2005, Campbell and Ohrt

2009). Population growth in the SLB had the effect of decreasing the renewable emergy available per person (Appendix 5-E), and of putting pressure on the environment from development and waste production. In the end, this process is self-limiting, but at the present rate of increase, it may be some time before the inflow of people is diminished by degrading natural resources. Indeed, other factors related to economic development may continue to draw more people to the region in the future. The overall quality of life for people in the SLB as indicated by the Total Emergy Used per person, which is high (Fig. 5.4) with values equal to those in Minnesota, a state with high levels of emergy use per capita compared to West Virginia and the U.S. as a whole (Campbell and Ohrt 2009).

5.4.10 Analysis of the Emergy Indices

The fraction of emergy use from renewable sources can be viewed as an indicator of movement toward or away from sustainability (see Fig. 5.7). If the renewable emergy is of local origin, it is an indicator of the self-sufficiency of the system. The fraction of energy use from locally renewable sources declined from 1997 to 2002 (Figs. 5.6, 5.21). After 2002, it increased abruptly indicating movement toward sustainability (or perhaps more accurately away from unsustainability), which was the result of the excess ground water use that occurred in 2002. This increase was due both to an increase in precipitation and to a relatively low level of emergy imported. On average, renewable emergy accounted for 44% of total emergy use over the 11-year period examined, which is five times that of an average location in the US (Campbell and Ohrt 2009). However, this index showed a 4% decline over the 11-year period examined, indicating the region was moving away from sustainability.

The fraction of emergy derived from home sources has a pattern similar to, but not the same as the emergy from renewable sources. As demonstrated in 2000 and 2002, the principal difference between these patterns is determined by the years of drought when local renewable resource contributions decline, (along with decreased precipitation) and the fraction of use from home sources increases due to increased use of groundwater (compare Figs. 5.9, 5.20, and 5.21). The use of ground water in this manner decreases the variability of total emergy use in the system by compensating for declines in emergy inflows from the renewable resource base. The fraction of emergy used from home sources is an indicator of self-sufficiency and in the SLB home sources exceed 40% in some years making it moderately self-sufficient. However, because the region has a high potential for developing solar, wind, and geothermal power, the potential self-sufficiency of the SLB using renewable sources alone is large. The principle of matching environmental emergy with appropriate purchased or economic inputs in the form of investment implies that we would expect economic investment from outside to be drawn into the region. Per capita income in the region is low, so the necessary investment capital probably is not available within the region itself. Thus, we might expect tension to arise between the desire of outside influence from the next larger system to obtain "green" energy and the desire of local people for self-determination of their lifestyle and energy self-sufficiency.

One index of how well the local system is doing is the emergy used annually by the system. The emergy used in the SLB remained fairly constant over the entire period (the coefficient of variation was 0.05) despite variability in the emergy inputs. Because the use of nonrenewable emergy from inside the system can be used to compensate for declines in the renewable emergy inflows in most years, the pattern of total emergy use in the system appears to follow closely the third component, imported emergy. Systems at all levels of organization compete for the available energy in resources. Emergy matching of a high with a low transformity resource develops the most emergy flow. Thus, imports and exports are continually adjusting to meet the need to increase emergy flow at all levels of organization under varying circumstances. In theory, the entire hierarchical, coupled ecological-economic system continually seeks win-win relationships that increase system empower. This concept is somewhat parallel to the general equilibrium model in economics where supply and demand are brought into relationship through a set of equilibrium prices. The objective function is different and the method of calculation is not determined in terms of emergy matching, but the two ideas are theoretically similar. Lu and Campbell (2009), Lu et al. (2006), and Lu et al. (2007) discussed additional indices that may be useful for answering particular questions about the relationship between emergy and economic flows between a local system and its larger system.

5.4.11 Effects of Missing Data, Unknown Information, and Uncertainty

The commodity flow data taken by the US Census Bureau met the data quality objectives for measuring total commodity movements for the studies of West Virginia and Minnesota (Campbell et al. 2005, Campbell and Ohrt 2009). In these studies, the estimated movements of individual commodities had higher uncertainties than the average of all commodities. The GI data were critical in allowing us to apply the revised method (Campbell et al. 2005) for calculating emergy import and export to and from a region. The methods reported by GI appear to be logical and deliberate, even though there is considerable uncertainty associated with some of their measurements. Principally, the export of "nonmetallic minerals, processed" appears to be grossly underestimated (see Appendix 5-F) and others were questionable.

The transformities and specific emergies by which the energy or mass flows are multiplied, respectively, to obtain emergy are critical numbers in the analysis (Appendix 5-C) and they are important to understand the general level of uncertainty associated with these numbers. Campbell (2003) analyzed five global water budgets, and determined the transformities of global hydrological flows, such as rain, evapotranspiration, and river flow, within an average standard deviation of 5.9% of the mean value. Odum (1996) determined the transformity of coal from its relative efficiency in producing electricity and its geological production process. The former method gave an estimate of 4.3E+4 sej/J and the latter 3.4 E+4 sej/J. The two values are within 12% of the mean value, which may be a rough estimate of the model uncertainty in determining transformities.

5.4.12 Strengths and Limitations of the Method

Emergy methods are comprehensive and based on thermodynamic laws and principles governing the order and organization of all systems; therefore, they have a broad capability to address many problems. In addition, Energy Systems Theory is a meta-theory in the sense that theory and methods from all other disciplines that are translated into Energy Systems Language and further analyzed within the context of the thermodynamic constraints that govern them. This is true because all real systems have an underlying energy basis. However, EmA is not a substitute for other approaches but a complement to them. Perhaps the greatest strength of EmA is that it can transform disparate quantities into similar quantities with the same units that are then directly comparable for decision-making.

The strengths of EmA are also its weaknesses. Because it is comprehensive, it often requires more data and information than other approaches. In addition, the more aspects of a system that one considers, the more complicated the emergy work can become, because it is forced by the imperative to be complete to incorporate all relevant data and theory into the emergy assessment. In addition, the uncertainty of the analysis grows with the complexity of data and models used. One of the greatest challenges in an emergy assessment is to set the proper boundaries for the study so that a particular set of research questions are answerable. Perhaps the greatest weakness of emergy is that it is an abstract concept that can be difficult to communicate to scientists and managers. To use it with facility requires years of study and a broad background in the natural and social sciences.

5.5 Conclusions

The process of assembling information on the SLB and diagramming the system demonstrated that it is a fully developed agricultural system with crop and livestock production, food processing, and animal waste processing components. This system is a high desert and may be under additional pressure due to climate change if drier, warmer years become more frequent in the future, which could threaten unique natural features like the sand dunes, local wetlands, and wildlife refuges. Farming in the region may come under pressure and the area irrigated may have to contract to meet the diminished capacity of the annual water budget. The alternative of drawing excess water for agriculture from groundwater storage may be a short-term solution to deal with shortages. Long term, however, such a solution poses a potential recipe for disaster, not only for the agricultural system, but also for the SLB as a whole.

Examination of Fraction of Renewable Emergy to Total Emergy Used revealed movement away from sustainability. Renewable emergy use declined 4% over the 11-year study period, and only about half of the present population could be supported at their standard of living on renewable emergy alone, indicating that the region as a whole is moving away from sustainability.

Social and economic systems in the SLB have been growing over the period examined in this study and we expect that this trend will continue in the future as the region becomes a center for the development of renewable energy. The EmA showed there are pulses within the general growth trend of the economy and the emergy exported experienced declines followed by rapid increases that make the overall trend irregular. Even though the SLB receives 31-51% of its emergy base from renewable sources, it depends on the larger system for the purchase of the majority of the emergy used; and therefore, it is subject to larger national trends. Perhaps, the national and global trend that is most likely to affect the SLB in the near future is the current movement toward developing renewable energy sources. The SLB has a rich potential for future development of solar, wind, and geothermal energy and could rely more on renewable sources of power in the future.

5.6 References

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Table 5.1 – Tabular format for an emergy analysis, providing a template for the calculation of the emergy values.

Column 1	Column 2	Column 3	Column 4	Column 5
Note	Item	Data	Solar Emergy/Unit	Solar Emergy
		J, g, $	sej/J, sej/g, sej/$	sej, sej/y

Table 5.2 – Definition of pathway flows for the systems model of the San Luis Basin (seven county area), Colorado shown in Fig. 5.1.

Pathway	Definition of Flow
R_0	Albedo
R_1	Wind passing through the Region
k_0	Solar radiation absorbed by the Region
k_1	Solar radiation absorbed by agricultural crops
k_2	Solar radiation absorbed by natural vegetation (shrubs)
k_3	Solar radiation absorbed by forests
k_4	Wind energy absorbed by agricultural crops
k_5	Wind energy absorbed by natural vegetation (shrubs)
k_6	Wind energy absorbed by forests
k_7	Wind energy absorbed by sand flats and dunes
k_8	Rain and snow falling on agricultural crops
k_9	Rain and snow falling on natural vegetation (shrubs)
k_{10}	Rain and snow falling on forests
k_{11}	Snow falling in the mountains
k_{12}	River water flowing out of the SLB
k_{13}	Runoff to rivers from the forests
k_{14}	Infiltration from forests to groundwater
k_{15}	Infiltration from rivers in forestland to groundwater
k_{16}	Groundwater uptake by forest vegetation
k_{17}	Nutrient and rainwater uptake by the forest
k_{18}	Evapotranspiration by the forest
k_{19}	Snow melt feeding mountain rivers
k_{20}	Sublimation of snow
k_{21}	Groundwater loss to deeper levels
k_{22}	Evapotranspiration from rivers in mountains
k_{23}	Water use for mining and processing ores
k_{24}	Forest biomass growth
k_{25}	Timber harvest
k_{26}	River flow crucial to dunes formation
k_{27}	Erosion of mountains
k_{28}	Wind erosion of dunes
k_{29}	Groundwater flow from mountains to the valley
k_{30}	River flow from mountains to rivers in valley Shrub land
k_{31}	River flow from mountains to agricultural land
k_{32}	Runoff to rivers from the shrub land
k_{33}	Infiltration from shrub land to groundwater
k_{34}	Infiltration from lakes and rivers in shrub land to groundwater
k_{35}	Groundwater uptake by shrub land vegetation
k_{36}	Nutrient and rainwater uptake by the shrub vegetation
k_{37}	Evapotranspiration by the shrub vegetation
k_{38}	Shrub biomass growth
k_{39}	Evapotranspiration from rivers and lakes in Shrub land
k_{40}	Groundwater loss to deeper levels
k_{41}	Groundwater flow from agricultural areas to the closed basin

Pathway	Definition of Flow
k_{42}	Surface water use in the region
k_{43}	Water use by production manufacturing
k_{44}	Runoff to rivers from the agricultural land
k_{45}	Infiltration from agricultural land to groundwater
k_{46}	Infiltration from rivers in farmland to groundwater
k_{47}	Groundwater and river water used to irrigate crops
k_{48}	Groundwater loss to deeper levels
k_{49}	Groundwater flow to New Mexico
k_{50}	Water and nutrients taken up by crops
k_{51}	Crop biomass growth
k_{52}	Evapotranspiration by crops
k_{53}	Evapotranspiration of water in rivers
k_{54}	Livestock biomass growth
k_{55}	Crops eaten by livestock
k_{56}	Water used by livestock
k_{57}	Waste produced by livestock
k_{58}	Waste produced by crops
k_{59}	Livestock processed or shipped
k_{60}	Crops processed or shipped
k_{61}	Geologic processes building landform and mineral deposits
k_{62}	Sand mined and processed
k_{63}	Crushed rock mined and processed
k_{64}	Minerals mined and processed
k_{65}	Electricity and fuels used by the mining industry
k_{66}	Goods and services used by the mining industry
k_{67}	Government control of mining
k_{68}	Mining industry inputs to manufacturing and construction
k_{69}	Waste produced by mining and processing ores
k_{70}	Knowledge and labor used in the mining industry
k_{71}	Water use by food processing
k_{72}	Water use by service and commerce
k_{73}	Water use by manufacturing and construction
k_{74}	Water use by the recreational systems
k_{75}	Fuels and electricity input to the recreational systems
k_{76}	Goods and services input to recreational systems
k_{77}	Government regulation of recreational systems
k_{78}	Human knowledge and labor used by recreational systems
k_{79}	Transport of fuels and electricity into the State
k_{80}	Transport of goods and services into the State
k_{81}	Government regulation of transportation
k_{82}	Human knowledge and labor used in the transportation sector
k_{83}	Goods and services input to the transportation sector
k_{84}	Fuels and electricity input to the transportation sector
k_{85}	Fuels and electricity used by the government sector
k_{86}	Goods and services input to the government sector
k_{87}	Human knowledge and labor used in the government sector
k_{88}	Federal government regulations
k_{89}	Federal taxes
k_{90}	Federal outlays
k_{91}	Money spent on fuels
k_{92}	Money spent on goods and services
k_{93}	Solar electricity generated in SLB joins the regional grid
k_{94}	Fuels and electricity input to the power distribution system

Pathway	Definition of Flow
k_{95}	Goods and services input to power distribution system
k_{96}	Government regulation of power distribution system
k_{97}	Human knowledge and labor used by power distribution system
k_{98}	Fuels and electricity input to education systems
k_{99}	Goods and services input to education systems
k_{100}	Government regulation of education
k_{101}	Human knowledge and labor used in the schools
k_{102}	Teaching
k_{103}	Learning
k_{104}	Increase in human knowledge and skills
k_{105}	Loss of information (knowledge and skills)
k_{106}	Gain of knowledge and skills with immigrants
k_{107}	Loss of knowledge and skills with emigrants
k_{108}	Government regulation of people
k_{109}	Goods and services used by people and households
k_{110}	Fuels and electricity used by people and households
k_{111}	Water used by people and households
k_{112}	Waste produced by people and households
k_{113}	Immigration
k_{114}	Emigration
k_{115}	Raw and processed ores exported
k_{116}	Manufactured products exported
k_{117}	Raw and processed food exported
k_{118}	Fuels and electricity used by production and manufacturing
k_{119}	Goods and services used by production and manufacturing
k_{120}	Government regulation of industry
k_{121}	Human knowledge and labor used in manufacturing
k_{122}	Waste produced by industry
k_{123}	Fuels and electricity used by food processing
k_{124}	Goods and services used by food processing
k_{125}	Government regulation of food processing industry
k_{126}	Human knowledge and labor used in food processing
k_{127}	Food processing inputs to manufacturing
k_{128}	Waste produced by food processing
k_{129}	Production and manufacturing inputs to service and commerce
k_{130}	Food processing inputs to service and commerce
k_{131}	Fuels and electricity used by service and commerce
k_{132}	Goods and services used by service and commerce
k_{133}	Government regulation of service and commerce
k_{134}	Human knowledge and labor used in service and commerce
k_{135}	Service and commerce used by tourists
k_{136}	Exports from the service and commerce sector
k_{137}	Tourists entering the State
k_{138}	Tourists leaving the State
k_{139}	Money gained from the sale of products and services
k_{140}	Money spent by tourists
k_{141}	Effects of wastes on forests
k_{142}	Effects of wastes on shrub land
k_{143}	Effects of wastes on agricultural lands
k_{144}	Wastes leaving the Region in water or air
k_{145}	Residents using recreation and cultural resources

Table 5.3 – Summary of annual emergy flows in the San Luis Basin, 1995-2005.

Note	Symbol	Item	1995 Emergy (E+20 sej)	1995 Dollars (E+6 $)	1995 2000 Em$ (E+6 Em$)	1996 Emergy (E+20 sej)	1996 Dollars (E+6 $)	1996 2000 Em$ (E+6 Em$)
63	R_A	Renewable sources used	32.4		1379.8	28.8		1227.1
	R_1	Renewable Electric Produced	0.0		0.0	0.0		0.0
64	N	Nonrenewable source flows	12.6		535.6	16.7		710.0
	N′	Internal fuels and minerals extracted	47.6		2025.2	43.9		1869.6
65	N_0	Dispersed Rural Source	1.2		52.6	5.3		227.1
66	N_1	Concentrated use, minerals, hydroelectric)	11.4		483.1	11.3		482.9
67	N_2	Exported without Use	43.2		1836.7	39.8		1695.7
68	F	Imported Fuels, Minerals+U, Electric	6.9		294.6	7.3		309.0
69	F_1	Fuels and minerals used (F+N_1-Renewable&Electric)	11.4		483.1	11.3		482.9
70	F_2	In region minerals used (F1- F)	4.4		188.5	4.1		173.9
71	G	Imported Goods (materials)	13.3		566.7	13.9		591.1
72	I	Dollars Paid for all Imports		312.5			304.9	
73	I_1	Dollars Paid for Service in Fuels, Minerals, Electric		71.8			76.8	
74	I_2	Dollars Paid for Service in Goods		240.7			228.1	
75	I_3	Dollars Paid for Services		0.0			0.0	
76	I_4	Dollars Spent by Tourists		55.3			57.4	
77	I_5	Federal Transfer Payments		23.5			25.1	
78	P_2I	Imported Services Total	8.1		346.0	7.9		336.9
79	P_2I_1	Imported Services in Fuels, Minerals, Electric	1.9		79.5	2.0		84.8
80	P_2I_2	Imported Services in Goods without fuels	6.3		266.5	5.9		252.1
81	P_2I_3	Imported Services	0.0		0.0	0.0		0.0
82	P_1I_4	Emergy Purchased by Tourists	1.4		61.2	1.5		63.4
83	P_1I_5	Net Emergy Purchased by Federal $	0.0		0.0	0.0		0.0
84	B	Exported Products without minerals	27.4		1164.0	31.5		1342.3
86	E	Dollars Paid for All Exports		826.8			861.3	
87	E_1	Dollars Paid for Goods without minerals		736.8			777.7	
88	E_2	Dollars Paid for Minerals Exported		90.1			83.6	
89	E_3	Dollars Paid for Exported Services		0.0			0.0	
90	E_4	Federal Taxes Paid		0.0			0.0	
91	P_2E	Exported Services Total	20.7			21.8		
92	P_2E_1	Exported Services in Goods other than minerals	18.4		0.8	19.6		0.8
93	P_2E_2	Exported Services in Minerals	2.3		0.1	2.2		0.1
94	P_2E3	Exported services	0.0		0.0	0.0		0.0
95	X	Gross Regional Product		1161.8			1229.6	
96	P_2	Emergy $ ratio for the US in 2000 sej/$	2.4E+12			2.4E+12		

Note	Symbol	Item	1997			1998		
			Emergy (E+20 sej)	Dollars (E+6 $)	2000 Em$ (E+6 Em$)	Emergy (E+20 sej)	Dollars (E+6 $)	2000 Em$ (E+6 Em$)
63	R_A	Renewable sources used	36.5		1555.0	32.1		1367.0
	R_1	Renewable Electric Produced	0.0		0.0	0.0		0.0
64	N	Nonrenewable source flows	12.8		544.2	14.3		607.4
	$N^`$	Internal fuels and minerals extracted	47.0		2001.6	48.6		2069.6
65	N_0	Dispersed Rural Source	1.3		56.9	2.5		104.7
66	N_1	Concentrated use, minerals, hydroelectric)	11.5		487.3	11.8		502.6
67	N_2	Exported without Use	42.7		1815.7	44.1		1877.5
68	F	Imported Fuels, Minerals+U, Electric	7.1		301.5	7.3		310.6
69	F_1	Fuels and minerals used (F+N_1-Renewable&Electric)	11.5		487.3	11.8		502.6
70	F_2	In region minerals used (F_1- F)	4.4		185.8	4.5		192.0
71	G	Imported Goods (materials)	14.6		620.1	14.8		630.1
72	I	Dollars Paid for all Imports		315.8			323.0	
73	I_1	Dollars Paid for Service in Fuels, Minerals, Electric		76.4			72.9	
74	I_2	Dollars Paid for Service in Goods		239.5			250.2	
75	I_3	Dollars Paid for Services		0.0			0.0	
76	I_4	Dollars Spent by Tourists		59.3			61.8	
77	I_5	Federal Transfer Payments		24.5			24.0	
78	P_2I	Imported Services Total	8.1		343.8	8.0		339.1
79	P_2I_1	Imported Services in Fuels, Minerals, Electric	2.0		83.1	1.8		76.5
80	P_2I_2	Imported Services in Goods without fuels	6.1		260.6	6.2		262.6
81	P_2I_3	Imported Services	0.0		0.0	0.0		0.0
82	P_1I_4	Emergy Purchased by Tourists	1.5		64.5	1.5		64.9
83	P_1I_5	Net Emergy Purchased by Federal $	0.0		0.0	0.0		0.0
84	B	Exported Products without minerals	31.3		1331.0	30.8		1309.4
86	E	Dollars Paid for All Exports		937.9			3536.1	
87	E_1	Dollars Paid for Goods without minerals		847.0			3420.2	
88	E_2	Dollars Paid for Minerals Exported		90.9			116.0	
89	E_3	Dollars Paid for Exported Services		0.0			0.0	
90	E_4	Federal Taxes Paid		0.0			0.0	
91	P_2E	Exported Services Total	23.2			23.4		
92	P_2E_1	Exported Services in Goods other than minerals	20.8		0.9	21.0		0.9
93	P_2E_2	Exported Services in Minerals	2.3		0.1	2.3		0.1
94	P_2E_3	Exported services	0.0		0.0	0.0		0.0
95	X	Gross Regional Product		1354.1			1385.7	
96	P_2	Emergy $ ratio for the US in 2000 sej/$	2.4E+12			2.4E+12		

Note	Symbol	Item	1999			2000		
			Emergy (E+20 sej)	Dollars (E+6 $)	2000 Em$ (E+6 Em$)	Emergy (E+20 sej)	Dollars (E+6 $)	2000 Em$ (E+6 Em$)
63	R_A	Renewable sources used	32.2		1370.5	29.6		1261.6
	R_1	Renewable Electric Produced	0.0		0.0	0.0		0.0
64	N	Nonrenewable source flows	11.8		501.3	16.9		718.5
	N′	Internal fuels and minerals extracted	34.6		1472.0	35.8		1524.9
65	N_0	Dispersed Rural Source	1.3		57.0	5.9		251.2
66	N_1	Concentrated use, minerals, hydroelectric)	10.4		444.3	11.0		467.2
67	N_2	Exported without Use	31.5		1339.9	32.6		1386.7
68	F	Imported Fuels, Minerals+U, Electric	7.3		312.2	7.7		328.9
69	F_1	Fuels and minerals used (F+N_1-Renewable&Electric)	10.4		444.3	11.0		467.2
70	F_2	In region minerals used (F1- F)	3.1		132.1	3.2		138.3
71	G	Imported Goods (materials)	18.2		776.3	21.3		905.3
72	I	Dollars Paid for all Imports		357.5			387.8	
73	I_1	Dollars Paid for Service in Fuels, Minerals, Electric		77.6			96.0	
74	I_2	Dollars Paid for Service in Goods		279.9			291.8	
75	I_3	Dollars Paid for Services		0.0			0.0	
76	I_4	Dollars Spent by Tourists		63.8			66.0	
77	I_5	Federal Transfer Payments		24.2			25.4	
78	P_2I	Imported Services Total	8.2		351.0	9.1		387.5
79	P_2I_1	Imported Services in Fuels, Minerals, Electric	1.8		76.2	2.3		95.9
80	P_2I_2	Imported Services in Goods without fuels	6.5		274.8	6.9		291.6
81	P_2I_3	Imported Services	0.0		0.0	0.0		0.0
82	P_1I_4	Emergy Purchased by Tourists	1.5		62.6	1.5		66.0
83	P_1I_5	Net Emergy Purchased by Federal $	0.0		0.0	0.0		0.0
84	B	Exported Products without minerals	27.3		1160.3	27.2		1155.6
86	E	Dollars Paid for All Exports		962.1			876.5	
87	E_1	Dollars Paid for Goods without minerals		867.1			808.7	
88	E_2	Dollars Paid for Minerals Exported		94.9			67.9	
89	E_3	Dollars Paid for Exported Services		0.0			0.0	
90	E_4	Federal Taxes Paid		0.0			0.0	
91	P_2E	Exported Services Total	20.2			19.5		
92	P_2E_1	Exported Services in Goods other than minerals	18.7		0.8	17.7		0.8
93	P_2E_2	Exported Services in Minerals	1.6		0.1	1.8		0.1
94	P_2E3	Exported services	0.0		0.0	0.0		0.0
95	X	Gross Regional Product		1486.0			1590.9	
96	P_2	Emergy $ ratio for the US in 2000 sej/$	2.4E+12			2.4E+12		

Note	Symbol	Item	2001			2002		
			Emergy (E+20 sej)	Dollars (E+6 $)	2000 Em$ (E+6 Em$)	Emergy (E+20 sej)	Dollars (E+6 $)	2000 Em$ (E+6 Em$)
63	R_A	Renewable sources used	30.3		1289.4	22.5		956.9
	R_1	Renewable Electric Produced	0.0		0.0	0.0		0.0
64	N	Nonrenewable source flows	13.0		551.3	19.9		845.5
	N′	Internal fuels and minerals extracted	41.3		1758.6	37.4		1593.6
65	N_0	Dispersed Rural Source	1.2		50.5	9.1		387.0
66	N_1	Concentrated use, minerals, hydroelectric)	11.8		500.7	10.8		458.6
67	N_2	Exported without Use	37.7		1602.4	34.7		1476.5
68	F	Imported Fuels, Minerals+U, Electric	8.1		344.6	8.0		341.5
69	F_1	Fuels and minerals used (F+N_1-Ren.&Elec.)	11.8		500.7	10.8		458.6
70	F_2	In region minerals used (F1- F)	3.7		156.2	2.8		117.1
71	G	Imported Goods (materials)	21.3		905.3	22.0		937.0
72	I	Dollars Paid for all Imports		402.2			394.3	
73	I_1	Dollars Paid for Service in Fuels, Minerals, Electric		106.3			93.4	
74	I_2	Dollars Paid for Service in Goods		295.9			300.9	
75	I_3	Dollars Paid for Services		0.0			0.0	
76	I_4	Dollars Spent by Tourists		69.7			67.0	
77	I_5	Federal Transfer Payments		26.6			27.1	
78	P_2I	Imported Services Total	8.8		374.4	8.2		346.9
79	P_2I_1	Imported Services in Fuels, Mineral, Electric	2.3		99.0	1.9		82.2
80	P_2I_2	Imported Services in Goods without fuels	6.5		275.4	6.2		264.7
81	P_2I_3	Imported Services	0.0		0.0	0.0		0.0
82	P_1I_4	Emergy Purchased by Tourists	1.5		64.9	1.4		58.9
83	P_1I_5	Net Emergy Purchased by Federal $	0.0		0.0	0.0		0.0
84	B	Exported Products without minerals	19.9		845.8	17.7		753.6
86	E	Dollars Paid for All Exports		654.0			718.9	
87	E_1	Dollars Paid for Goods without minerals		566.1			648.5	
88	E_2	Dollars Paid for Minerals Exported		88.0			70.4	
89	E_3	Dollars Paid for Exported Services		0.0			0.0	
90	E_4	Federal Taxes Paid		0.0			0.0	
91	P_2E	Exported Services Total	12.1			14.9		
92	P_2E_1	Exported Services in Goods other than minerals	10.1		0.4	13.4		0.6
93	P_2E_2	Exported Services in Minerals	1.9		0.1	1.5		0.1
94	P_2E3	Exported services	0.0		0.0	0.0		0.0
95	X	Gross Regional Product		1600.3			1630.2	
96	P_2	Emergy $ ratio for the US in 2000 sej/$	2E+12			2E+12		

Note	Symbol	Item	2003			2004		
			Emergy (E+20 sej)	Dollars (E+6 $)	2000 Em$ (E+6 Em$)	Emergy (E+20 sej)	Dollars (E+6 $)	2000 Em$ (E+6 Em$)
63	R_A	Renewable sources used	28.5		1211.7	31.0		1318.7
	R_1	Renewable Electric Produced	0.0		0.0	0.0		0.0
64	N	Nonrenewable source flows	14.3		610.0	12.3		523.7
	N′	Internal fuels and minerals extracted	23.7		1007.6	31.3		1331.3
65	N_0	Dispersed Rural Source	4.0		171.4	1.5		62.2
66	N_1	Concentrated use, minerals, hydroelectric)	10.3		438.6	10.8		461.4
67	N_2	Exported without Use	21.4		911.3	28.8		1225.0
68	F	Imported Fuels, Minerals+U, Electric	8.0		342.2	8.3		355.2
69	F_1	Fuels and minerals used (F+N_1-Renewable&Electric)	10.3		438.6	10.8		461.4
70	F_2	In region minerals used (F1- F)	2.3		96.4	2.5		106.3
71	G	Imported Goods (materials)	15.3		650.3	16.5		704.2
72	I	Dollars Paid for all Imports		371.5			379.0	
73	I_1	Dollars Paid for Service in Fuels, Minerals, Electric		105.9			127.4	
74	I_2	Dollars Paid for Service in Goods		265.6			251.6	
75	I_3	Dollars Paid for Services		0.0			0.0	
76	I_4	Dollars Spent by Tourists		71.3			73.6	
77	I_5	Federal Transfer Payments		29.8			0.0	
78	P_2I	Imported Services Total	7.4		316.9	7.7		327.7
79	P_2I_1	Imported Services in Fuels, Minerals, Electric	2.1		90.3	2.6		110.2
80	P_2I_2	Imported Services in Goods without fuels	5.3		226.5	5.1		217.5
81	P_2I_3	Imported Services	0.0		0.0	0.0		0.0
82	P_1I_4	Emergy Purchased by Tourists	1.4		60.8	1.5		63.6
83	P_1I_5	Net Emergy Purchased by Federal $	0.0		0.0	0.0		0.0
84	B	Exported Products without minerals	18.5		786.2	62.3		2652.8
86	E	Dollars Paid for All Exports		933.3			3536.1	
87	E_1	Dollars Paid for Goods without minerals		885.9			3420.2	
88	E_2	Dollars Paid for Minerals Exported		47.4			116.0	
89	E_3	Dollars Paid for Exported Services		0.0			0.0	
90	E_4	Federal Taxes Paid		0.0			0.0	
91	P_2E	Exported Services Total	18.7			71.8		
92	P_2E_1	Exported Services in Goods other than minerals	17.8		0.8	69.5		3.0
93	P_2E_2	Exported Services in Minerals	1.0		0.0	2.4		0.1
94	P_2E3	Exported services	0.0		0.0	0.0		0.0
95	X	Gross Regional Product		1709.5			1849.8	
96	P_2	Emergy $ ratio for the US in 2000 sej/$	2E+12			2E+12		

Note	Symbol	Item	2005		
			Emergy (E+20 sej)	Dollars (E+6 $)	2000 Em$ (E+6 Em$)
63	R_A	Renewable sources used	29.9		1272.5
	R_1	Renewable Electric Produced	0.0		0.0
64	N	Nonrenewable source flows	12.0		511.6
	N′	Internal fuels and minerals extracted	31.1		1325.0
65	N_0	Dispersed Rural Source	1.3		53.3
66	N_1	Concentrated use, minerals, hydroelectric)	10.8		458.2
67	N_2	Exported without Use	28.7		1221.0
68	F	Imported Fuels, Minerals+U, Electric	8.3		354.3
69	F_1	Fuels and minerals used (F+N_1-Renewable&Electric)	10.8		458.2
70	F_2	In region minerals used (F_1- F)	2.4		103.9
71	G	Imported Goods (materials)	17.0		721.8
72	I	Dollars Paid for all Imports		416.3	
73	I_1	Dollars Paid for Service in Fuels, Minerals, Electric		155.2	
74	I_2	Dollars Paid for Service in Goods		261.1	
75	I_3	Dollars Paid for Services		0.0	
76	I_4	Dollars Spent by Tourists		73.1	
77	I_5	Federal Transfer Payments		0.0	
78	P_2I	Imported Services Total	8.0		338.4
79	P_2I_1	Imported Services in Fuels, Minerals, Electric	3.0		126.1
80	P_2I_2	Imported Services in Goods without fuels	5.0		212.2
81	P_2I_3	Imported Services	0.0		0.0
82	P_1I_4	Emergy Purchased by Tourists	1.4		59.4
83	P_1I_5	Net Emergy Purchased by Federal $	0.0		0.0
84	B	Exported Products without minerals	67.2		2861.6
86	E	Dollars Paid for All Exports		3788.4	
87	E_1	Dollars Paid for Goods without minerals		3667.0	
88	E_2	Dollars Paid for Minerals Exported		121.4	
89	E_3	Dollars Paid for Exported Services		0.0	
90	E_4	Federal Taxes Paid		0.0	
91	P_2E	Exported Services Total	72.4		
92	P_2E_1	Exported Services in Goods other than minerals	70.0		3.0
93	P_2E_2	Exported Services in Minerals	2.3		0.1
94	P_2E3	Exported services	0.0		0.0
95	X	Gross Regional Product		1975.7	
96	P_2	Emergy $ ratio for the US in 2000 sej/$	2E+12		

Table 5.4 – Emergy indices and indicators for the San Luis Basin, 1995-2005. Our focus for this study was on Item 106.

Item	Name of Index	Expression	Units†	1995 (x E+20)*	1996 (x E+20)*	1997 (x E+20)*
97	Renewable Use	RA	sej y-1	32.43	28.84	36.54
98	In Region Non-renewable Use	N0+N1	sej y-1	12.59	16.68	12.79
99	Imported Emergy	F+G+P2I	sej y-1	28.37	29.07	29.73
100	Total Emergy Inflows	R+F+G+P2I	sej y-1	60.80	57.91	66.28
101	Total Emergy Used	U=(RA+N0+F1+G+P2I)	sej y-1	66.46	67.33	71.98
102	Total Exported Emergy	B+P2E+N2	sej y-1	91.25	93.21	97.12
103	Emergy used from Home Sources	(N0+F2+R)/U		0.57	0.57	0.59
104	Imports-Exports	(F+G+P2I)- (B+P2E+N2)	sej y-1	-62.87	-64.14	-67.38
105	Ratio of Exports to Imports	(B+P1E+N2)/ (F+G+P2I)		3.22	3.21	3.27
106	**Fraction Used, Locally Renewable**	**R/U**		**0.49**	**0.43**	**0.51**
107	Fraction of Use Purchased Outside	(F+G+P2I)/U		0.43	0.43	0.41
108	Fraction Used, Imported Services	P2I/U		0.12	0.12	0.11
109	Fraction of Use that is Free	(R+N0)/U		0.51	0.51	0.53
110	Ratio of Purchased to Free	(F1+G+P2I)/(R+N0)		0.97	0.97	0.90
111	Environmental Loading Ratio	(F1+N0+G+P2I)/R		1.05	1.33	0.97
112	Investment Ratio	(F+G+P2I)/(R+N0+F2)		0.74	0.76	0.70
113	Use per Unit Area	U/Area	sej/m2	2.76E+11	2.79E+11	2.99E+11
114	Use per Person	U/Population	sej/pers.	1.52E+17	1.51E+17	1.59E+17
115	Renewable Carrying Capacity	(R/U)*Population	people	21366	19088	22992
116	Developed Carrying Capacity	8*(R/U)*Population	people	170926	152703	183940
117	SLB Gross Regional Product	GRP [1]	$/yr	1.16E+09	1.23E+09	1.35E+09
118	Ratio of SLB Emergy Use to GRP	U/GRP	sej/$	5.72E+12	5.48E+12	5.32E+12
119	Ratio of U.S. Emergy Use to GDP	U/GDP	sej/$	2.60E+12	2.60E+12	2.56E+12
120	Ratio of Electricity Use /Emergy Use	El/U	J/sej	0.037	0.038	0.037
121	Fuel Use per Person	F2/Population	sej/pers.	1.00E+16	1.02E+16	9.73E+15
122	Population	Population	people	43793	44566	45289
123	Area	Area	m2	2.41E+10		
124	Renewable empower density	RA/Area	sej m-2	1.34E+11	1.20E+11	1.52E+11
125	Emergy Yield Ratio	(B+P1E+N2)/ (F+G+P2I)		3.22	3.21	3.27
126	Emergy Index of Sustainability	EYR/ELR		3.06	2.40	3.37
127	Local Effect of Investment	U/(F+G+P2I)		2.34	2.32	2.42

* Units in 10^{23} except as noted. † Where the "Units" column is blank, the indicators are dimensionless.
[1] See Appendix 5-G for estimation of GRP.

Item	Name of Index	Expression	Units†	1998 (x E+20)*	1999 (x E+20)*	2000 (x E+20)*
97	Renewable Use	RA	sej y-1	32.12	32.21	29.65
98	In Region Non-renewable Use	N0+N1	sej y-1	14.27	11.78	16.88
99	Imported Emergy	F+G+P2I	sej y-1	30.07	33.83	38.11
100	Total Emergy Inflows	R+F+G+P2I	sej y-1	62.20	66.03	67.76
101	Total Emergy Used	U=(RA+N0+F1+G+P2I)	sej y-1	69.17	70.48	76.91
102	Total Exported Emergy	B+P2E+N2	sej y-1	98.25	78.98	79.24
103	Emergy used from Home Sources	(N0+F2+R)/U		0.57	0.52	0.50
104	Imports-Exports	(F+G+P2I)- (B+P2E+N2)	sej y-1	-68.18	-45.16	-41.12
105	Ratio of Exports to Imports	(B+P1E+N2)/ (F+G+P2I)		3.27	2.33	2.08
106	**Fraction Used, Locally Renewable**	**R/U**		**0.46**	**0.46**	**0.39**
107	Fraction of Use Purchased Outside	(F+G+P2I)/U		0.43	0.48	0.50
108	Fraction Used, Imported Services	P2I/U		0.12	0.12	0.12
109	Fraction of Use that is Free	(R+N0)/U		0.50	0.48	0.46
110	Ratio of Purchased to Free	(F1+G+P2I)/(R+N0)		1.00	1.10	1.16
111	Environmental Loading Ratio	(F1+N0+G+P2I)/R		1.15	1.19	1.59
112	Investment Ratio	(F+G+P2I)/(R+N0+F2)		0.77	0.92	0.98
113	Use per Unit Area	U/Area	sej/m2	2.87E+11	2.92E+11	3.19E+11
114	Use per Person	U/Population	sej/pers.	1.51E+17	1.52E+17	1.63E+17
115	Renewable Carrying Capacity	(R/U)*Population	people	21317	21193	18154
116	Developed Carrying Capacity	8*(R/U)*Population	people	170536	169544	145234
117	SLB Gross Regional Product	GRP [1]	$/yr	1.39E+09	1.49E+09	1.59E+09
118	Ratio of SLB Emergy Use to GRP	U/GRP	sej/$	4.99E+12	4.74E+12	4.83E+12
119	Ratio of U.S. Emergy Use to GDP	U/GDP	sej/$	2.47E+12	2.31E+12	2.35E+12
120	Ratio of Electricity Use /Emergy Use	El/U	J/sej	0.039	0.039	0.037
121	Fuel Use per Person	F2/Population	sej/pers.	9.94E+15	9.90E+15	1.03E+16
122	Population	Population	people	45902	46377	47097
123	Area	Area	m2			
124	Renewable empower density	RA/Area	sej m-2	1.33E+11	1.34E+11	1.23E+11
125	Emergy Yield Ratio	(B+P1E+N2)/ (F+G+P2I)		3.27	2.33	2.08
126	Emergy Index of Sustainability	EYR/ELR		2.83	1.96	1.30
127	Local Effect of Investment	U/(F+G+P2I)		2.30	2.08	2.02

* Units in 10^{23} except as noted. † Where the "Units" column is blank, the indicators are dimensionless.
[1] See Appendix 5-G for estimation of GRP.

Item	Name of Index	Expression	Units†	2001 (x E+20)*	2002 (x E+20)*	2003 (x E+20)*
97	Renewable Use	RA	sej y-1	30.30	22.49	28.47
98	In Region Non-renewable Use	N0+N1	sej y-1	12.96	19.87	14.33
99	Imported Emergy	F+G+P2I	sej y-1	38.17	38.20	30.77
100	Total Emergy Inflows	R+F+G+P2I	sej y-1	68.47	60.68	59.24
101	Total Emergy Used	U=(RA+N0+F1+G+P2I)	sej y-1	73.33	72.53	65.54
102	Total Exported Emergy	B+P2E+N2	sej y-1	69.59	67.27	58.60
103	Emergy used from Home Sources	(N0+F2+R)/U		0.48	0.47	0.53
104	Imports-Exports	(F+G+P2I)- (B+P2E+N2)	sej y-1	-31.42	-29.07	-27.83
105	Ratio of Exports to Imports	(B+P1E+N2)/ (F+G+P2I)		1.82	1.76	1.90
106	**Fraction Used, Locally Renewable**	**R/U**		**0.41**	**0.31**	**0.43**
107	Fraction of Use Purchased Outside	(F+G+P2I)/U		0.52	0.53	0.47
108	Fraction Used, Imported Services	P2I/U		0.12	0.11	0.11
109	Fraction of Use that is Free	(R+N0)/U		0.43	0.44	0.50
110	Ratio of Purchased to Free	(F1+G+P2I)/(R+N0)		1.33	1.30	1.02
111	Environmental Loading Ratio	(F1+N0+G+P2I)/R		1.42	2.23	1.30
112	Investment Ratio	(F+G+P2I)/(R+N0+F2)		1.09	1.11	0.89
113	Use per Unit Area	U/Area	sej/m2	3.04E+11	3.01E+11	2.72E+11
114	Use per Person	U/Population	sej/pers.	1.56E+17	1.53E+17	1.38E+17
115	Renewable Carrying Capacity	(R/U)*Population	people	19383	14698	20681
116	Developed Carrying Capacity	8*(R/U)*Population	people	155064	117581	165445
117	SLB Gross Regional Product	GRP[1]	$/yr	1.60E+09	1.63E+09	1.71E+09
118	Ratio of SLB Emergy Use to GRP	U/GRP	sej/$	4.58E+12	4.45E+12	3.83E+12
119	Ratio of U.S. Emergy Use to GDP	U/GDP	sej/$	2.19E+12	2.07E+12	2.00E+12
120	Ratio of Electricity Use /Emergy Use	El/U	J/sej	0.039	0.041	0.046
121	Fuel Use per Person	F2/Population	sej/pers.	1.11E+16	1.06E+16	1.06E+16
122	Population	Population	people	46907	47404	47598
123	Area	Area	m2			
124	Renewable empower density	RA/Area	sej m-2	1.26E+11	9.33E+10	1.18E+11
125	Emergy Yield Ratio	(B+P1E+N2)/ (F+G+P2I)		1.82	1.76	1.90
126	Emergy Index of Sustainability	EYR/ELR		1.28	0.79	1.46
127	Local Effect of Investment	U/(F+G+P2I)		1.92	1.90	2.13

* Units in 10^{23} except as noted. † Where the "Units" column is blank, the indicators are dimensionless.
[1] See Appendix 5-G for estimation of GRP.

Item	Name of Index	Expression	Units†	2004 (x E+20)*	2005 (x E+20)*
97	Renewable Use	RA	sej y-1	30.99	29.90
98	In Region Non-renewable Use	N0+N1	sej y-1	12.31	12.02
99	Imported Emergy	F+G+P2I	sej y-1	32.60	33.24
100	Total Emergy Inflows	R+F+G+P2I	sej y-1	63.58	63.14
101	Total Emergy Used	U=(RA+N0+F1+G+P2I)	sej y-1	67.54	66.84
102	Total Exported Emergy	B+P2E+N2	sej y-1	162.97	168.30
103	Emergy used from Home Sources	(N0+F2+R)/U		0.52	0.50
104	Imports-Exports	(F+G+P2I)- (B+P2E+N2)	sej y-1	-130.37	-135.06
105	Ratio of Exports to Imports	(B+P1E+N2)/ (F+G+P2I)		5.00	5.06
106	**Fraction Used, Locally Renewable**	**R/U**		**0.46**	**0.45**
107	Fraction of Use Purchased Outside	(F+G+P2I)/U		0.48	0.50
108	Fraction Used, Imported Services	P2I/U		0.11	0.12
109	Fraction of Use that is Free	(R+N0)/U		0.48	0.47
110	Ratio of Purchased to Free	(F1+G+P2I)/(R+N0)		1.08	1.15
111	Environmental Loading Ratio	(F1+N0+G+P2I)/R		1.18	1.24
112	Investment Ratio	(F+G+P2I)/(R+N0+F2)		0.93	0.99
113	Use per Unit Area	U/Area	sej/m2	2.80E+11	2.77E+11
114	Use per Person	U/Population	sej/pers.	1.40E+17	1.39E+17
115	Renewable Carrying Capacity	(R/U)*Population	people	22117	21520
116	Developed Carrying Capacity	8*(R/U)*Population	people	176938	172157
117	SLB Gross Regional Product	GRP[1]	$/yr	1.85E+09	1.98E+09
118	Ratio of SLB Emergy Use to GRP	U/GRP	sej/$	3.65E+12	3.38E+12
119	Ratio of U.S. Emergy Use to GDP	U/GDP	sej/$	2.03E+12	1.91E+12
120	Ratio of Electricity Use /Emergy Use	El/U	J/sej	0.044	0.046
121	Fuel Use per Person	F2/Population	sej/pers.	1.10E+16	1.09E+16
122	Population	Population	people	48207	48101
123	Area	Area	m2		
124	Renewable empower density	RA/Area	sej m-2	1.29E+11	1.24E+11
125	Emergy Yield Ratio	(B+P1E+N2)/ (F+G+P2I)		5.00	5.06
126	Emergy Index of Sustainability	EYR/ELR		4.24	4.10
127	Local Effect of Investment	U/(F+G+P2I)		2.07	2.01

* Units in 10^{23} except as noted. † Where the "Units" column is blank, the indicators are dimensionless.
[1] See Appendix 5-G for estimation of GRP.

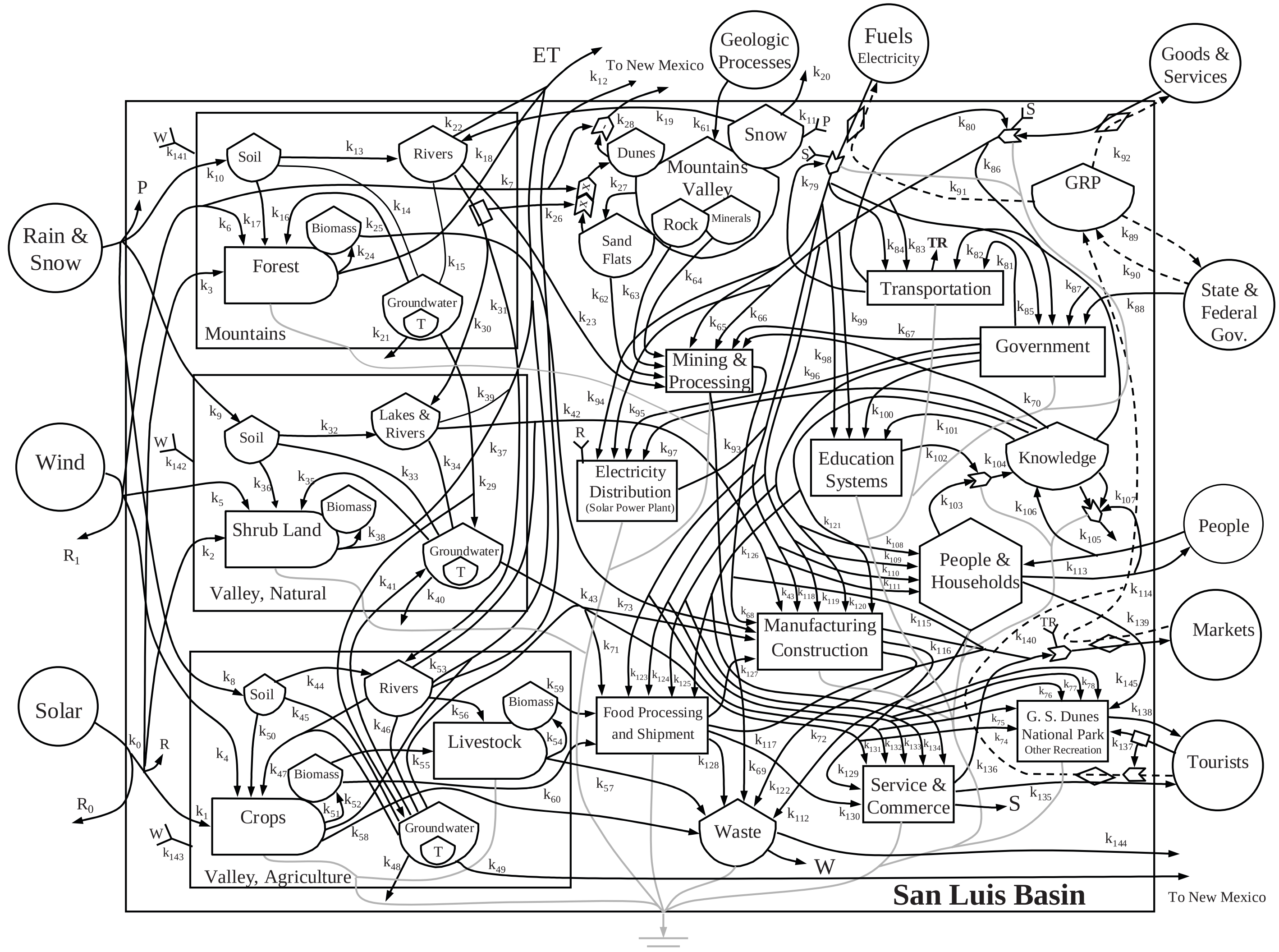

Figure 5.1 – An Energy Systems Diagram of the San Luis Basin showing the major features of this environmental system.

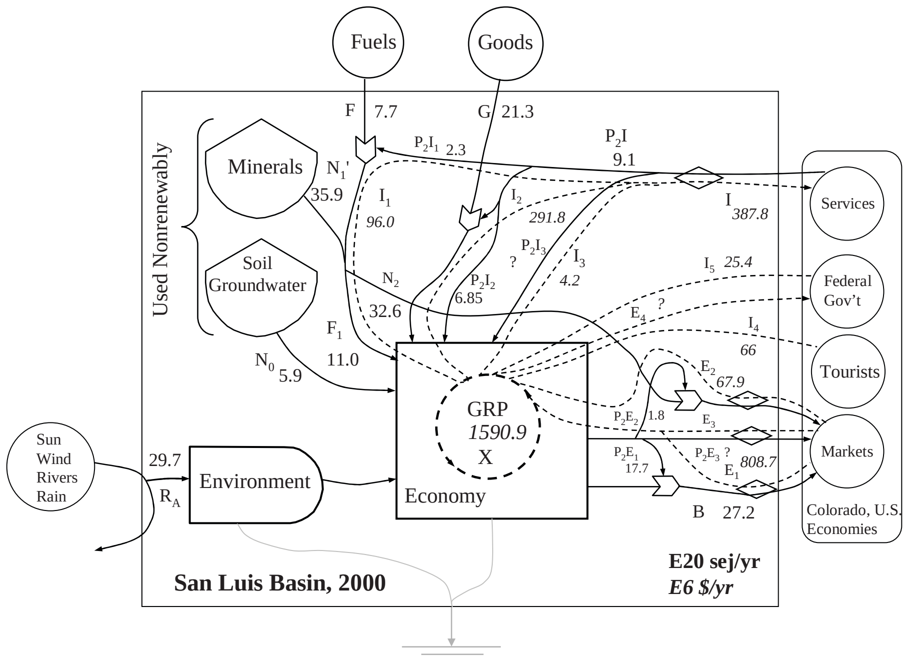

Figure 5.2 – An aggregated model used to calculate summary variables and indices for the San Luis Basin system from 1995 to 2005. Year 2000 is presented here as an example.

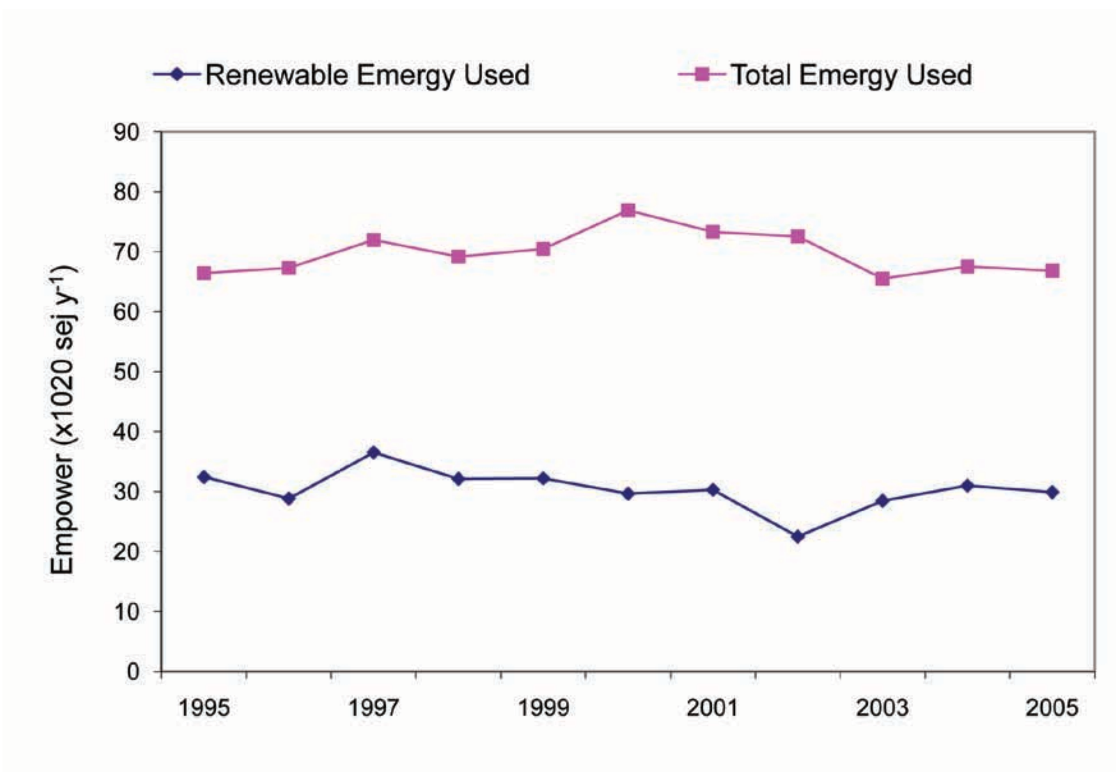

Figure 5.3 – Total emergy used and renewable emergy used in the San Luis Basin from 1995 to 2005.

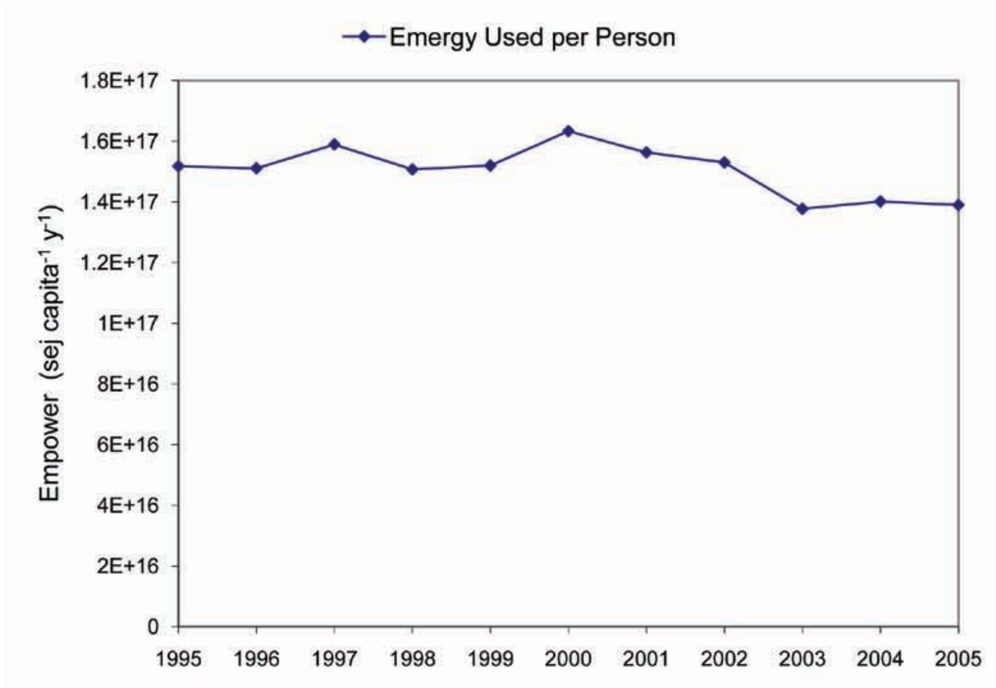

Figure 5.4 – The total emergy used per person in the San Luis Basin from 1995 to 2005.

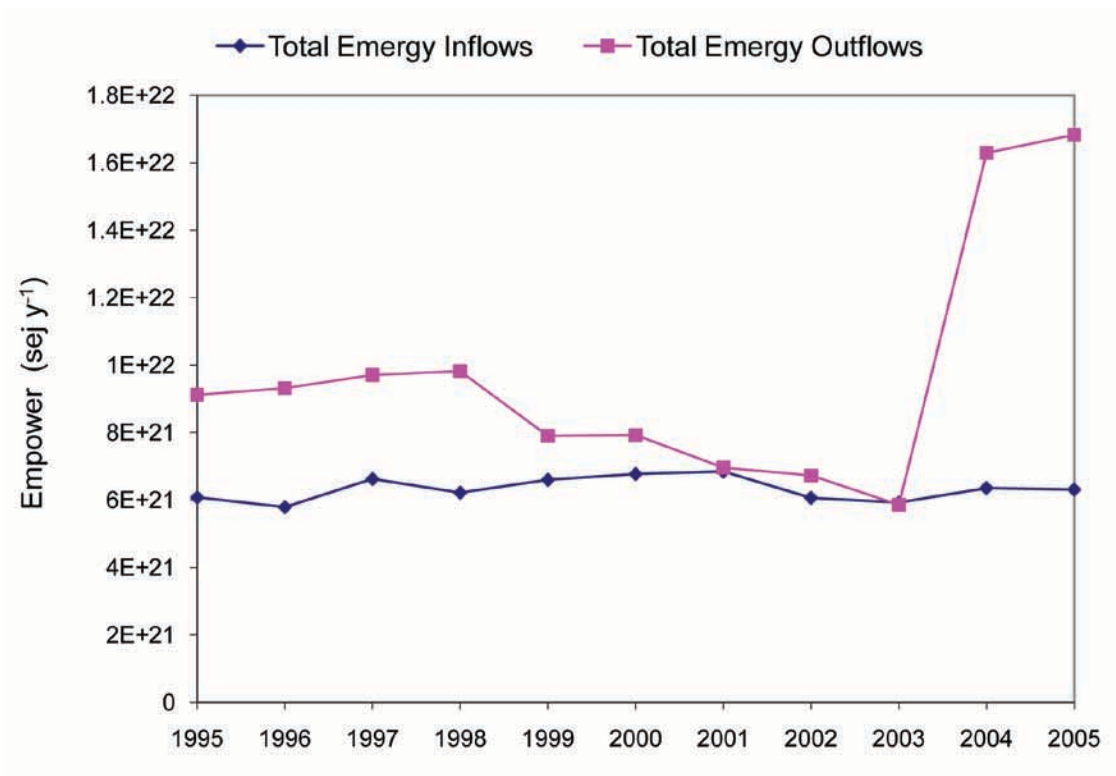

Figure 5.5 – Emergy inflows from renewable sources, imported fuels, electricity, goods and services, emergy outflows in exported materials, the services in material products, services, and nonrenewable resources exported directly in the San Luis Basin, 1995-2005.

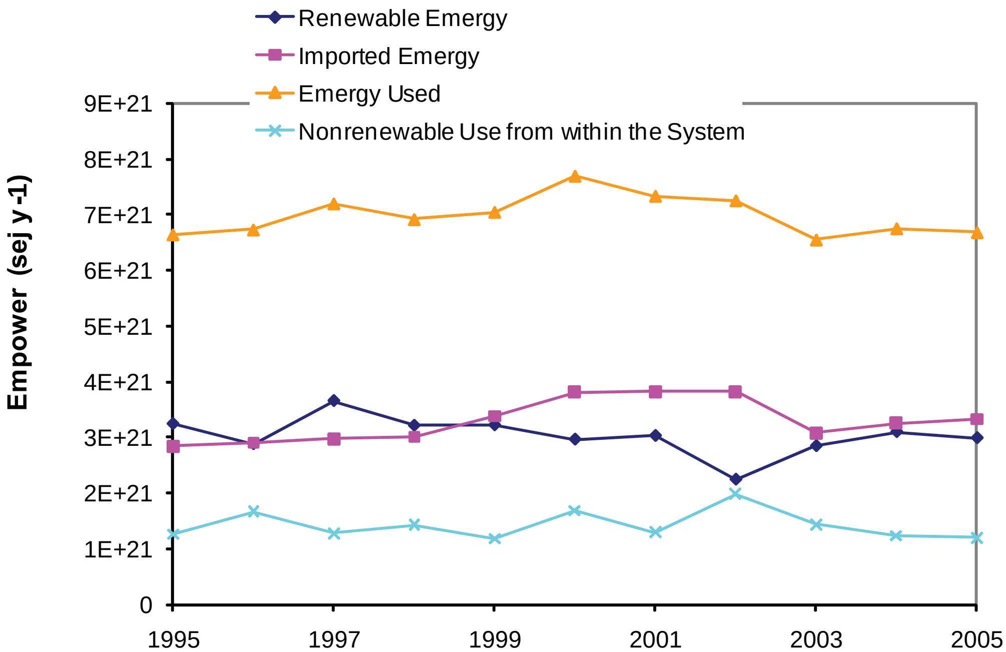

Figure 5.6 – A comparison of the total emergy used by the system with the renewable, local nonrenewable and imported emergy that contribute to it in the San Luis Basin, 1995-2005.

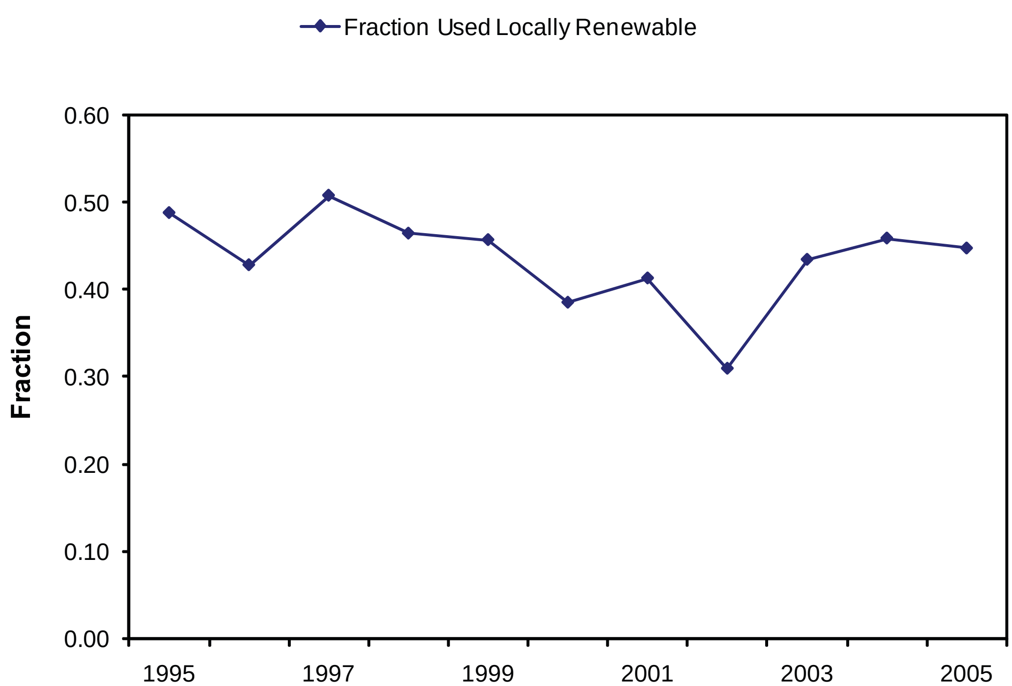

Figure 5.7 – Fraction of renewable emergy to total emergy use in the San Luis Basin from 1995 to 2005.

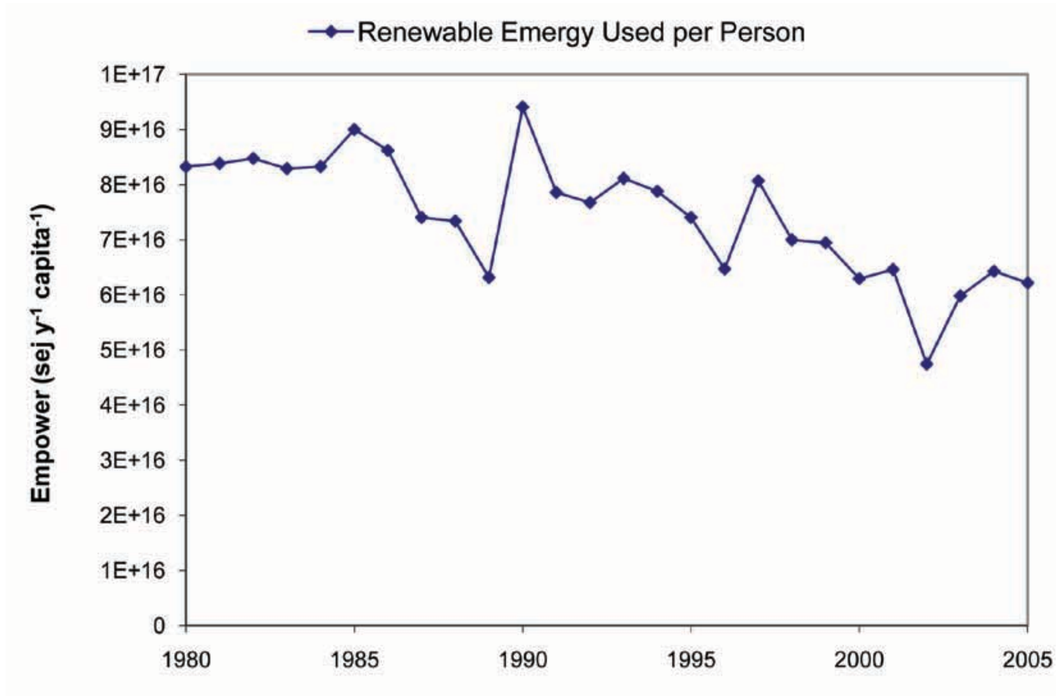

Figure 5.8 – The renewable emergy used per person in the SLB region from 1980 to 2005.

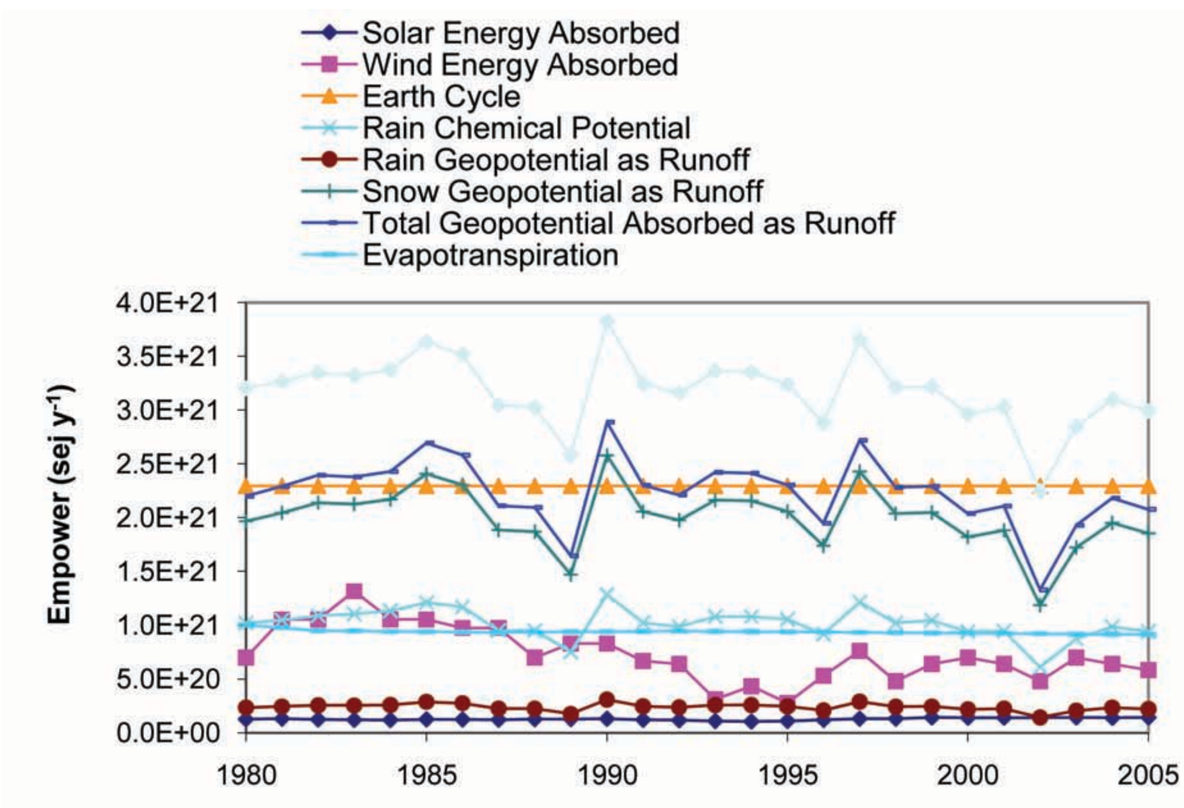

Figure 5.9 – The renewable emergy inputs to the San Luis Basin, 1980-2005.

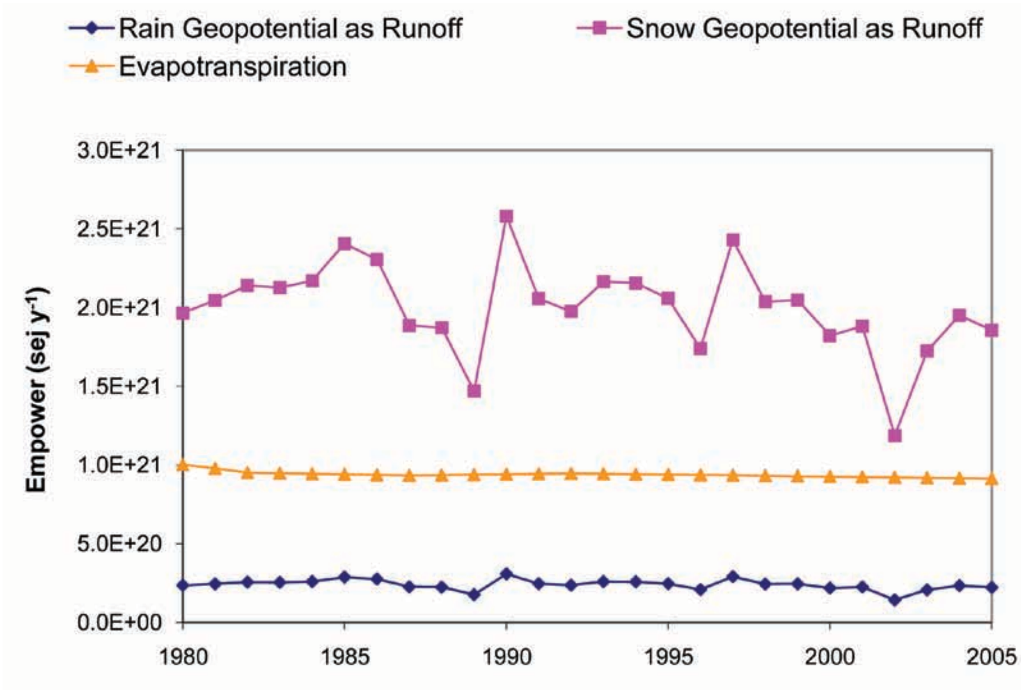

Figure 5.10 – The renewable emergy base for the San Luis Basin, 1980-2005.

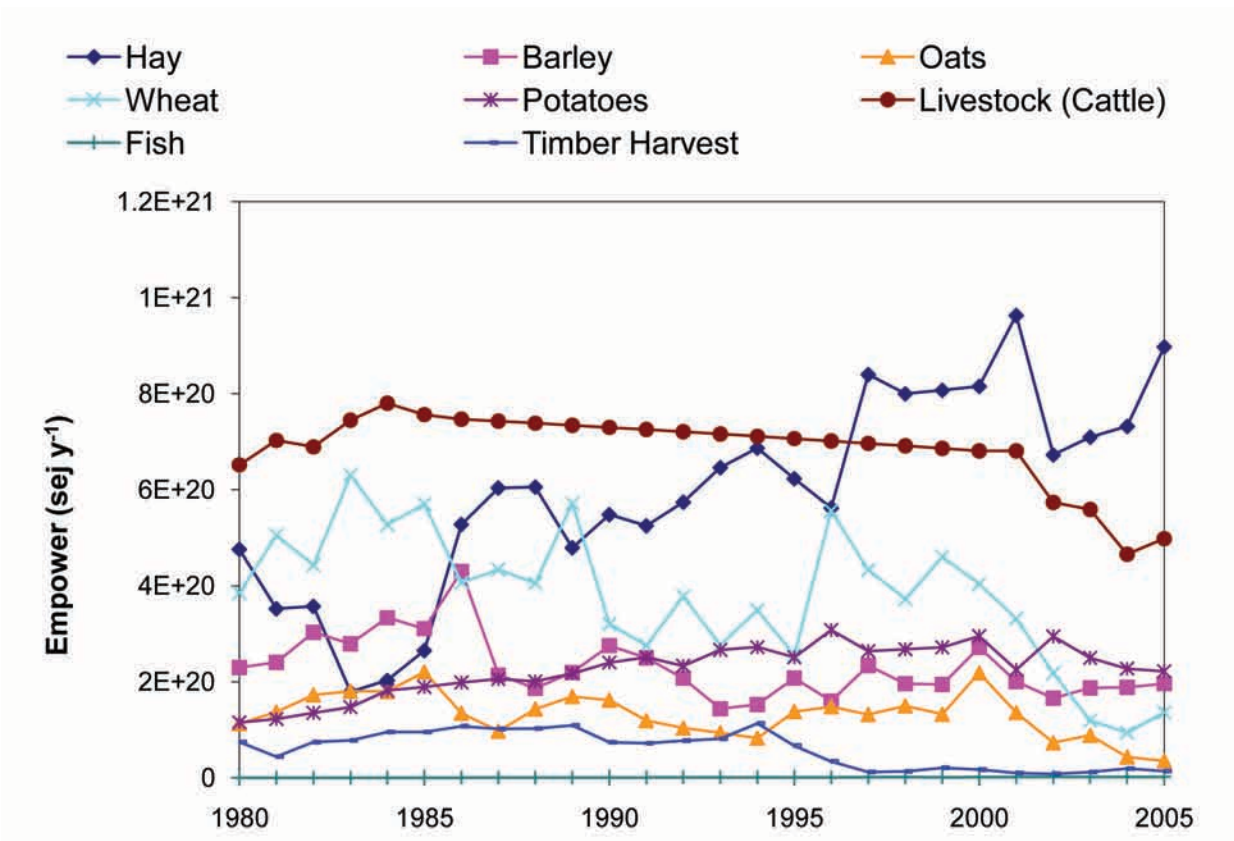

Figure 5.11 – Agricultural production in the San Luis Basin supported primarily by renewable resources, 1980-2005.

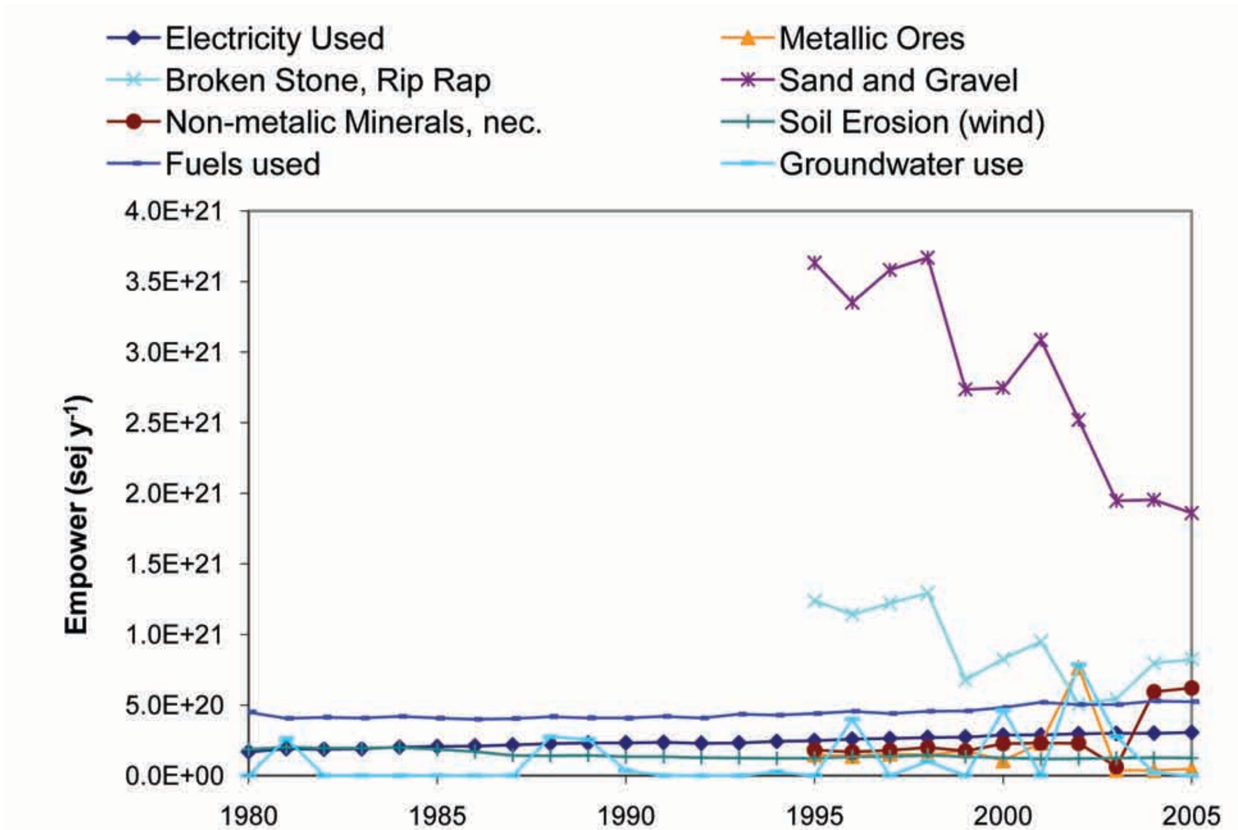

Figure 5.12 – Major categories of nonrenewable resources used and/or produced in the seven counties of the San Luis Basin, 1980-2005.

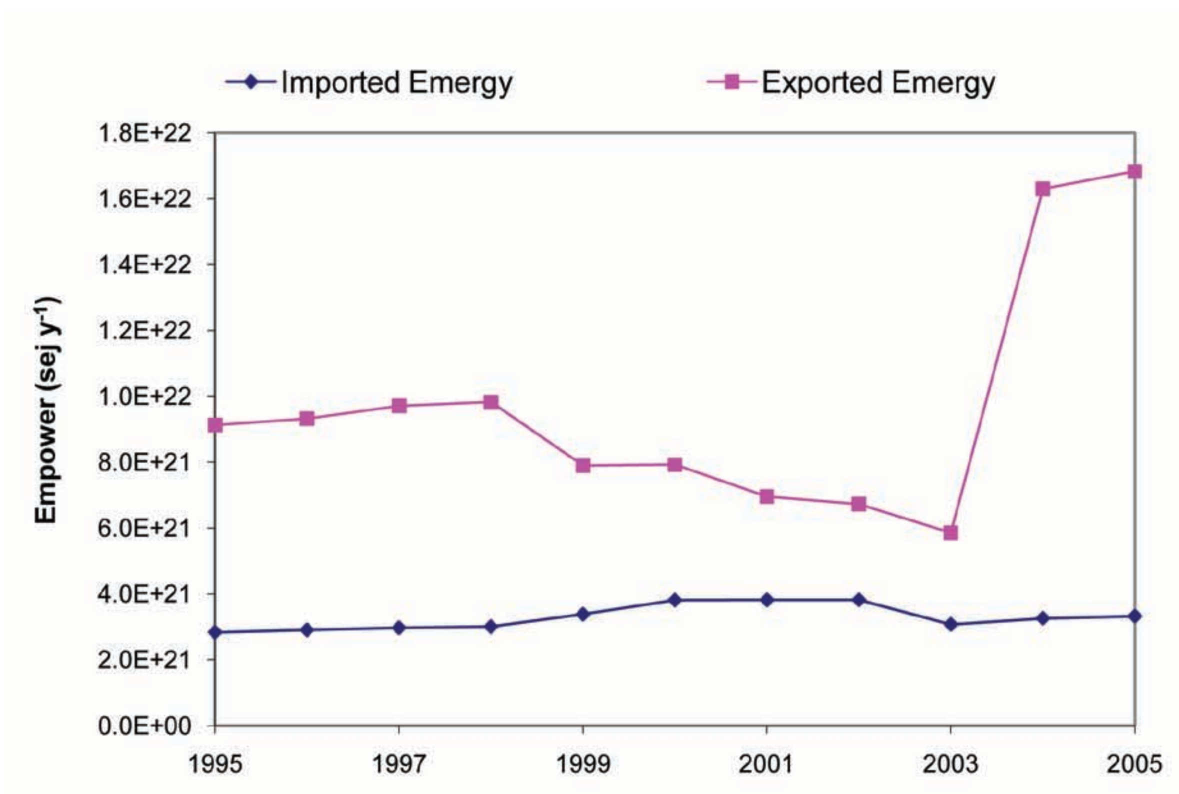

Figure 5.13 – The emergy exported from and imported to the San Luis Basin from 1995 to 2005.

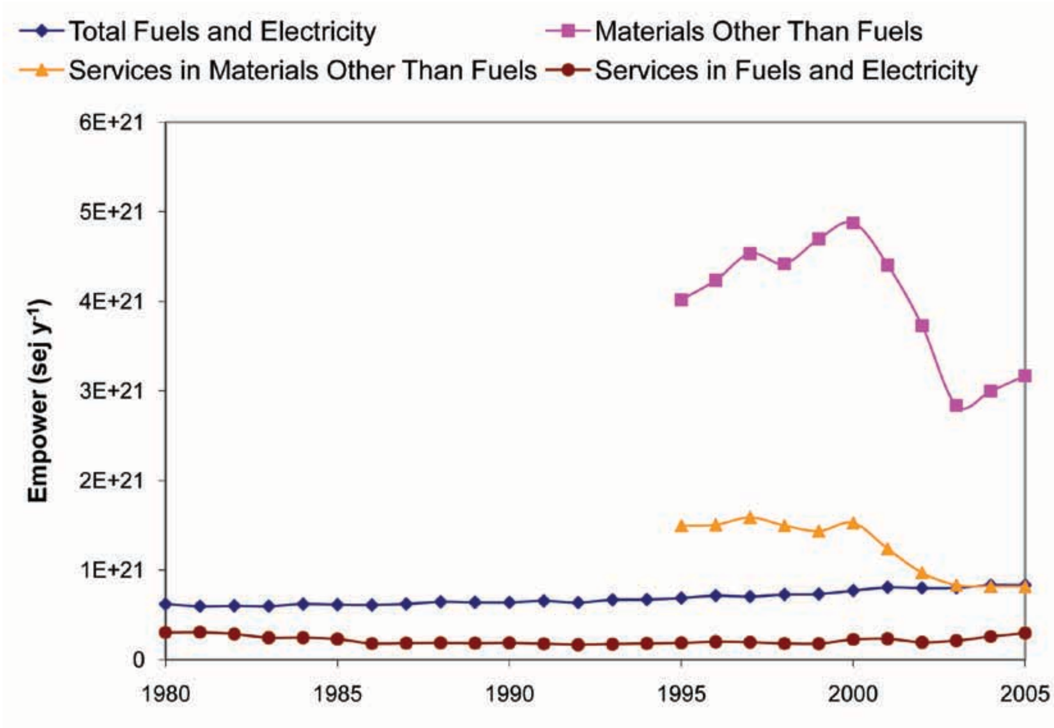

Figure 5.14 – Major categories of emergy imported into the San Luis Basin, 1980-2005.

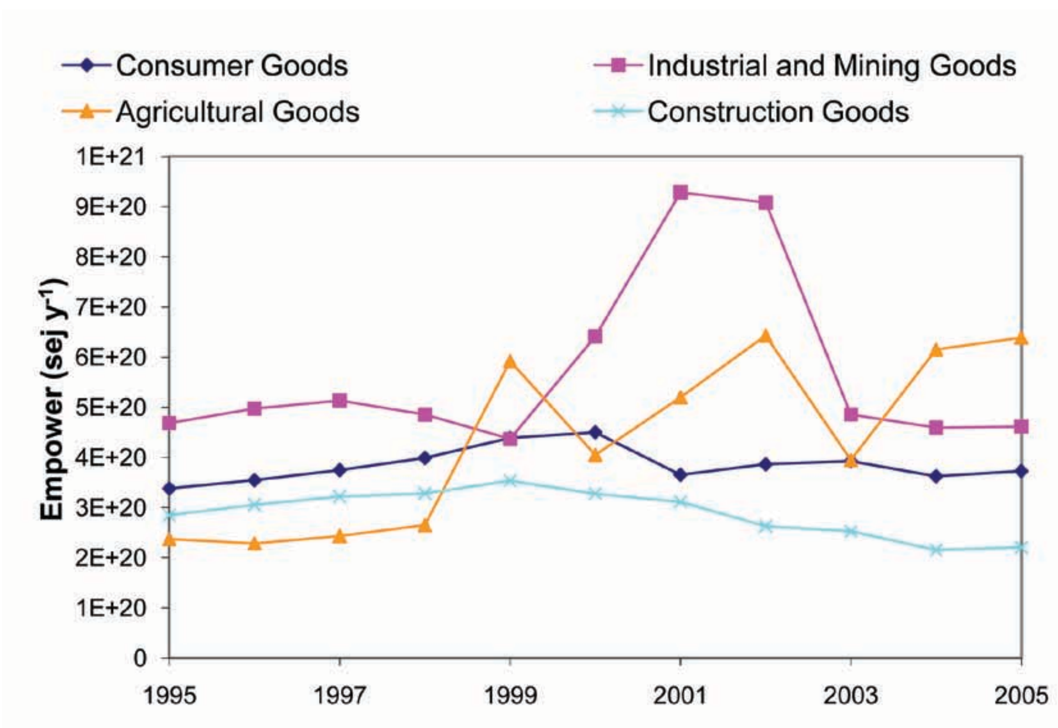

Figure 5.15 – The categories of material goods other than fuels imported to the SLB from 1995 to 2005.

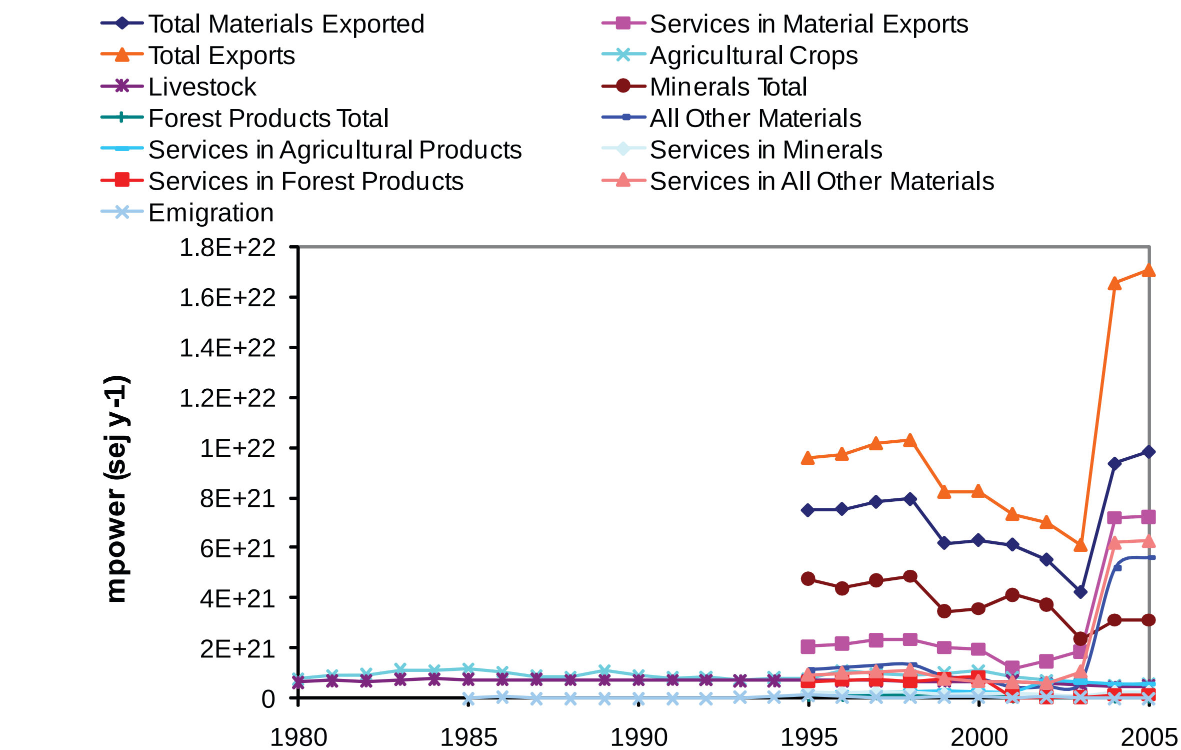

Figure 5.16 – Emergy exported from the San Luis Basin, 1980-2005: totals and aggregate categories Total exports include total materials and total services exported. Total materials exported includes agricultural and forest products, livestock minerals, and all other materials. Services in materials exported includes services in services in minerals, all other materials, agricultural and forest products. Export of pure services was not evaluated and emigration is shown, but was not included in the total.

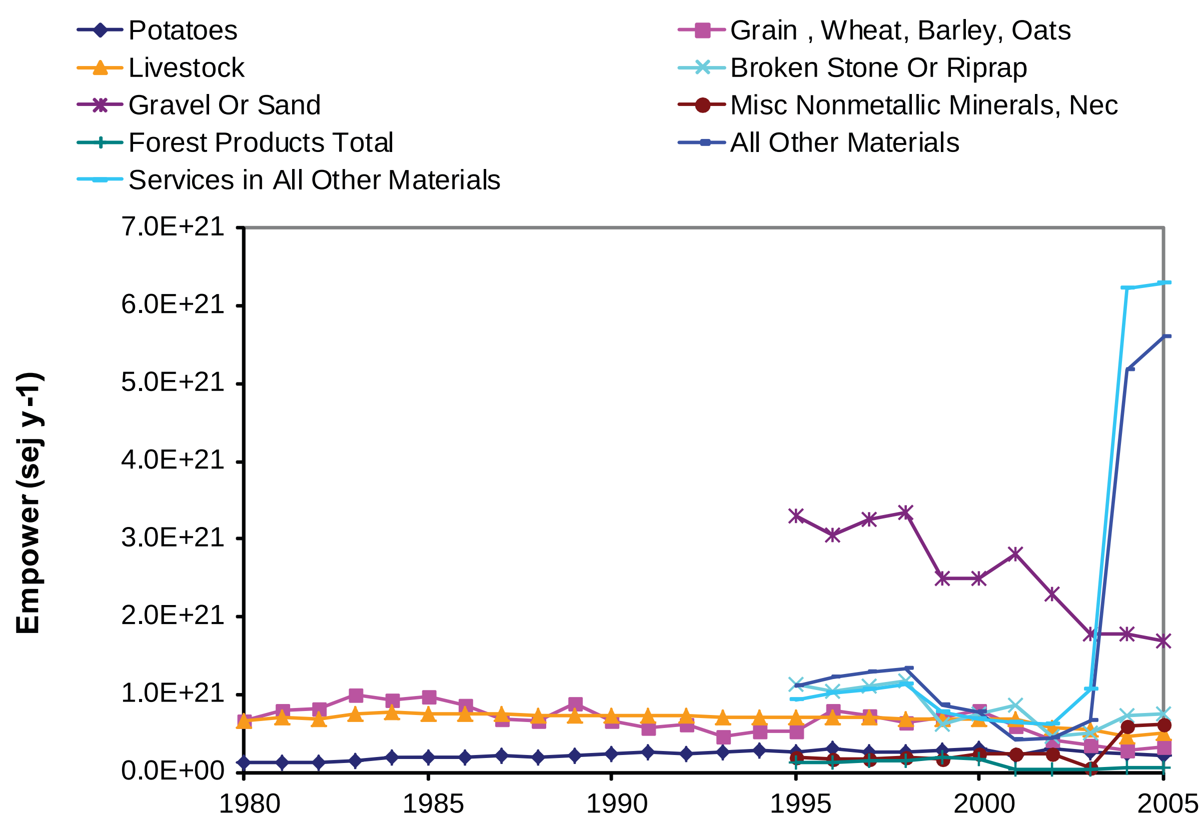

Figure 5.17 – Selected categories of agricultural, forest product, and mineral exports from the San Luis Basin, 1980-2005. The “All Other Materials” and the services in that category are shown to facilitate further discussion.

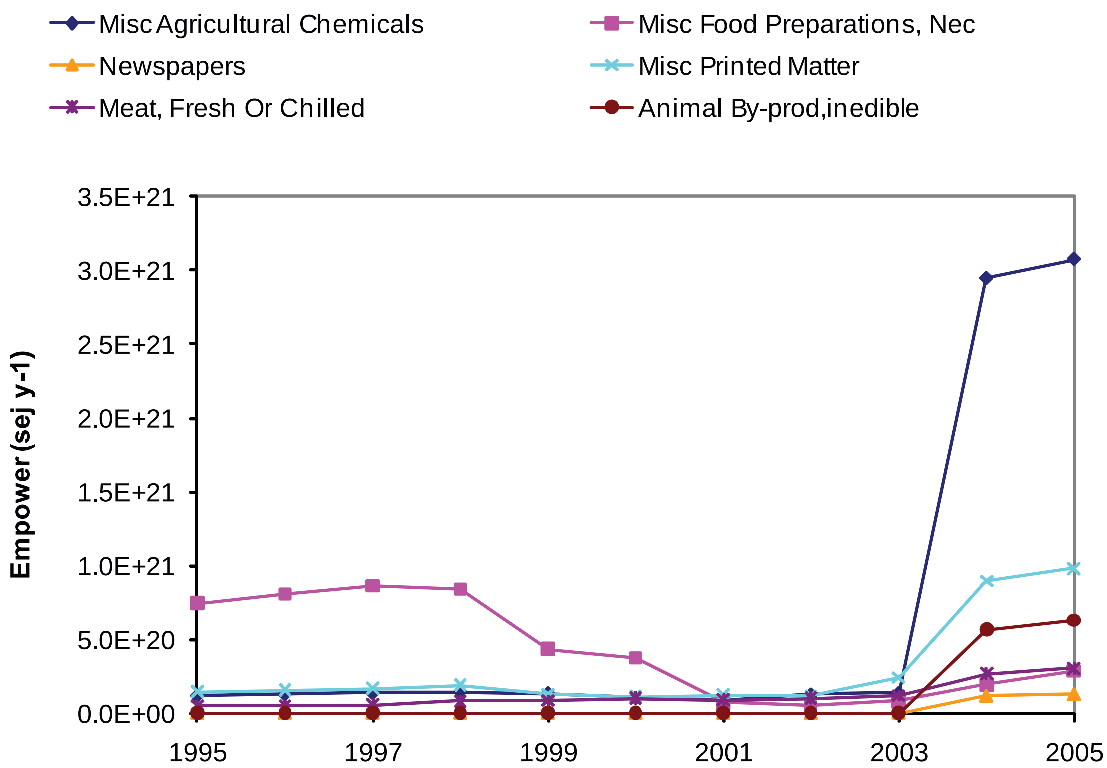

Figure 5.18 – The six largest classes of exports contained in "All Other Materials" exported from the San Luis Basin, 1995-2005.

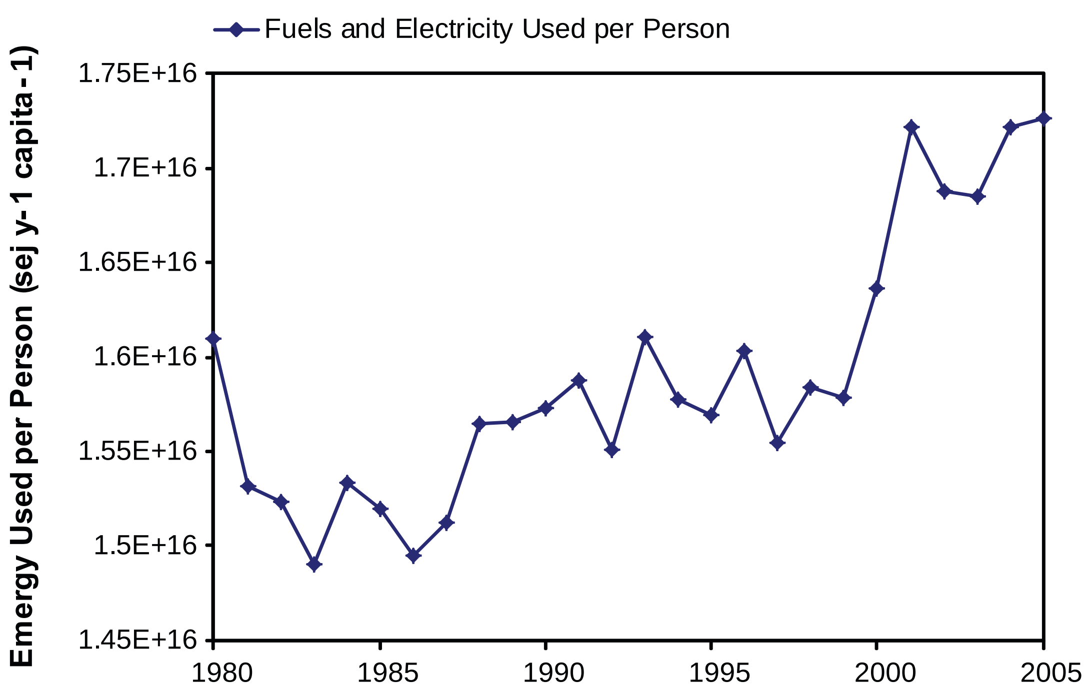

Figure 5.19 – The emergy of fuels and electricity used per person in the San Luis Basin from 1980 to 2005.

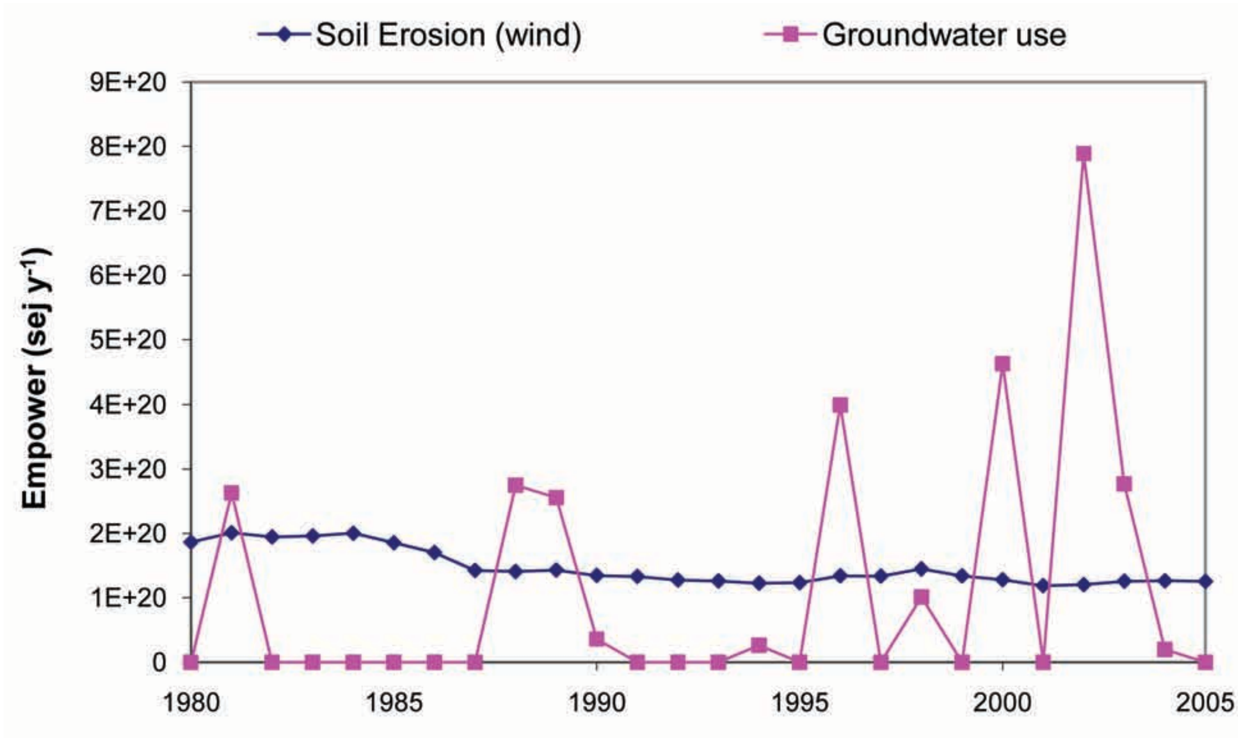

Figure 5.20 – Renewable emergy sources of the San Luis Basin (1980-2005) that are being used in a nonrenewable manner.

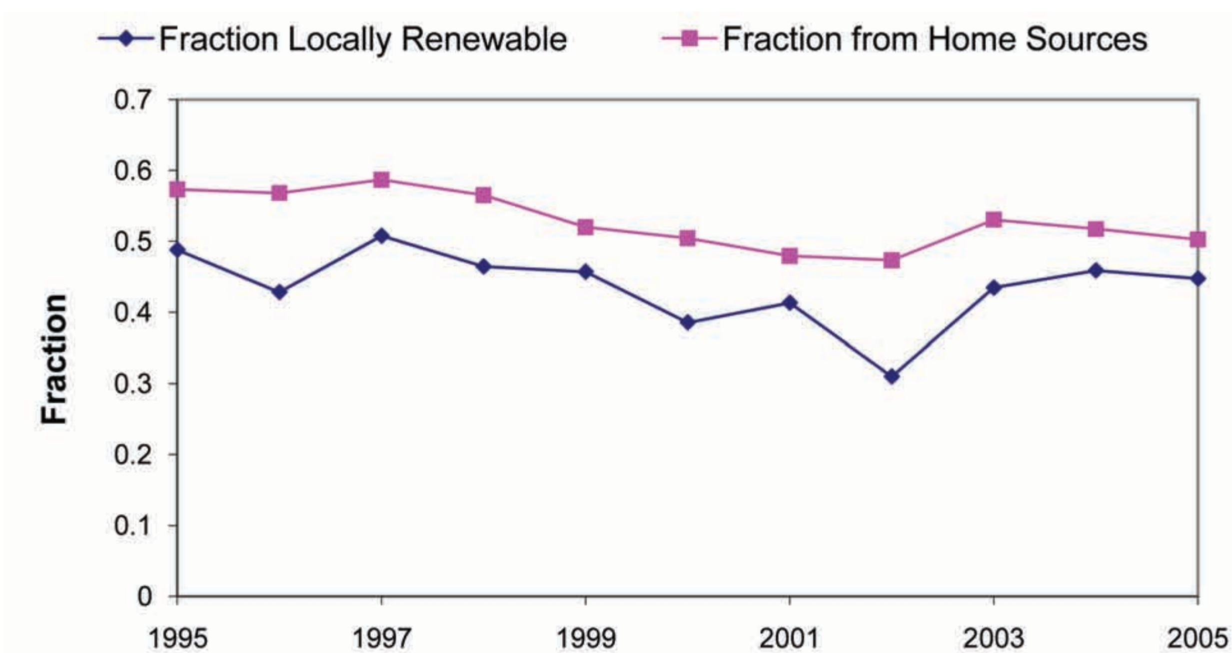

Figure 5.21 – The fraction of total emergy use that comes from local renewable emergy and the fraction of use from home sources in the San Luis Basin, 1995-2005.

Appendix 5-A: Detailed Steps for Emergy Analysis

An emergy evaluation of the SLB was performed in seven steps.

1. The spatial and temporal boundaries of the system under analysis were specified. System boundaries were chosen based on the research question to be answered, considering the issue to be studied.
2. A diagram of a detailed Emergy Systems Model was created using the Energy Systems Language (ESL; Odum 1971). The diagram represented the main features of the system components and flows that exist within the specified boundaries. Performance of the second step required prior study of the system and data gathering from the literature and from meetings with experts on the SLB.
3. Translated this knowledge of the system into an aggregated ESL diagram addressing the specific questions to be answered with the simplest possible model formulation. Simplification of the detailed model was done by aggregating components or flows of similar function, thus information was not discarded in this process.
4. Emergy analysis tables were set-up and descriptions of the system's sources, components, and pathways in the aggregated diagram were transferred to the tables where the calculations needed to evaluate these pathways quantitatively were compiled.
5. Gathered and assembled the raw data needed to complete the emergy analysis tables along with the conversion factors (energy contents, transformities, specific emergies, etc.) needed to convert the raw data into emergy.
6. After the raw data were converted into emergy, summary variables were defined and calculated using the aggregate diagram as a guide (Lu et al. 2007, Odum 1996).
7. Calculated emergy indices representing various aspects of system structure and function and interpret the meaning of these indices relative to our knowledge of their values in other systems. The methods used to carry out an emergy analysis of West Virginia and Minnesota are presented in detail in two recent EPA publications, Campbell et al. (2005) and Campbell and Ohrt (2009).

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Campbell, D.E., Ohrt, A. 2009. Environmental accounting using emergy: evaluation of Minnesota. USEPA Project Report, EPA/600/R-09/002, 138 pp.

Lu, H.F., Campbell, D.E., Chen, J., Qin, P., Ren, H. 2007. Conservation and economic vitality of nature reserves: an emergy evaluation of the Yancheng Biosphere Reserve. Biological Conservation 139, 415-438.

Odum, H.T. 1971. An energy circuit language for ecological and social systems, in: Patten, B. (Ed.), Systems Analysis and Simulation in Ecology, Vol. 2, Academic Press, New York, pp. 139-211.

Odum, H.T. 1996. Environmental Accounting: Emergy and Environmental Decision Making. John Wiley & Sons, New York.

Appendix 5-B: Additional Indices Calculated for the Emergy Analysis of the San Luis Basin

We present revised definitions for two aspects of the relationship between a socioeconomic system and its associated larger systems. First, the Emergy Yield Ratio (EYR) for a local system, often characterized as U/F, is redefined as Y/F (see original definition in Odum, 1996), where Y or yield is equivalent to exports of the socioeconomic system. Second, the ratio formed by the total emergy flow in the system (U) and the feedback (F) from the larger system is defined as the Local Effect of Investment (LEI) or the effect of feedback from the larger system on the local system's empower. This ratio is different from existing energy investment ratios , which look at the matching between purchased feedbacks and local renewable and nonrenewable resources. Table 5-B.1 and Fig. 5-B.1 present some emergy indicators and indices used in the analysis of the sustainability of regional environmental systems.

The EYR for the SLB was defined to be the emergy value of the exports divided by the feedback from the larger system, which in this case is represented by imports. This definition is more consistent with the original conception of the EYR (Odum 1996), which was used to characterize a production process, rather than with the commonly used definition of the EYR for a state nation, or region as the ratio of total system emergy use (U) divided by the feedback from the larger system. In this case, exports are the productive yield to the larger system received from the local system, thus the ratio of exports to imports is more appropriately termed the EYR of a regional system. The ratio of U to the feedback from the larger system is redefined as the local effect of investment, LEI, which represents the local changes in empower that result from investments by the larger system in the local system. It captures the local empower return on investment and as such it is a measure of the change in well-being of the local system as a function of emergy invested by the larger system. The redefined indices more accurately characterize both indices based on their function and lead to logical inferences about the welfare of both local and larger systems (Campbell 2008).

The Emergy Sustainability Index (ESI; Brown and Ulgiati, 1997) of the SLB is determined according to the variation of its two components, the EYR and the Environmental Loading Ratio (ELR; Fig. 5-B.2). Trends in these indices show that a slow increase in environmental loading combined with a slow decline in the EYR resulted in declining sustainability from 1997 until 2002. After 2002, the ELR falls rapidly as the EYR increased rapidly resulting in a 5-fold increase in the ESI from 0.79 in 2002 to 4.1 in 2005.

The balance of total emergy inflow and outflow is a new index, which we calculated for this study. It characterizes the macroscopic emergy balance by including all inflows and outflows across the system borders including the renewable emergy. It gives an overall balance of inflows and outflows, which one might expect to be approximately balanced for a system in a dynamic steady state. Although this flow is not large compared to the others evaluated in this study, the index in its current form does not include the emergy of water flowing out of the system as an outflow of renewable emergy. The pattern of this index shows that outflows exceed inflows in most years except in 2001 and 2003 when the two are nearly in balance. This situation is in contrast to the export-import balance for which outflows always exceed inflows by a considerable margin. Internal resources used are not included in the inflows to the system, but can show up in outflow; thus, when outflow markedly exceeds inflow, it may indicate that capital storages within the system are being depleted.

The ESI characterizes sustainability as the ratio of the EYR to the ELR, thus it has high values when the larger system receives larger yields from its investment in the local system, and when the intensity of nonrenewable emergy use to attain those yields is less. The ESI was above 2 in eight of the eleven years evaluated, which indicates the SLB would be classified as a sustainable system within the context established by Brown and Ulgiati (1997) and subsequent studies. However, the fact that this index falls below 2 from 2001 to 2003 raises concern the system may become less sustainable in the future. The ELR increased to a maximum in 2002 as the EYR declined to a minimum in the same year resulting in minimum sustainability in that year. The year 2002 was a drought year in which the system was supported by a large, unsustainable use of groundwater, and after this time the ESI increased rapidly as a result of a large increase in EYR (i.e., during this period, for almost the same inputs of emergy from the larger system, there was a marked increase in the emergy of exports to the larger system). This increase could only come either from the system's internal resources or from additional value added to imports by the improved application of local labor. Over the course of the 11 years examined, this index showed the system was moving toward sustainability, but this trend was determined entirely by the upsurge of exports in the final three years of the study.

A final index of the relative sustainability of the SLB is the renewable carrying capacity of the system (Table 5.4). This index shows the system had the potential to support 21520 people out of the current (2005) population of 48101 at their present standard of living using renewable emergy inflows alone. This assumes that these inflows have not been further upgraded to support socio-economic activities (e.g., by generating electricity from solar or wind power). During the 11-year period examined, there was a 4% decline in the renewable carrying capacity of the SLB from 48.7% to 44.7% of the current population, but in 2002 only 31% of the people in the SLB could have been supported by the renewable emergy that was available in that year. This index shows the SLB was moving away from sustainability over the period examined and although the decline was moderate, it could become worse, if the natural precipitation regime is altered by regional climate change in a similar manner to that predicted for the State of New Mexico (2005). The percent renewable emergy used is the most important factor determining this index and thus the two indices give related results.

Another look at system well-being is shown by the relationship between EYR, ESI, and LEI (Fig. 5-B.2). EYR is in an overall declining trend from 1998 until 2002, and ESI and LEI are in a declining trend from 1997 until 2002. Between 2002 and 2005, the EYR increased 2.87 times, the ESI increased 5.18 times, and the LEI increased 1.06 times. Although the EYR and ESI recover strongly after 2002, the total emergy use in the local system increases only slightly. The ESI, EYR, and LEI reflect the relative advantages and disadvantages that may exist in the relationship between the SLB and its larger system trading partners (imports). The pattern of the EYR and the ESI shows large benefits accruing to the larger system in the economic recovery that took place in the region from 2002 to 2005, but the LEI indicates that this increase resulted in only a slight increase (6%) in the efficacy of external investments in the region in increasing well-being in the SLB.

The EYR shows the benefit to the larger system and ranged from a low of 1.76 times the emergy invested in 2002 to a high of 5.06 in 2005. From 1995 to 2005, the LEI shows that about 2 times the invested emergy flow was stimulated in the SLB by each unit of emergy invested from outside. This multiplier remained positive (1.90 to 2.42) over the 11-year time period and thus investment from the larger system has improved local well-being over the entire time.

An examination of other emergy indices of sustainability indicated there was a movement away from sustainability in the SLB over the period from 1995 to 2005. Renewable emergy use declined 4% over the 11-year study period and approximately half of the present population could be supported at their current standard of living on renewable emergy alone. The ESI, which increased 34% from 1995 to 2005, provided perspective on the relationship between the SLB and its larger systems. From our results, it appears the SLB and its larger systems go through cycles of improving and declining sustainability and that pulsing apparently plays a role in this variability.

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Table 5-B.1 – Some emergy indicators and indices used in the analysis of the sustainability of regional environmental systems. Symbols and expressions refer to Fig. 5-B.1.

Name of Index	Symbol or Expression	Definition
Total Emergy Flow	U	Empower (emergy/time) of the regional network. A measure of the local system's well-being.
Renewable Emergy Inflow Absorbed	R_A	Renewable emergy inputs to the system without double counting.
Percent renewable	R_A/U	A measure of the potential for sustainability of the present system.
Feedback or investment from the larger system	F = M + S	Feedback is the sum of material, M, and service, S, feedbacks.
Local Effect of Investment (LEI)	U/F	Effect of external investment on system empower.
Yield	Y	For a regional system Y is equivalent to exports, i.e., yield to larger systems.
Emergy Yield Ratio (EYR)	Y/F	Emergy return to the larger system on its investments. Y is equal to exports in the case of a local system and F is equivalent to imports.
Nonrenewable Emergy Inflow	N, N_0	N, nonrenewable, i.e. fossil fuels, N_0, renewable sources being used in a nonrenewable manner, e.g., soil or groundwater used faster than their replacement rate.
Environmental Loading Ratio (ELR)	$(F+N+N_0)/R$	Potential effect of nonrenewable emergy use on the environment
Emergy Sustainability Index (ESI)	EYR/ELR	In this index sustainability increases with greater returns to the larger system and decreases with greater potential for environmental damage to the local system.

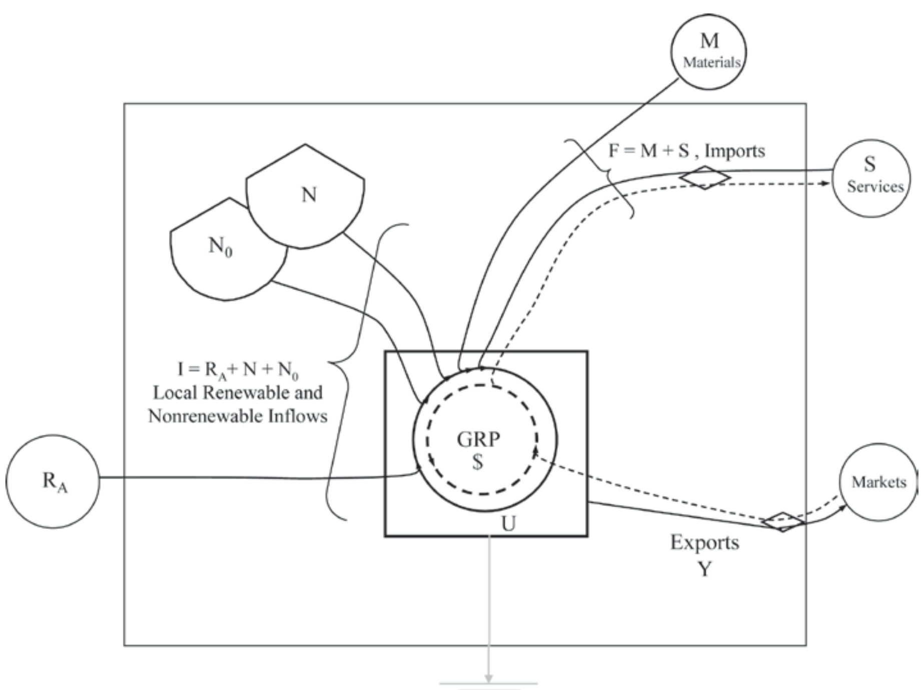

Figure 5-B.1 – An Energy Systems Diagram used to define the emergy indices (Table 5-B.1) to assess regional sustainability.

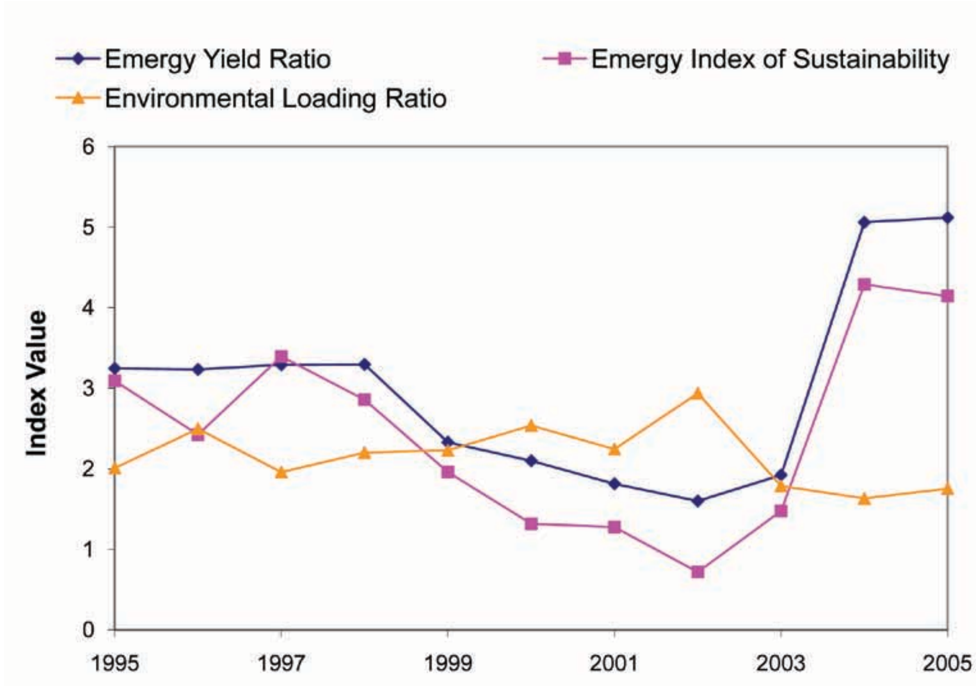

Figure 5-B.2 – The Emergy Sustainability Index (ESI = EYR/ELR) and its components the emergy yield ratio (EYR) and the Environmental Loading Ratio (ELR) in the San Luis Basin from 1995 to 2005.

Appendix 5-C: Calculating Emergy per Unit Factors

To calculate emergy units, data are converted first to energy or mass units and then into emergy units by multiplying the values by the appropriate coefficients (the emergy per unit values). When only the transformity (emergy per unit available energy) of a quantity was available and the variable was given in units of mass, it was first converted to energy by multiplying by the energy per unit mass. Then it was converted into emergy by multiplying by the transformity. Quantities were aggregated by similar function into composite variables considered most important for defining key interactions. An example of the calculation process follows: crop production is reported as bushels of grain harvested. The bushels of a particular crop are converted to mass by multiplying by the average dry weight of a bushel of that type of grain. The mass of grain is converted to energy by multiplying by the energy content in joules per gram dry weight (gdwt). Next, the energy content of the grain is converted to emergy by multiplying by the transformity. Finally, the emergy of all grain crops are summed to obtain the total emergy of grain production.

Accounting units of mass and volume are most often used to record the physical quantity of items used by society. Other physical units may be used for environmental data (e.g., velocity for wind, energy flux for solar radiation, heat flux for geothermal energy, etc.). In almost all cases, these original units can be converted to energy or mass using readily available formulae and/or average conversion factors (Campbell and Ohrt 2009). The mass of a bushel of wheat and the energy content of a gram of wheat are examples of conversion factors that can easily be found in the literature, the transformity of a joule of wheat, although available in the emergy literature, might be harder to find for the average investigator. The energy content of many items has been widely tabulated, but a similar compendium of transformities and other emergy per unit factors does not exist at the present time. Therefore, in any emergy evaluation, the investigator will invariably have to calculate transformities for certain items. The first choice is to determine the transformity in the context of the production system of the item used in the system under study. If this information is not available, the emergy per unit values may be determined by analyzing a fast and efficient production process (i.e., one operating at the optimum efficiency for maximum power; see Odum and Pinkerton 1955) for the item. If the production process is unknown or not easily documented, transformities may be determined using one of the ten methods given in Odum (1996). The emergy per unit factors used in this study are given in Tables 5-C.1 to 5-C.3. This appendix contains the derivation and assumptions used for new and revised emergy per unit calculations that were needed to complete this study.

Table 5-C.1 – Emergy per Unit Factors (solar transformities and specific emergies) used in the San Luis Basin study. The units for the emergy per unit factors are solar emjoules per joule (sej/j) for transformities unless otherwise noted.

Item	Emergy/ unit#	Adjustment Ratio†	Adjusted Transformity
Renewable Emergy Inflows			
Solar energy reaching the surface of the earth by definition	1	1	1
Solar energy absorbed	1.21	1.21	1.21
Kinetic Energy of Wind (Odum 1996)	1496	0.9809	1467
Earth Cycle Energy (Odum 1996)	34377	0.9809	33720
Rain, Chemical Potential (Odum 1996, Campbell 2003a)	18200	NA	18100
Chem. Potential Energy of Evapotranspiration (Campbell 2003a)	NA	NA	28100
Rain, Geo-Potential on Land (Odum 1996 Campbell 2003a)	10488	0.9809	10100
Snow, Geo-Potential on Land (Campbell and Ohrt 2009)	1.03E+05	0.9809	1.01E+05
Rain, Geo-Potential Runoff (streams) (Odum 1996)	27764	0.9809	27200
Snow, Geo-Potential Runoff (Campbell and Ohrt 2009)	1.03E+05	0.9809	1.01E+05
Wave Energy (Lake Superior) (Campbell and Ohrt 2009)	30550	0.9809	30000
Rivers, Chemical Potential (Odum 1996, Campbell 2003a)	48459	NA	50100
Rivers, Geo-potential (Odum 1996)	27764	0.9809	27200
Nitrogen Deposition ammonia (Odum 1996) sej/g	3.9E+09	0.9809	3.8E+09
Adjusted from calculations made using the 15.83 baseline			
NH_3 (Campbell 2003b) sej/g	2.4E+09		
NO_x (Campbell 2003b) sej/g	1.2E+10		
Ammonia (Campbell 2003b) sej/g	NA	NA	1.4E+09
NO, NO_2, NO_3 (Campbell 2003b) sej/g	NA	NA	6.8E+09
Sulfur Deposition S transformity (Campbell and Ohrt 2009) sej/g	NA	NA	1.58E+11
Chloride Ion, Cl^-, Deposition (Campbell and Ohrt 2009) sej/g	NA	NA	1.31E+10
Renewable Products			
Agricultural Crops (without services, listed below)			
Hay (Campbell et al. 2005); see also Brandt-Williams (2002) sej/g	NA	NA	7.39E+08
Wheat (Campbell and Ohrt 2009) sej/g	NA	NA	2.88E+09
Barley (average of Oats and Wheat) sej/g	NA	NA	3.46E+09
Oats (Campbell et al. 2005; see also Brandt-Williams 2002) sej/g	NA	NA	4.05E+09
Potatoes, (Campbell et al. 2005; see also Brandt-Williams 2002) sej/g	NA	NA	2.32E+08
Livestock (Odum et al. 1998)	2.00E+06	0.9809	1961800
Beef (Brandt-Williams 2002)	5.64E+05	0.9809	553228
Fish Production (Odum et al. 1998)	2.00E+05	0.9809	1961800
Hydroelectricity (Odum 1996)	1.23E+05	0.9809	120258
Net Timber Growth (Tilley 1999)	2.10E+04	0.9809	20599
Timber Harvest with Service (Tilley 1999)	7.00E+04	0.9809	68663
Ground Water (Odum et al. 1998)	1.62E+05	0.9809	159068

- Emergy per unit values calculated on the 15.83 E24 sej/y baselines can be converted to the 9.26 line by multiplying by 0.585. † - The adjustment ratio converts values calculated using the 9.44 E24 sej/y planetary baseline to their values on the 9.26 E24 sej/y baseline used in this study and recommended by Campbell et al. (2005).

Item	Emergy/ unit[#]	Adjustment Ratio[†]	Adjusted Transformity
Solid Waste Production (Brown & Buranakarn 2000) sej/g	6.40E+09	0.9809	6.28E+09
Cement with fly ash	1.40E+10		
Concrete recycled aggregate	4.82E+09		
Recycled steel	3.09E+09		
Recycled aluminum	1.20E+10		
Recycled lumber	3.22E+09		
Lumber from recycled plastic	5.58E+09		
Tile from glass	2.16E+09		
Average for Solid Waste	6.40E+09		
Nonrenewable Inflows			
Energy			
Coal (Odum 1996, Campbell and Ohrt 2009)	4.00E+04	NA	3.78E+04
Geologic processes. 9.44E24 sej/y baseline	3.40E+04		
Relative efficiency in electricity generation	4.30E+04		
Average	3.85E+04		
Rounded value commonly used.	4.00E+04		
Natural Gas (Odum 1996, Bastianoni et al. 2005)	4.80E+04	NA	4.35E+04
Geologic processes. 9.26 baseline	4.00E+04		
Relative efficiency. 9.44 baseline	4.80E+04		
Average on the 9.26 baseline	4.35E+04		
Crude Oil (Odum 1996, Bastianoni et al. 2005)	5.40E+04	NA	5.42E+04
Geologic processes. 9.26 baseline	5.54E+04		
Relative efficiency. 9.44 baseline	5.40E+04		
Average on the 9.26 baseline	5.42E+04		
Electricity from coal (Campbell et al. 2005, Odum 1996)	1.74E+05	0.9809	1.70E+05
Minerals			
Iron Ore (Odum 1996)	6.20E+07	0.9809	6.08E+07
Sand and Gravel (Campbell et al. 2005) sej/g	NA	NA	1.31E+09
Limestone (Odum 1996) sej/g	1.00E+09	0.9809	9.81E+08
Dolomite (Campbell and Ohrt 2009)	NA	NA	1.98E+07
Dolomite (Campbell and Ohrt 2009) sej/g	NA	NA	1.08E+10
Peat (Odum 1996) sej/g	3.60E+08	0.9809	3.53E+08
Granite (Odum 1996) sej/g	5.00E+08	0.9809	4.90E+08
Clay (Odum 1996) sej/g	2.00E+09	0.9809	1.96E+09
Sandstone (Odum 1996) sej/g	1.00E+09	0.9809	9.81E+08
Alumina/Bauxite (Odum 1996)	1.50E+07	0.9809	14713500
Soil Erosion, top soil, (Odum 1996)	74000	0.9809	72600
Tourism (dollars) (Campbell and Lu 2009)	NA	NA	2.60E+12

Item	Emergy/ unit[#]	Adjustment Ratio[†]	Adjusted Transformity
Tourism (virtual) (calculated this study)	NA	NA	4.60E+12
Uranium (Cohen et al. 2007) sej/g	1.6 E+11	0.585	9.36E+10
Electricity from Uranium (Campbell and Ohrt 2009)	NA	NA	4.81E+04
Imported Goods			
Petroleum (refined) (Odum 1996, Bastianoni et al. 2009)	6.60E+04	NA	6.58E+04
Fuels (services for 2000) (Campbell and Lu 2009)	NA	NA	2.35E+12
Electricity (services 2000) (Campbell and Lu 2009)	NA	NA	2.35E+12
Services (2000) (Campbell and Lu 2009)	NA	NA	2.35E+12
Federal Government (spent in US) (Campbell and Lu 2009)	NA	NA	2.35E+12
Goods w/o iron ore and fuels (materials)	NA	NA	Variable
Iron ore as taconite (Campbell and Ohrt 2009) sej/g	NA	NA	3.61E+09
Steel (Brown and Buranakarn 2000) sej/g	3.45E+09	0.9809	3.38E+09
Wood and Wood Products	NA	NA	
Lumber and Wood Products, (Tilley 1999)	NA	NA	7.90E+04
Furniture and Fixtures	NA	NA	
Paper Products, (Campbell and Cai 2007)	NA	NA	2.22E+05
N fertilizer, (Odum 1996) sej/g	3.80E+09	0.9809	3.73E+09
P fertilizer, (Odum 1996) sej/g	3.90E+09	0.9809	3.83E+09
Potash, (Odum 1996) sej/g	1.10E+09	0.9809	1.08E+09
Storages			
Forests (Tilley 1999)	NA	NA	28234
Water, lakes (Campbell and Ohrt 2009).	NA	NA	1.81E+04
Soil (Top soil) (Odum 1996)	74000	0.9809	72600
Iron ore (Campbell and Ohrt 2009)	6.20E+07	0.9809	6.08E+07
Iron (specific emergy) sej/g	1.20E+10	0.9809	3.51E+09
Peat (Odum 1996)	1.90E+04	0.9809	1.86E+04
Sand & Gravel (Campbell et al. 2005) sej/g	NA	NA	1.31E+09
Limestone (Odum 1996)	1.00E+09	0.9809	9.81E+08
Dolomite (Campbell and Ohrt 2009) sej/g	NA	NA	1.08E+10
Nickel (Campbell and Ohrt 2009) sej/g	2.00E+11	0.9809	2.55E+10
Copper (Campbell and Ohrt 2009) sej/g	9.80E+10	0.9809	1.14E+11
Platinum (Campbell and Ohrt 2009) sej/g	3.70E+11	0.9809	1.13E+11
People (Odum 1996) sej/individual	NA	NA	NA
Preschool sej/individual	3.40E+16	0.9809	3.34E+16
School sej/individual	9.40E+16	0.9809	9.22E+16
College Grad sej/individual	2.80E+17	0.9809	2.75E+17
Post-College sej/individual	1.31E+18	0.9809	1.28E+18
Elderly (70+) (Campbell et al. 2005) sej/individual	NA	NA	1.69E+17

Item	Emergy/ unit#	Adjustment Ratio†	Adjusted Transformity
Public Status sej/individual	3.93E+18	0.9809	3.85E+18
Legacy sej/individual	7.85E+18	0.9809	7.70E+18
Emergy to Money Ratio for the United States (Campbell and Lu 2009) sej/$	Year	NA	
	1980	5.5421E+12	
	1981	4.9734E+12	
	1982	4.3017E+12	
	1983	3.7936E+12	
	1984	3.7571E+12	
	1985	3.5117E+12	
	1986	3.1773E+12	
	1987	3.1736E+12	
	1988	3.1685E+12	
	1989	2.9942E+12	
	1990	2.8753E+12	
	1991	2.6836E+12	
	1992	2.5672E+12	

Table 5-C.2 – Specific emergies for imports (sej/g). All commodity specific emergies are without services and relative to the 9.26E24 sej/y baseline. Values of the emergy per unit factors for the commodity classes in this table were determined from the data given in Table 5-C.1 and other data given in the calculations shown in Table 5-C.3. The note numbers connect to Table 5-C.3. Wwt = wet weight; otherwise numbers are dwt = dry weight.

Note	New Commodity Classes	Specific Emergy w/o services	Units
1	Fresh and Leafy Vegetables	3.58E+08	sej/g wwt
2	Fresh Fish or Whale Products	1.58E+10	sej/g wwt
3	Manganese Ores	3.50E+11	sej/g
4	Bituminous Coal	1.11E+09	sej/g
5	Natural Gasoline	2.92E+09	sej/g
6	Dimension Stone, quarry	8.17E+08	sej/g
7	Broken Stone or Riprap	4.90E+08	sej/g
8	Gravel, Sand	1.31E+09	sej/g
9	Clay and ceramics	1.96E+09	sej/g
10	Chemical or Fertilizer Mineral Crude	2.88E+09	sej/g
11	Meat, Fresh or Chilled	1.83E+10	sej/g wwt
12	Meat, Fresh Frozen	2.11E+10	sej/g wwt
13	Meat Products	2.28E+10	sej/g wwt
14	Animal By-product, inedible	9.87E+10	sej/g wwt
15	Poultry, fresh, frozen and processed and eggs	9.95E+08	sej/g wwt
16	Milk & Milk Products	3.19E+09	sej/g wwt
17	Canned or Cured Sea Foods	1.62E+10	sej/g
18	Fruit and Vegetables processed	3.19E+09	sej/g wwt
19	Frozen Specialties	1.22E+10	sej/g wwt
20	Flour or Other Grain Mill Products	3.36E+09	sej/g
21	Prepared or Canned Feed	5.07E+09	sej/g
22	Flour and meal	6.19E+09	sej/g
23	Dog, cat or Other Pet Food	5.24E+09	sej/g
24	Sugar and candy	1.33E+09	sej/g
25	Malt Liquors	1.65E+08	sej/g
26	Malt	3.46E+09	sej/g
27	Wine, brandy or Brandy Spirit	1.18E+09	sej/g
28	Distilled or Blended Liquors	5.68E+08	sej/g
29	Soft Drinks or Mineral Water	1.20E+08	sej/g
30	Misc Flavoring Extracts	7.10E+08	sej/g
31	Soybean Oil or By-products	3.11E+10	sej/g
32	Marine Fats or Oils	1.37E+11	sej/g
33	Macaroni, spaghetti, etc.	5.22E+09	sej/g
34	Miscellaneous Food Preparations	7.84E+09	sej/g
35	Men's or Boy's Clothing	1.41E+10	sej/g
36	Canvas Products	1.41E+10	sej/g

Note	New Commodity Classes	Specific Emergy w/o services	Units
37	Primary Forest Materials	3.77E+08	sej/g
38	Lumber + Sawmill	5.18E+08	sej/g
39	Millwork or Cabinetwork	7.78E+08	sej/g
40	Plywood or Veneer	2.11E+09	sej/g
41	Prefabricated & Structural Wood Products.	1.97E+09	sej/g
42	Treated Wood Products	2.02E+09	sej/g
43	Miscellaneous Wood Products	1.72E+09	sej/g
44	Mattresses Furniture	2.89E+09	sej/g
45	Pulp or Pulp Mill Products	7.28E+08	sej/g
46	Paper and Paper Products	4.26E+09	sej/g
47	Paper or Building Board	2.15E+09	sej/g
48	Newspaper and Printed matter	4.26E+09	sej/g
49	Potassium or Sodium Compound	7.45E+09	sej/g
50	Industrial Gases	9.63E+10	sej/g
51	Misc Industrial Inorganic Chemicals	2.75E+09	sej/g
52	Misc Indus Organic Chemicals	5.94E+09	sej/g
53	Plastic Matter or Synthetic Fibers	3.09E+09	sej/g
54	Fertilizers	2.88E+09	sej/g
55	Miscellaneous Agricultural Chemicals	1.45E+10	sej/g
56	Adhesives	3.73E+08	sej/g
57	Explosives	3.73E+09	sej/g
58	Chemical Preparations	7.45E+09	sej/g
59	Petroleum Refining Products	2.64E+09	sej/g
60	Liquefied Gases, Coal or Petroleum	3.11E+09	sej/g
61	Asphalt	2.64E+09	sej/g
62	Tires, Rubber Products	4.22E+09	sej/g
63	Plastic	4.13E+09	sej/g
64	Portland Cement	1.93E+09	sej/g
65	Brick, ceramics	2.15E+09	sej/g
66	Concrete Products	1.32E+09	sej/g
67	Ready mix concrete, wet	1.62E+09	sej/g
68	Lime or Gypsum Products	1.61E+09	sej/g
69	Non-metallic Minerals Processed	3.69E+09	sej/g
70	Blast Furnace Or Coke	2.12E+09	sej/g
71	Primary Iron or Steel Products	3.31E+09	sej/g
72	Electrometallurgical Products	6.64E+10	sej/g
73	Iron or Steel Shapes	3.31E+09	sej/g
74	Primary Aluminum Smelter Products	1.27E+10	sej/g
75	Copper or Alloy Basic Shapes	5.03E+10	sej/g

Note	New Commodity Classes	Specific Emergy w/o services	Units
76	Aluminum Or Alloy Basic Shapes	1.27E+10	sej/g
77	Miscellaneous Nonferrous Basic Shapes, Wire	3.15E+10	sej/g
78	Metal products	4.02E+09	sej/g
79	Industrial Machinery and motors	7.76E+09	sej/g
80	Carbon Products For Electric Uses	1.45E+11	sej/g
81	Household Machinery & Components	4.02E+09	sej/g
82	Electronics, precision instruments	1.91E+10	sej/g
83	Toys, Games, Sports, Household	5.43E+09	sej/g
84	Matches	8.68E+09	sej/g
85	Rubber or Plastic Scrap	4.17E+09	sej/g
86	Warehouse & Distribution Center	NA	
87	Rail International Drayage	NA	

Table 5-C.3 – Determination of the specific emergies for imported commodity classes in Table 5-C.2. All commodity specific emergies are without services and relative to the 9.26E24 sej/y baseline.

Notes	Commodity Class, Calculations	Source, Assumptions	Values	Units
1	Average for Vegetables given below	(Campbell and Ohrt 2009, Brandt-Williams 2002)	3.58E+08	sej/g
	Average of 6 vegetables.	Cabbages	2.29E+08	sej/g
		Tomatoes	3.25E+08	sej/g
		Cucumbers	2.59E+07	sej/g
		Green beans	9.68E+08	sej/g
		Bell Peppers	2.85E+08	sej/g
		Sweet corn	3.13E+08	sej/g
2	Fresh Fish Or Whale Products			
	Average of 3 species	Tilapia, (Brown et al. 1992)	5310	J/g
		Salmon, (Odum 2000)	6410	J/g
		Catfish, (Odum et al. 1998)	5650	J/g
		Avg. heat content fish	5790	J/g
		Tilapia	5.53E+05	sej/J
		Salmon	5.67E+06	sej/J
		Catfish	1.96E+06	sej/J
		Average specific emergy of 3 fish species	2.73E+06	sej/J
3	Manganese Ores	(Cohen et al. 2007)	1.58E+10	sej/g
4	Bituminous Coal	(Campbell and Ohrt 2009)	3.78E+04	sej/J
		Coal heat content	29400	J/g
		Specific Emergy	1.11E+09	sej/g
5	Natural Gasoline	(Bastianoni et al. 2009)	2.92E+09	sej/g
6	Dimension Stone		8.17E+08	sej/g
	Limestone	(Odum 1996)	9.81E+08	sej/g
7	Granite	(Odum 1996)	4.90E+08	sej/g
8	Sandstone	(Campbell et al. 2005)	9.81E+08	sej/g
	Average of 3 stones	Average	8.17E+08	sej/g
9	Clay	(Odum 1996)	1.96E+9	sej/g
10	Fertilizer		2.87E+09	sej/g
	N fertilizer	(Odum 1996)	3.73E+09	sej/g
	P fertilizer	(Odum 1996)	3.83E+09	sej/g
	Potash	(Odum 1996)	1.08E+09	sej/g
	Average		2.87E+09	sej/g

Notes	Commodity Class, Calculations	Source, Assumptions	Values	Units
11	Meat, Fresh or Chilled			
	Assume, average of beef and pork plus energy used in slaughter and cutting.	Beef, (Brandt-Williams 2002)	1.33E+10	sej/g
		Pork	2.01E+10	sej/g
		Hogs, (Cavalett et al. 2006)	1.28E+06	sej/J
		Hogs	15730	J/g
		Average	1.67E+10	sej/g
	Slaughter and cutting		1.54E+09	sej/g
	Estimate for Meat, Fresh or Chilled	(Carlsson-Kanayama and Faist 2000) http://www.infra.kth.se/fms/pdf/energyuse.pdf	1.83E+10	sej/g
	Meat Processing	Energy Use for Meat Processing		
		MJ/90 g (megajoules per 90 g)		
	slaughter, cutting	0.815	9056	J/g
	grinding, freezing	0.14	1556	J/g
	storage	1.375	15278	J/g
	frying or cooking	0.895	9944	J/g
	Total	3.225		
	Estimate Energy required for meat processing	Assume electricity is used for processing energy.	35833	J/g
12	Meat, Fresh Frozen			
	Add grinding, freezing and storage to 11.		2.87E+09	sej/g
13	Meat Products			
	add cooking and frying to above		1.69E+09	sej/g
			2.28E+10	sej/g
14	Animal By-product, inedible	Assume Beef carcass is 19% bone	0.185	
	Pig carcass is 18% bone and skin	Specific emergy	9.87E+10	sej/g
15	Poultry, fresh, frozen and processed and eggs	(Odum et al. 1998)	9.95E+08	sej/g wwt
16	Milk & Milk Products	Milking, cheese making	0.24	MJ/15 g
	(Carlsson-Kanayama & Faist 2000)	Storage	0.04	MJ/15 g
		Total	0.28	MJ/15 g
		Processing	3.18E+09	(sej/g wwt)
		Cheese	4.78E+09	(sej/g wwt)
		Milk	1.60E+09	(sej/g wwt)
		Average Milk and Cheese	3.19E+09	(sej/g wwt)
17	Canned Or Cured Sea Foods	Pickling	2297	J/g
	fish plus pickling		3.91E+08	sej/g

Notes	Commodity Class, Calculations	Source, Assumptions	Values	Units
18	Fruit and Vegetables processed	Oranges	1.37E+08	sej/g
	Oranges + freeze drying and pickling	Freeze drying	3.35E+04	J/g
	(Carlsson-Kanayama and Faist 2000)	Pickling	2.30E+03	J/g
		Average	1.79E+04	J/g
		Emergy	3.19E+09	(sej/g wwt)
19	Frozen Specialties		1.22E+10	sej/g wwt
	Average of Frozen Meat and Fruit and Vegetables Processed			
20	Flour or Other Grain Mill Products	Wheat	2.88E+09	sej/g
	Wheat + energy of milling	Milling	2.84E+03	J/g
	(Carlsson-Kanayama and Faist 2000)		3.36E+09	sej/g
21	Prepared or Canned Feed	Corn, (Brandt-Williams 2002)	8.53E+09	sej/g
		Soybean, (Brandt-Williams 2002)	6.19E+09	sej/g
		Sorghum, (Brandt-Williams 2002)	1.49E+09	sej/g
		Oats, (Brandt-Williams 2002)	4.05E+09	sej/g
		Average	5.07E+09	sej/g
22	Flour and meal			
	Average corn and wheat plus milling	Wheat	2.88E+09	sej/g
		Corn	8.53E+09	sej/g
		Milling	2838	J/g
			6.19E+09	sej/g
23	Dog, cat or other pet food	Corn, (Brandt-Williams 2002)	8.53E+09	sej/g
		Soybean, (Brandt-Williams 2002)	6.19E+09	sej/g
		Chicken	9.95E+08	sej/g
			5.24E+09	sej/g
24	Sugar and candy	(Odum et al. 1986)	16190	J/g
		Transformity	8.24E+04	sej/J
		Specific Emergy	1.33E+09	sej/g
25	Malt Liquors	Rain water sej/g (Campbell 2003a)	85740	sej/g
	Use fraction water, barley, and alcohol in beer	Beer composition (content)	0.9196	
		Alcohol content	0.06	
		Barley content	0.02	
	http://bioenergy.ornl.gov/papers/misc/energy_conv.html	Ethanol heat content	2.67E+04	J/g
		Transformity ethanol (Odum 1996)	58860	sej/J
		Specific emergy ethanol	1.57E+09	sej/g
		Emergy	1.65E+08	

Notes	Commodity Class, Calculations	Source, Assumptions	Values	Units
26	Malt	Use barley		
27	Wine, brandy or brandy Spirit	(Bastianoni et al. 2001)	3.41E+05	sej/J
		Wine	1.18E+09	sej/g
		Grapes	9.72E+08	sej/g
		Wine		
	Alternate estimate for wine	Water content	0.8658	
		Alcohol content	0.104	
		Grape essence	0.0302	
		factor (weight of grapes per weight of wine)	1.68	
		Water (fraction x specific emergy water)	7.42E+04	sej/g
		Alcohol (fraction x specific emergy alcohol)	1.64E+08	sej/g
		Grapes (fraction x factor* specific emergy grapes)	1.64E+09	sej/g
		Total Wine	1.80E+09	sej/g
28	Distilled or Blended Liquors	86 proof whisky (water content)	0.639	
		Alcohol by weight	0.361	
		Emergy	5.68E+08	sej/g
29	Soft Drinks or Mineral Water	water	0.9031	
	Fraction times specific emergy of ingredients	sugar	0.0897	
		Emergy	1.20E+08	sej/g
30	Miscellaneous Flavoring Extracts	Vanilla extract		
		Water	0.5258	
		Alcohol by weight	0.344	
		Sugar	0.1265	
		Emergy	7.10E+08	sej/g
31	Soybean Oil or By-products	Soybeans (Brandt-Williams 2002)	6.19E+09	sej/g
	http://www.ces.purdue.edu/extmedia/GQ/GQ-39.html	Fat content	0.1994	
		specific emergy soybean oil	3.11E+10	sej/g
32	Marine Fats or Oils	Oily fish avg. of herring, mackerel, Chinook salmon		
		Fraction oil	0.1155	
		Fish oil (energy content)	7710	sej/J
		specific emergy fish oil	1.37E+11	sej/g

Notes	Commodity Class, Calculations	Source, Assumptions	Values	Units
33	Macaroni, spaghetti, etc.	Bread making		
	Assume noodles are similar to bread.	Milling	0.21	mJ/74 g
	Wheat + emergy to process	Baking	0.725	mJ/74 g
	(Carlsson-Kanayama and Faist 2000)	Storage	0.08	mJ/74 g
		Milling	2838	J/g
		Baking	9797	J/g
		Storage	1081	J/g
		Total	13716	J/g
		Specific Emergy for processing	2.34E+09	sej/g
			5.22E+09	sej/g
34	Miscellaneous Food Preparations			
	Corn, soy, wheat, oats + emergy to process	Average	5.41E+09	sej/g
		Processing emergy as fraction of total	144.81%	
		Specific Emergy	7.84E+09	sej/g
35	Men's or Boy's Clothing	Cotton (Odum 1996)	1.41E+10	sej/g
36	Canvas Products	Cotton (Odum 1996)	1.41E+10	sej/g
37	Primary Forest Materials	Logs avg. soft and hardwood (Tilley 1999)	19620	sej/J
		Energy per gram dry weight.	19200	J/g
		Specific Emergy	3.77E+08	sej/g
38	Lumber + Sawmill	Lumber (Tilley 1999)	27000	sej/J
		Specific emergy	5.18E+08	sej/g
39	Millwork or Cabinetwork	Specific emergy	7.78E+08	sej/g
	Assume 50% increase over lumber due to energy and materials used in processing			
40	Plywood or Veneer	Plywood (Tilley 1999)	110000	sej/J
		Specific emergy	2.11E+09	sej/g
41	Prefabricated & Structural Wood Products	Average lumber and plywood	1.32E+09	sej/g
	Assume 50% increase due to energy and materials used in processing plywood and lumber	Specific emergy of Prefabricated wood products	1.97E+09	sej/g
42	Treated Wood Products	Paint (Buranakarn 1998)	1.50E+10	sej/g
	Lumber plus 0.1 paint	Specific Emergy	2.02E+09	sej/g
43	Miscellaneous Wood Products	Average value of 4 preceding wood products	1.72E+09	sej/g
44	Mattresses Furniture	(Buranakarn 1998)	2.89E+09	sej/g
45	Pulp or Pulp Mill Products	Wood pulp (Campbell and Cai 2007, Tilley 1999)	37900	sej/J
		Specific Emergy	7.28E+08	sej/g

Notes	Commodity Class, Calculations	Source, Assumptions	Values	Units
46	Paper and Paper Products	Paper (Campbell and Cai 2007, Tilley 1999)	222000	sej/J
		Specific Emergy	4.26E+09	sej/g
47	Paper or Building Board	Paper board (Campbell and Cai 2007, Tilley 1999)	112000	sej/J
			2.15E+09	sej/g
48	Newspaper and Printed matter	Assume paper	4.26E+09	sej/g
49	Potassium Or Sodium Compound	Caustic soda (Pritchard 2000)	7.45E+09	sej/g
50	Industrial Gases	Nitrogen gas (Campbell 2003b)	9.63E+10	sej/g
51	Miscellaneous Industrial Inorganic Chemicals	Average of hydrated lime, caustic soda, diatomite, sulfuric acid (Odum et al. 2000)	2.75E+09	sej/g
52	Miscellaneous Industrial Organic Chemicals	pesticides	1.45E+10	sej/g
		glue	3.73E+08	sej/g
	Average pesticides, glue, petroleum products.	Specific emergy	5.94E+09	sej/g
53	Plastic Matter or Synthetic Fibers	plastics (Buranakarn 1998)	3.09E+09	sej/g
54	Fertilizers	Average N, P, K (Odum 1996)	2.88E+09	sej/g
55	Miscellaneous Agricultural Chemicals	Assume pesticides (Brown and Arding 1991)	1.45E+10	sej/g
56	Adhesives	Assume glue (Buranakarn 1998)	3.73E+08	sej/g
57	Explosives	Assume similar to ammonium fertilizer	3.73E+09	sej/g
58	Chemical Preparations	Assume average of glue and pesticides	7.45E+09	sej/g
59	Petroleum Refining Products	(Bastianoni et al. 2009)	2.64E+09	sej/g
60	Liquefied Gases, Coal or Petroleum	LPG (Bastianoni et al. 2009)	3.11E+09	sej/g
61	Asphalt	(Bastianoni et al. 2009)	2.64E+09	sej/g
62	Tires, Rubber Products	Rubber (Buranakarn 1998)	4.22E+09	sej/g
63	Plastic	(Buranakarn 1998)		
		Polyethylene	5.17E+09	sej/g
		Plastics	3.09E+09	sej/g
		Average	4.13E+09	sej/g
64	Portland Cement	(Buranakarn 1998)	1.93E+09	sej/g
65	Brick ceramics	(Buranakarn 1998)	2.15E+09	sej/g
66	Concrete Products	(Haukoos 1995)	1.32E+09	sej/g
67	Ready mix concrete, Wet	Average sand and gravel and cement	1.62E+09	sej/g
68	Lime or Gypsum Products	(Pritchard 2000)	1.61E+09	sej/g

Notes	Commodity Class, Calculations	Source, Assumptions	Values	Units
69	Non-metallic Minerals Processed	(Buranakarn 1998, Haukoos 1995)		
	Average of glass and ceramics	Glass	4.61E+09	sej/g
		Flat glass	1.57E+09	sej/g
		Float glass	7.53E+09	sej/g
		Average	4.57E+09	sej/g
		Ceramics	2.81E+09	sej/g
		Average Specific Emergy	3.69E+09	sej/g
70	Blast Furnace or Coke	(Bastianoni et al. 2009)	2.12E+09	sej/g
71	Primary Iron or Steel Products	(Buranakarn 1998, Haukoos 1995)		
	Average iron and steel	Pig Iron	2.60E+09	sej/g
		Steel Conventional	4.02E+09	sej/g
		Average	3.31E+09	sej/g
72	Electrometallurgical Products	(Odum et al. 1987)	6.64E+10	sej/g
73	Iron or Steel Shapes	Use iron and steel	3.31E+09	sej/g
74	Primary Aluminum Smelter Products	(Odum 2002) Al sheet and recycle	1.27E+10	sej/g
75	Copper or Alloy Basic Shapes	(Buranakarn 1998)	5.03E+10	sej/g
76	Aluminum or Alloy Basic Shapes	(Odum 1996)	1.27E+10	sej/g
77	Miscellaneous Nonferrous Basic Shapes, Wire	Average copper and aluminum	3.15E+10	sej/g
78	Metal products	Assume steel	4.02E+09	sej/g
79	Industrial Machinery and motors	(Odum 1996)	7.76E+09	sej/g
80	Carbon Products For Electric Uses	Specific Emergy of Graphite		
	use graphite @ 10% of world coal	World Coal	7.55E+17	grams
		World Graphite	2.9E+14	grams
		Graphite/coal ratio	0.000384106	
		Heat Content Graphite	32805	J/g
		Transformity of Graphite	9.83E+07	sej/J
		Specific Emergy Graphite	2.89E+12	
			1.45E+11	sej/g
81	Household Machinery & Components	Assume steel	4.02E+09	sej/g
82	Electronics, precision instruments	Use average Steel, plastics, copper	1.91E+10	sej/g
83	Toys, Games, Sports, Household	Use average plastic, wood, paper, Al	5.43E+09	sej/g
84	Matches	Use average of lumber and phosphorus	8.68E+09	sej/g
		Phosphorus (Odum 1996)	1.74E+10	sej/g
85	Rubber or Plastic Scrap	Use average of rubber and plastic	4.17E+09	sej/g

Table 5-C.4 – Specific emergies for exports. All commodity specific emergies are without services and relative to the 9.26E24 sej/y baseline. Values of the emergy per unit factors for the commodity classes in this table were determined from the data given in Tables 5-C.1 and 5-C.3, as well as data provided in Table 5-C.5. The note numbers connect to Table 5-C.5. Wwt = wet weight, otherwise numbers are dwt = dry weight. Any commodity class that is the same as that found in the calculations for imports was determined in the same manner as shown in Table 5-C3 and the calculation is not repeated here.

Note	New Commodity Classes	Specific Emergy w/o services	Units
1	Field Crops	2.32E+08	sej/g wwt
2	Grain	2.94E+09	sej/g
3	Oil Kernels, Nuts or Seeds	6.23E+09	sej/g
4	Miscellaneous Field Crops	2.32E+08	sej/g
5	Citrus Fruits	1.37E+08	sej/g wwt
6	Fresh Vegetables	3.58E+08	sej/g
7	Horticultural Specialties	1.23E+09	sej/ g wwt
8	Metallic Ores	1.77E+11	sej/g
9	Iron Ores	3.51E+09	sej/g
10	Manganese Ores	3.50E+11	sej/g
11	Crude Petroleum	2.32E+09	sej/g
12	Broken Stone or Riprap	4.90E+08	sej/g
13	Gravel or Sand	1.31E+09	sej/g
14	Miscellaneous Nonmetallic Minerals	1.96E+09	sej/g
15	Meat, Fresh or Chilled	1.83E+10	sej/ g wwt
16	Meat, Fresh Frozen and Meat Products	2.11E+10	sej/g wwt
17	Animal By-products, inedible	9.87E+10	sej/g wwt
18	Flour or Other Grain Mill Products	3.36E+09	sej/g
19	Prepared or Canned Feed	5.07E+09	sej/g
20	Rice, Corn flour and Cereal preparations	5.69E+09	sej/g
21	Dog, cat or Other Pet Food	5.24E+09	sej/g
22	Soybean Oil or By-products	3.11E+10	sej/g
23	Miscellaneous Food Preparations	7.84E+09	sej/g
24	Primary Forest Materials	3.77E+08	sej/g
25	Lumber or Dimension Stock	5.18E+08	sej/g
26	Treated Wood Products	2.02E+09	sej/g
27	Miscellaneous Wood Products	1.72E+09	sej/g
28	Newspapers	4.26E+09	sej/g
29	Miscellaneous Printed Matter	4.26E+09	sej/g
30	Industrial Chemicals	0.00E+00	sej/g
31	Potassium or Sodium Compound	7.45E+09	sej/g
32	Industrial Gases	9.63E+10	sej/g
33	Miscellaneous Industrial Organic Chemicals	5.94E+09	sej/g

Note	New Commodity Classes	Specific Emergy w/o services	Units
34	Miscellaneous Industrial Inorganic Chemicals	2.75E+09	sej/g
35	Miscellaneous Agricultural Chemicals	1.45E+10	sej/g
36	Miscellaneous Glassware, Blown or Pressed	4.57E+09	sej/g
37	Concrete Products	1.32E+09	sej/g
38	Ready-mix Concrete, Wet	1.62E+09	sej/g
39	Nonmetal Minerals, Processed etc.	3.69E+09	sej/g
40	Steel and Wire Products	4.02E+09	sej/g
41	Total Machinery - Motor V	7.76E+09	sej/g
42	Motor Vehicles - Transportation Equipment	7.76E+09	sej/g
43	Metal Scrap or Tailings	4.02E+09	sej/g
44	Textile and paper waste	8.78E+09	sej/g
45	Chemical or Petroleum Waste	5.67E+09	sej/g
46	Rubber or Plastic Scrap	4.17E+09	sej/g
47	Warehouse & Distribution Center	NA	
48	Rail and Air Drayage	NA	

Table 5-C.5 – Specific emergies for imports. All commodity specific emergies are without services and relative to the 9.26E24 sej/y baseline.

Notes	Commodity Class, Calculations	Source, Assumptions	Values	Units
1	Field Crops	Assume potatoes	2.32E+08	sej/g wwt
2	Grain	Wheat	2.88E+09	sej/g
		Rice	1.89E+09	sej/g
		Oats	4.05E+09	sej/g
		Average	2.94E+09	sej/g
3	Oil Kernels, Nuts or Seeds			
	Assume pecans	(Brandt-Williams 2002)	6.23E+09	sej/g
4	Miscellaneous Field Crops	Assume potatoes	2.32E+08	sej/ g wwt
5	Citrus Fruits	Assume oranges	1.37E+08	sej/ g wwt
6	Fresh Vegetables	Same as imports	3.58E+08	sej/ g wwt
7	Horticultural Specialties			
	Average 3 arbitrary plants	Cabbages	2.29E+08	sej/ g wwt
		Lettuce	3.90E+08	sej/ g wwt
		Sorghum	1.19E+08	sej/ g wwt
		Average	2.46E+08	sej/ g wwt
	Assume average plant sold is 5 years old		1.23E+09	sej/ g wwt
8	Metallic Ores	Average Iron and MN	1.77E+11	sej/g
9	Iron Ores	(Cohen et al. 2007)	3.51E+09	sej/g
10	Manganese Ores (MN)	(Cohen et al. 2007)	3.50E+11	sej/g
11	Crude Petroleum	(Bastianoni et al. 2005)	2.32E+09	sej/g
12	Broken Stone or Riprap	Same as Imports	4.90E+08	sej/g
13	Gravel or Sand	Same as Imports	1.31E+09	sej/g
14	Miscellaneous Nonmetallic Minerals	Assume clay, (Odum 1996)	1.96E+09	sej/g
15	Meat, Fresh or Chilled	Same as Imports	1.83E+10	sej/ g wwt
16	Meat, Fresh Frozen and Meat Products	Same as Imports	2.11E+10	sej/ g wwt
17	Animal By-products, inedible	Same as Imports	9.87E+10	sej/ g wwt
18	Flour or Other Grain Mill Products	Same as Imports	3.36E+09	sej/g
19	Prepared or Canned Feed	Same as Imports	5.07E+09	sej/g
20	Rice, Corn flour and Cereal preparations		5.69E+09	sej/g
	Average (Rice + Corn) + Milling energy			
21	Dog, cat or Other Pet Food	Same as Imports	5.24E+09	sej/g
22	Soybean Oil or By-products	Same as Imports	3.11E+10	sej/g
23	Miscellaneous Food Preparations	Same as Imports	7.84E+09	sej/g
24	Primary Forest Materials	Same as Imports	3.77E+08	sej/g
25	Lumber or Dimension Stock	Same as Imports	5.18E+08	sej/g
26	Treated Wood Products	Same as Imports	2.02E+09	sej/g
27	Miscellaneous Wood Products	Same as Imports	1.72E+09	sej/g
28	Newspapers	Same as Imports	4.26E+09	sej/g

Notes	Commodity Class, Calculations	Source, Assumptions	Values	Units
29	Miscellaneous Printed Matter		4.26E+09	sej/g
30	Industrial Chemicals	(Campbell and Ohrt 2009)	2.68E+09	sej/g
		Caustic soda (Pritchard 2000)	7.31E+09	sej/g
		Hydrated lime (Pritchard 2000)	1.31E+09	sej/g
		Diatomite (Pritchard 2000)	1.99E+09	sej/g
		Sulfuric acid (Pritchard 2000)	8.96E+07	sej/g
		Average	2.68E+09	sej/g
31	Potassium or Sodium Compound	Same as Imports	7.45E+09	sej/g
32	Industrial Gases	Same as Imports	9.63E+10	sej/g
33	Miscellaneous Industrial Organic Chemicals	Same as Imports	5.94E+09	sej/g
34	Miscellaneous Industrial Inorganic Chemicals	Same as Imports	2.75E+09	sej/g
35	Miscellaneous Agricultural Chemicals	Same as Imports	1.45E+10	sej/g
36	Miscellaneous Glassware, Blown or Pressed		4.57E+09	sej/g
37	Concrete Products	Same as Imports	1.32E+09	sej/g
38	Ready-mix Concrete, Wet	Same as Imports	1.62E+09	sej/g
39	Nonmetal Minerals, Processed etc.	Same as Imports	3.69E+09	sej/g
40	Steel and Wire Products	Assume Steel	4.02E+09	sej/g
41	Total Machinery - Motor V	Same as Imports	7.76E+09	sej/g
42	Motor Vehicles + Transportation Equipment	Assume machinery	7.76E+09	sej/g
43	Metal Scrap or Tailings	Assume Steel	4.02E+09	sej/g
44	Textile and Paper Waste	Average	8.78E+09	sej/g
		Cotton (Odum 1996)	1.33E+10	sej/g
		Paper, same as imports	4.26E+09	sej/g
45	Chemical or Petroleum Waste	Average coke, pesticides, glue	5.67E+09	sej/g
46	Rubber or Plastic Scrap	Same as Imports	4.17E+09	sej/g

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Appendix 5-D: Further Description of the San Luis Basin Regional Model

The major physiographic systems within the SLB are aggregated into three classes: 1) mountains which are to a large extent forested, 2) the valley floor, which is divided into an area covered by the natural shrub vegetation of the region including phreatophytes and xerophytes (e.g., sagebrush), and 3) agricultural land, which is generally irrigated with surface or groundwater. Cottonwood and other trees grow along riparian habitat and are included in the symbol for shrub lands vegetation (Fig. 5.1). Each vegetation subsystem includes surface and groundwater with flows appropriate for the location (i.e., considering drainage). Groundwater storages include a specified temperature, because geothermal energy is a potentially important energy source in the region. Much of the valley floor is occupied by agriculture, growing mainly grains and potatoes. Specialized agricultural crops (e.g., quinoa) that require high altitude can be grown in the SLB, which has an average elevation of approximately 2300 m. Some livestock, mostly cattle, are raised in the valley and are included in the agricultural subsystem.

The high elevation valley is surrounded by still higher mountains with peaks that rise more than 1800 m above the valley floor (San Luis Valley Development Resources Group 2007). The work of geological processes deep in the earth has given rise to many of the present salient features of the SLB. The SLB itself was originally formed as a rift valley (Chapin and Cather 1994). Also in the past, various periods of orogeny gave rise to the mountains with stores of rock and concentrated mineral deposits (e.g., perlite) suitable for mining. Erosion of the mountains over millions of years filled the deep rift valley with sediments, which are deeply bedded with layers of ground water present throughout the sediment deposit (CWCB 2000, Mayo et al. 2006). In recent times, sandy plains and the unique wind regime of the basin along with the dogleg shape of the Sangre de Cristo range on the eastern border of the valley have given rise to a dune field containing the highest sand dunes in North America (San Luis Valley Development Resources Group 2007). Seasonal river flow from the Sangre de Cristo Mountains plays an important part in the maintenance of these dunes (Madole et al. 2008) as indicated by the interaction symbol in the model (Fig. 5.1) describing dune production as an interaction of the sand supply on the valley floor with wind and water flows. Finally, the high mountains surrounding the valley ensure that a large part of the water that falls on the basin comes down as snow (Emery 1979).

The primary economic systems of the region are centered on its natural resources (e.g., food processing and shipment, mining and processing ores and building materials, and recreation). Service and commerce, education, transportation, and government are connected within the system network (Fig. 5.1) as noted by the pathways defined in Table 5.2. In addition, people are an important storage of capital within the system and we documented the effects of immigration and emigration on the annual emergy inflows to and outflows from the SLB. For example, in 1989 the emergy brought into the SLB by immigrants exceeded the emergy of petroleum used in that year. Net movement of people appeared to follow economic opportunity, so managers might indirectly work to increase the movement of people to the SLB by zoning land for industrial and commercial use. Also, elected officials might alter the tax structure to attract more or less business to the region. Tourists enter and leave the system and are apparently attracted by the extraordinary features in the natural environment of the region (e.g., Great Sand Dunes National Park and Preserve, various wildlife preserves with rare species, hot springs, etc.).

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Appendix 5-E: Emergy Analysis Tables For Renewable Inflows, Renewable Production, Nonrenewable Productions And Use, Imports And Exports, And Additional Figures Not Included In Body Of Report

Table 5-E.1 – Renewable emergy inflows to the San Luis Basin.

Year	Solar Energy Absorbed (sej/y)	Wind Energy Absorbed (sej/y)	Earth Cycle (sej/y)	Rain Chemical Potential (sej/y)	Rain Geopotential on the Land (sej/y)	Snow Geopotential on Land (sej/y)	Rain Geopotential as Runoff (sej/y)	Snow Geopotential as Runoff (sej/y)	Total Geopotential as Runoff (sej/y)	Evapo-transpiration (sej/y)	Renewable* Emergy Base (sej/y)
1980	1.26E+20	6.98E+20	2.30E+21	1.02E+21	1.73E+21	1.73E+22	2.35E+20	1.97E+21	2.20E+21	1.00E+21	3.20E+21
1981	1.31E+20	1.05E+21	2.30E+21	1.05E+21	1.77E+21	1.77E+22	2.44E+20	2.05E+21	2.29E+21	9.78E+20	3.27E+21
1982	1.23E+20	1.05E+21	2.30E+21	1.09E+21	1.84E+21	1.84E+22	2.56E+20	2.14E+21	2.40E+21	9.50E+20	3.35E+21
1983	1.21E+20	1.32E+21	2.30E+21	1.11E+21	1.86E+21	1.86E+22	2.54E+20	2.13E+21	2.38E+21	9.46E+20	3.33E+21
1984	1.19E+20	1.05E+21	2.30E+21	1.13E+21	1.92E+21	1.92E+22	2.59E+20	2.17E+21	2.43E+21	9.43E+20	3.37E+21
1985	1.25E+20	1.05E+21	2.30E+21	1.21E+21	2.05E+21	2.05E+22	2.87E+20	2.41E+21	2.69E+21	9.40E+20	3.63E+21
1986	1.23E+20	9.75E+20	2.30E+21	1.17E+21	1.97E+21	1.97E+22	2.75E+20	2.31E+21	2.58E+21	9.36E+20	3.52E+21
1987	1.22E+20	9.75E+20	2.30E+21	9.50E+20	1.60E+21	1.60E+22	2.25E+20	1.89E+21	2.11E+21	9.33E+20	3.04E+21
1988	1.26E+20	6.98E+20	2.30E+21	9.50E+20	1.60E+21	1.61E+22	2.23E+20	1.87E+21	2.09E+21	9.35E+20	3.03E+21
1989	1.27E+20	8.29E+20	2.30E+21	7.50E+20	1.27E+21	1.27E+22	1.75E+20	1.47E+21	1.65E+21	9.38E+20	2.58E+21
1990	1.30E+20	8.29E+20	2.30E+21	1.29E+21	2.16E+21	2.17E+22	3.08E+20	2.58E+21	2.89E+21	9.40E+20	3.83E+21
1991	1.21E+20	6.68E+20	2.30E+21	1.02E+21	1.72E+21	1.72E+22	2.46E+20	2.06E+21	2.30E+21	9.43E+20	3.24E+21
1992	1.16E+20	6.38E+20	2.30E+21	9.86E+20	1.65E+21	1.66E+22	2.36E+20	1.98E+21	2.21E+21	9.45E+20	3.16E+21
1993	1.09E+20	3.12E+20	2.30E+21	1.08E+21	1.81E+21	1.81E+22	2.58E+20	2.16E+21	2.42E+21	9.43E+20	3.36E+21
1994	1.04E+20	4.33E+20	2.30E+21	1.08E+21	1.81E+21	1.81E+22	2.57E+20	2.16E+21	2.41E+21	9.41E+20	3.35E+21
1995	1.10E+20	2.78E+20	2.30E+21	1.05E+21	1.77E+21	1.78E+22	2.46E+20	2.06E+21	2.30E+21	9.38E+20	3.24E+21
1996	1.19E+20	5.29E+20	2.30E+21	9.16E+20	1.55E+21	1.55E+22	2.08E+20	1.74E+21	1.95E+21	9.36E+20	2.88E+21
1997	1.31E+20	7.62E+20	2.30E+21	1.21E+21	2.04E+21	2.04E+22	2.90E+20	2.43E+21	2.72E+21	9.34E+20	3.65E+21
1998	1.31E+20	4.80E+20	2.30E+21	1.02E+21	1.72E+21	1.72E+22	2.43E+20	2.04E+21	2.28E+21	9.31E+20	3.21E+21
1999	1.42E+20	6.38E+20	2.30E+21	1.04E+21	1.76E+21	1.76E+22	2.44E+20	2.05E+21	2.29E+21	9.29E+20	3.22E+21
2000	1.41E+20	6.98E+20	2.30E+21	9.38E+20	1.59E+21	1.59E+22	2.17E+20	1.82E+21	2.04E+21	9.26E+20	2.96E+21
2001	1.41E+20	6.38E+20	2.30E+21	9.45E+20	1.59E+21	1.59E+22	2.25E+20	1.88E+21	2.11E+21	9.23E+20	3.03E+21
2002	1.39E+20	4.80E+20	2.30E+21	6.12E+20	1.03E+21	1.03E+22	1.42E+20	1.19E+21	1.33E+21	9.21E+20	2.25E+21
2003	1.42E+20	6.98E+20	2.30E+21	8.74E+20	1.47E+21	1.47E+22	2.06E+20	1.72E+21	1.93E+21	9.18E+20	2.85E+21
2004	1.39E+20	6.38E+20	2.30E+21	9.86E+20	1.66E+21	1.67E+22	2.33E+20	1.95E+21	2.18E+21	9.15E+20	3.10E+21
2005	1.42E+20	5.82E+20	2.30E+21	9.42E+20	1.59E+21	1.59E+22	2.22E+20	1.86E+21	2.08E+21	9.13E+20	2.99E+21

* The Renewable emergy base for the systems consists of the sum of the geopotential of runoff from rain and snow and the evapotranspiration.

Table 5-E.2 – Production in the San Luis Basin that is based primarily on renewable resources.

Year	Agricultural Crops (Total) (sej/y)	Hay (sej/y)	Barley (sej/y)	Oats (sej/y)	Wheat (sej/y)	Potatoes (sej/y)	Livestock (Cattle) (sej/y)	Fish (sej/y)	Timber Harvest (sej/y)
1980	1.32E+21	4.76E+20	2.30E+20	1.13E+20	3.85E+20	1.16E+20	6.52E+20	0.00E+00	7.43E+19
1981	1.36E+21	3.52E+20	2.41E+20	1.37E+20	5.05E+20	1.22E+20	7.03E+20	0.00E+00	4.38E+19
1982	1.41E+21	3.57E+20	3.03E+20	1.73E+20	4.43E+20	1.35E+20	6.89E+20	0.00E+00	7.44E+19
1983	1.42E+21	1.79E+20	2.79E+20	1.81E+20	6.30E+20	1.47E+20	7.45E+20	0.00E+00	7.78E+19
1984	1.42E+21	2.03E+20	3.33E+20	1.80E+20	5.27E+20	1.82E+20	7.80E+20	0.00E+00	9.54E+19
1985	1.56E+21	2.65E+20	3.11E+20	2.21E+20	5.70E+20	1.89E+20	7.56E+20	4.73E+16	9.54E+19
1986	1.70E+21	5.28E+20	4.30E+20	1.35E+20	4.07E+20	1.99E+20	7.47E+20	3.07E+17	1.08E+20
1987	1.55E+21	6.04E+20	2.14E+20	9.71E+19	4.34E+20	2.06E+20	7.43E+20	3.07E+17	1.02E+20
1988	1.54E+21	6.06E+20	1.87E+20	1.43E+20	4.05E+20	2.01E+20	7.39E+20	3.31E+17	1.03E+20
1989	1.66E+21	4.79E+20	2.20E+20	1.69E+20	5.71E+20	2.17E+20	7.34E+20	3.31E+17	1.09E+20
1990	1.55E+21	5.48E+20	2.75E+20	1.62E+20	3.20E+20	2.40E+20	7.30E+20	3.31E+17	7.40E+19
1991	1.42E+21	5.25E+20	2.50E+20	1.19E+20	2.76E+20	2.51E+20	7.25E+20	7.09E+17	7.22E+19
1992	1.50E+21	5.74E+20	2.07E+20	1.04E+20	3.78E+20	2.33E+20	7.21E+20	8.99E+17	7.76E+19
1993	1.43E+21	6.46E+20	1.44E+20	9.41E+19	2.77E+20	2.67E+20	7.16E+20	8.99E+17	8.16E+19
1994	1.54E+21	6.87E+20	1.52E+20	8.28E+19	3.49E+20	2.72E+20	7.11E+20	8.99E+17	1.13E+20
1995	1.48E+21	6.23E+20	2.08E+20	1.38E+20	2.56E+20	2.51E+20	7.06E+20	8.99E+17	6.69E+19
1996	1.73E+21	5.62E+20	1.60E+20	1.48E+20	5.56E+20	3.08E+20	7.02E+20	8.99E+17	3.43E+19
1997	1.90E+21	8.40E+20	2.34E+20	1.32E+20	4.33E+20	2.64E+20	6.96E+20	1.37E+18	1.20E+19
1998	1.79E+21	8.00E+20	1.96E+20	1.50E+20	3.72E+20	2.68E+20	6.91E+20	1.49E+18	1.35E+19
1999	1.87E+21	8.07E+20	1.95E+20	1.32E+20	4.60E+20	2.72E+20	6.86E+20	1.23E+18	2.09E+19
2000	2.00E+21	8.15E+20	2.72E+20	2.18E+20	4.04E+20	2.95E+20	6.81E+20	1.51E+18	1.71E+19
2001	1.86E+21	9.63E+20	2.01E+20	1.36E+20	3.32E+20	2.25E+20	6.81E+20	1.75E+18	9.99E+18
2002	1.42E+21	6.73E+20	1.66E+20	7.31E+19	2.18E+20	2.94E+20	5.74E+20	1.80E+18	8.30E+18
2003	1.35E+21	7.10E+20	1.87E+20	8.83E+19	1.19E+20	2.50E+20	5.59E+20	1.84E+18	1.21E+19
2004	1.29E+21	7.32E+20	1.89E+20	4.36E+19	9.39E+19	2.27E+20	4.66E+20	2.13E+18	1.95E+19
2005	1.49E+21	8.98E+20	1.96E+20	3.54E+19	1.36E+20	2.22E+20	4.98E+20	2.06E+18	1.38E+19

Table 5-E.3 – Nonrenewable emergy inflows in the San Luis Basin.

Year	Coal Used (sej/y)	Natural Gas Used (sej/y)	Petroleum Fuels Used (sej/y)	Electricity Used (sej/y)	Crude Oil Produced* (sej/y)	Metallic Ores* (sej/y)	Broken Stone, Rip Rap*# (sej/y)	Sand and Gravel*# (sej/y)	Non-metallic Minerals* (sej/y)	Soil Erosion (sej/y)	Ground-water (sej/y)
1980	2.28E+19	1.36E+20	2.91E+20	1.69E+20						1.87E+20	0.00E+00
1981	2.09E+19	1.19E+20	2.66E+20	1.91E+20						2.01E+20	2.63E+20
1982	1.48E+19	1.30E+20	2.70E+20	1.87E+20						1.95E+20	0.00E+00
1983	9.62E+18	1.23E+20	2.76E+20	1.90E+20						1.96E+20	0.00E+00
1984	1.16E+19	1.32E+20	2.76E+20	2.01E+20						2.00E+20	0.00E+00
1985	1.10E+19	1.24E+20	2.73E+20	2.06E+20						1.85E+20	0.00E+00
1986	1.03E+19	1.12E+20	2.78E+20	2.10E+20						1.70E+20	0.00E+00
1987	9.68E+18	1.17E+20	2.78E+20	2.17E+20						1.43E+20	0.00E+00
1988	9.07E+18	1.28E+20	2.82E+20	2.28E+20						1.41E+20	2.75E+20
1989	8.18E+18	1.34E+20	2.67E+20	2.31E+20						1.43E+20	2.56E+20
1990	8.97E+18	1.32E+20	2.66E+20	2.32E+20						1.35E+20	3.59E+19
1991	9.06E+18	1.43E+20	2.69E+20	2.35E+20						1.33E+20	0.00E+00
1992	8.65E+18	1.34E+20	2.66E+20	2.30E+20						1.28E+20	0.00E+00
1993	8.70E+18	1.47E+20	2.80E+20	2.32E+20						1.26E+20	0.00E+00
1994	9.31E+18	1.36E+20	2.84E+20	2.42E+20						1.23E+20	2.62E+19
1995	7.94E+18	1.40E+20	2.91E+20	2.48E+20	7.28E+15	1.49E+20	1.24E+21	3.63E+21	1.82E+20	1.24E+20	0.00E+00
1996	4.01E+18	1.51E+20	3.01E+20	2.59E+20	1.34E+18	1.38E+20	1.14E+21	3.35E+21	1.68E+20	1.34E+20	4.00E+20
1997	8.27E+18	1.49E+20	2.84E+20	2.63E+20	2.44E+18	1.54E+20	1.22E+21	3.58E+21	1.80E+20	1.34E+20	0.00E+00
1998	4.23E+18	1.52E+20	3.00E+20	2.71E+20	5.62E+18	1.46E+20	1.29E+21	3.67E+21	1.99E+20	1.45E+20	1.01E+20
1999	5.40E+18	1.47E+20	3.06E+20	2.73E+20	2.33E+18	1.78E+20	6.77E+20	2.74E+21	1.75E+20	1.34E+20	0.00E+00
2000	5.11E+18	1.52E+20	3.26E+20	2.87E+20	6.62E+17	1.06E+20	8.27E+20	2.75E+21	2.27E+20	1.28E+20	4.62E+20
2001	5.91E+18	1.84E+20	3.30E+20	2.87E+20	7.88E+17	2.31E+20	9.50E+20	3.09E+21	2.31E+20	1.19E+20	0.00E+00
2002	4.21E+18	1.84E+20	3.15E+20	2.97E+20	5.33E+17	7.64E+20	5.06E+20	2.52E+21	2.29E+20	1.20E+20	7.89E+20
2003	5.40E+18	1.72E+20	3.26E+20	2.99E+20	8.70E+17	3.94E+19	5.43E+20	1.95E+21	6.31E+19	1.26E+20	2.77E+20
2004	5.00E+18	1.72E+20	3.53E+20	3.00E+20	1.10E+18	3.66E+19	7.93E+20	1.95E+21	5.94E+20	1.26E+20	2.00E+19
2005	4.13E+18	1.78E+20	3.42E+20	3.06E+20	2.27E+18	4.80E+19	8.26E+20	1.86E+21	6.21E+20	1.25E+20	0.00E+00

* Assumed from Global Insight Inc. data to be produced in the Basin. # Ten percent was added for local consumption.

Table 5-E.4 – Imports into the San Luis Basin.

Year	Coal (sej/y)	Petroleum (sej/y)	Natural Gas (sej/y)	Electricity (sej/y)	Total Fuels and Electricity (sej/y)	Materials other than fuels (sej/y)	Services in materials other than fuels (sej/y)	Services in Fuels (sej/y)	Services in Electricity (sej/y)	Total Goods and Services (sej/y)	Immigration (sej/y)	Tourism (sej/y)	Federal and State Outlays (sej/y)
1980	2.28E+19	1.36E+20	2.91E+20	1.69E+20	6.19E+20			2.37E+20	6.76E+19				
1981	2.09E+19	1.19E+20	2.66E+20	1.91E+20	5.97E+20			2.27E+20	7.99E+19				
1982	1.48E+19	1.30E+20	2.70E+20	1.87E+20	6.01E+20			2.07E+20	7.93E+19				
1983	9.62E+18	1.23E+20	2.76E+20	1.90E+20	5.98E+20			1.74E+20	7.11E+19				
1984	1.16E+19	1.32E+20	2.76E+20	2.01E+20	6.21E+20			1.72E+20	7.38E+19				
1985	1.10E+19	1.24E+20	2.73E+20	2.06E+20	6.13E+20			1.57E+20	7.19E+19		1.23E+20		4.89E+19
1986	1.03E+19	1.12E+20	2.78E+20	2.10E+20	6.10E+20			1.14E+20	6.57E+19		0.00E+00		5.09E+19
1987	9.68E+18	1.17E+20	2.78E+20	2.17E+20	6.22E+20			1.19E+20	6.56E+19		3.21E+19		5.31E+19
1988	9.07E+18	1.28E+20	2.82E+20	2.28E+20	6.46E+20			1.17E+20	7.02E+19		1.80E+20		5.48E+19
1989	8.18E+18	1.34E+20	2.67E+20	2.31E+20	6.40E+20			1.17E+20	6.72E+19		3.80E+20		5.12E+19
1990	8.97E+18	1.32E+20	2.66E+20	2.32E+20	6.40E+20			1.23E+20	6.43E+19		2.93E+20		4.98E+19
1991	9.06E+18	1.43E+20	2.69E+20	2.35E+20	6.56E+20			1.15E+20	6.14E+19		1.63E+19		4.77E+19
1992	8.65E+18	1.34E+20	2.66E+20	2.30E+20	6.38E+20			1.08E+20	5.80E+19		7.39E+19		4.85E+19
1993	8.70E+18	1.47E+20	2.80E+20	2.32E+20	6.68E+20			1.14E+20	5.86E+19		0.00E+00		5.24E+19
1994	9.31E+18	1.36E+20	2.84E+20	2.42E+20	6.71E+20			1.18E+20	6.23E+19		0.00E+00		5.86E+19
1995	7.94E+18	1.40E+20	2.91E+20	2.48E+20	6.87E+20	1.33E+21	6.26E+20	1.22E+20	6.46E+19	2.83E+21	0.00E+00	1.44E+20	6.12E+19
1996	4.01E+18	1.51E+20	3.01E+20	2.59E+20	7.15E+20	1.39E+21	5.92E+20	1.33E+20	6.65E+19	2.90E+21	0.00E+00	1.49E+20	6.52E+19
1997	8.27E+18	1.49E+20	2.84E+20	2.63E+20	7.04E+20	1.46E+21	6.13E+20	1.30E+20	6.55E+19	2.97E+21	0.00E+00	1.52E+20	6.26E+19
1998	4.23E+18	1.52E+20	3.00E+20	2.71E+20	7.27E+20	1.48E+21	6.17E+20	1.15E+20	6.51E+19	3.00E+21	0.00E+00	1.52E+20	5.91E+19
1999	5.40E+18	1.47E+20	3.06E+20	2.73E+20	7.32E+20	1.82E+21	6.46E+20	1.18E+20	6.13E+19	3.38E+21	0.00E+00	1.47E+20	5.59E+19
2000	5.11E+18	1.52E+20	3.26E+20	2.87E+20	7.71E+20	1.83E+21	6.85E+20	1.61E+20	6.48E+19	3.51E+21	0.00E+00	1.55E+20	5.96E+19
2001	5.91E+18	1.84E+20	3.30E+20	2.87E+20	8.08E+20	2.13E+21	6.47E+20	1.71E+20	6.19E+19	3.81E+21	0.00E+00	1.52E+20	5.82E+19
2002	4.21E+18	1.84E+20	3.15E+20	2.97E+20	8.00E+20	2.20E+21	6.22E+20	1.33E+20	6.03E+19	3.82E+21	0.00E+00	1.39E+20	5.60E+19
2003	5.40E+18	1.72E+20	3.26E+20	2.99E+20	8.02E+20	1.53E+21	5.32E+20	1.46E+20	6.62E+19	3.07E+21	0.00E+00	1.43E+20	5.97E+19
2004	5.00E+18	1.72E+20	3.53E+20	3.00E+20	8.30E+20	1.65E+21	5.11E+20	1.89E+20	6.94E+19	3.25E+21	9.16E+19	1.50E+20	
2005	4.13E+18	1.78E+20	3.42E+20	3.06E+20	8.30E+20	1.70E+21	4.99E+20	2.23E+20	7.30E+19	3.32E+21	1.45E+20	1.40E+20	

Table 5-E.5 – Exports from the San Luis Basin.

Year	Total Materials Exported (sej/y)	Services in material exports (sej/y)	Total Exports (sej/y)	Agricultural Crops (sej/y)	Potatoes (sej/y)	Grain, Wheat, Barley, Oats (sej/y)	Vegetables, Fruit, Nuts, Seeds (sej/y)	Horticulture Specialties (sej/y)	Livestock (sej/y)	Minerals Total (sej/y)	Metallic Ores (sej/y)
1980				7.72E+20	1.16E+20	6.57E+20			6.52E+20		
1981				9.25E+20	1.22E+20	8.03E+20			7.03E+20		
1982				9.53E+20	1.35E+20	8.18E+20			6.89E+20		
1983				1.14E+21	1.47E+20	9.91E+20			7.45E+20		
1984				1.11E+21	1.82E+20	9.32E+20			7.80E+20		
1985				1.17E+21	1.89E+20	9.85E+20			7.56E+20		
1986				1.06E+21	1.99E+20	8.60E+20			7.47E+20		
1987				8.87E+20	2.06E+20	6.81E+20			7.43E+20		
1988				8.64E+20	2.01E+20	6.63E+20			7.39E+20		
1989				1.09E+21	2.17E+20	8.74E+20			7.34E+20		
1990				9.04E+20	2.40E+20	6.64E+20			7.30E+20		
1991				8.19E+20	2.51E+20	5.68E+20			7.25E+20		
1992				8.58E+20	2.33E+20	6.24E+20			7.21E+20		
1993				7.30E+20	2.67E+20	4.63E+20			7.16E+20		
1994				8.07E+20	2.72E+20	5.34E+20			7.11E+20		
1995	7.49E+21	2.07E+21	9.57E+21	7.88E+20	2.51E+20	5.27E+20	1.08E+18	8.63E+18	7.06E+20	4.76E+21	1.49E+20
1996	7.55E+21	2.18E+21	9.73E+21	1.11E+21	3.08E+20	7.95E+20	1.13E+18	8.18E+18	7.02E+20	4.39E+21	1.38E+20
1997	7.83E+21	2.32E+21	1.01E+22	9.95E+20	2.64E+20	7.21E+20	1.53E+18	9.19E+18	6.96E+20	4.70E+21	1.54E+20
1998	7.94E+21	2.34E+21	1.03E+22	9.22E+20	2.68E+20	6.42E+20	1.34E+18	1.08E+19	6.91E+20	4.86E+21	1.46E+20
1999	6.19E+21	2.02E+21	8.21E+21	1.00E+21	2.72E+20	7.16E+20	1.52E+18	1.20E+19	6.86E+20	3.46E+21	1.78E+20
2000	6.30E+21	1.95E+21	8.25E+21	1.10E+21	2.95E+20	7.85E+20	1.46E+18	1.44E+19	6.81E+20	3.58E+21	1.06E+20
2001	6.12E+21	1.21E+21	7.33E+21	8.35E+20	2.25E+20	5.95E+20	1.78E+18	1.29E+19	6.81E+20	4.13E+21	2.31E+20
2002	5.52E+21	1.49E+21	7.00E+21	7.24E+20	2.94E+20	4.08E+20	1.24E+19	9.47E+18	5.74E+20	3.74E+21	7.64E+20
2003	4.22E+21	1.87E+21	6.09E+21	6.10E+20	2.50E+20	3.38E+20	1.39E+19	8.56E+18	5.59E+20	2.37E+21	3.94E+19
2004	9.36E+21	7.18E+21	1.65E+22	5.31E+20	2.27E+20	2.82E+20	1.32E+19	8.41E+18	4.66E+20	3.13E+21	3.66E+19
2005	9.84E+21	7.24E+21	1.71E+22	5.72E+20	2.22E+20	3.24E+20	1.36E+19	1.20E+19	4.98E+20	3.11E+21	4.80E+19

Year	Crude Petroleum (sej/y)	Broken Stone Or Riprap (sej/y)	Gravel Or Sand (sej/y)	Misc Nonmetallic Minerals, Nec (sej/y)	Forest Products Total (sej/y)	Primary Forest Products, Logs (sej/y)	Lumber and dimension stock (sej/y)	Wood Products (sej/y)
1980								
1981								
1982								
1983								
1984								
1985								
1986								
1987								
1988								
1989								
1990								
1991								
1992								
1993								
1994								
1995	7.19E+15	1.13E+21	3.30E+21	1.82E+20	1.222E+20	1.11439E+19	5.434E+19	5.6669E+19
1996	1.33E+18	1.04E+21	3.05E+21	1.68E+20	1.324E+20	1.20767E+19	5.89E+19	6.1418E+19
1997	2.41E+18	1.11E+21	3.26E+21	1.80E+20	1.416E+20	1.29163E+19	6.299E+19	6.5687E+19
1998	5.55E+18	1.18E+21	3.34E+21	1.99E+20	1.377E+20	1.31497E+19	5.826E+19	6.6308E+19
1999	2.30E+18	6.16E+20	2.49E+21	1.75E+20	1.818E+20	2.31487E+19	6.752E+19	9.1163E+19
2000	6.54E+17	7.51E+20	2.50E+21	2.27E+20	1.737E+20	2.12302E+19	7.06E+19	8.1919E+19
2001	7.78E+17	8.64E+20	2.81E+21	2.31E+20	4.672E+19	8.4775E+18	3.478E+18	3.4765E+19
2002	5.26E+17	4.60E+20	2.29E+21	2.29E+20	2.7E+19	4.98659E+18	3.397E+18	1.8621E+19
2003	8.59E+17	4.94E+20	1.77E+21	6.31E+19	2.749E+19	5.28069E+18	2.06E+18	2.0149E+19
2004	1.08E+18	7.21E+20	1.78E+21	5.94E+20	5.397E+19	1.21393E+19	9.845E+18	3.1991E+19
2005	2.25E+18	7.51E+20	1.69E+21	6.21E+20	5.682E+19	1.29705E+19	1.045E+19	3.3402E+19

Year	All other materials (sej/y)	Services in Agricultural Products (sej/y)	Services in Minerals (sej/y)	Services in Forest Products (sej/y)	Services in All Other materials (sej/y)	Emigration by age (sej/y)
1980						
1981						
1982						
1983						
1984						
1985						0
1986						7.032E+19
1987						0
1988						0
1989						0
1990						0
1991						0
1992						0
1993						4.9303E+19
1994						6.7808E+19
1995	1.119E+21	2.296E+20	2.344E+20	6.7331E+20	9.35722E+20	1.2821E+20
1996	1.209E+21	2.253E+20	2.17E+20	7.2813E+20	1.01145E+21	6.4372E+19
1997	1.294E+21	2.509E+20	2.325E+20	7.6716E+20	1.06632E+21	4.1769E+19
1998	1.326E+21	2.757E+20	2.342E+20	6.9573E+20	1.13029E+21	3.7275E+19
1999	8.571E+20	3.034E+20	1.566E+20	7.9454E+20	7.68159E+20	6.0803E+19
2000	7.651E+20	2.661E+20	1.828E+20	8.192E+20	6.81173E+20	6.2125E+19
2001	4.247E+20	2.85E+20	1.925E+20	9.5246E+19	6.33211E+20	2.8154E+19
2002	4.464E+20	6.722E+20	1.456E+20	6.1747E+19	6.06636E+20	6.6619E+19
2003	6.514E+20	6.598E+20	9.502E+19	5.1814E+19	1.06415E+21	4.9303E+19
2004	5.184E+21	5.802E+20	2.356E+20	1.4459E+20	6.22359E+21	0
2005	5.598E+21	5.682E+20	2.319E+20	1.4389E+20	6.29179E+21	0

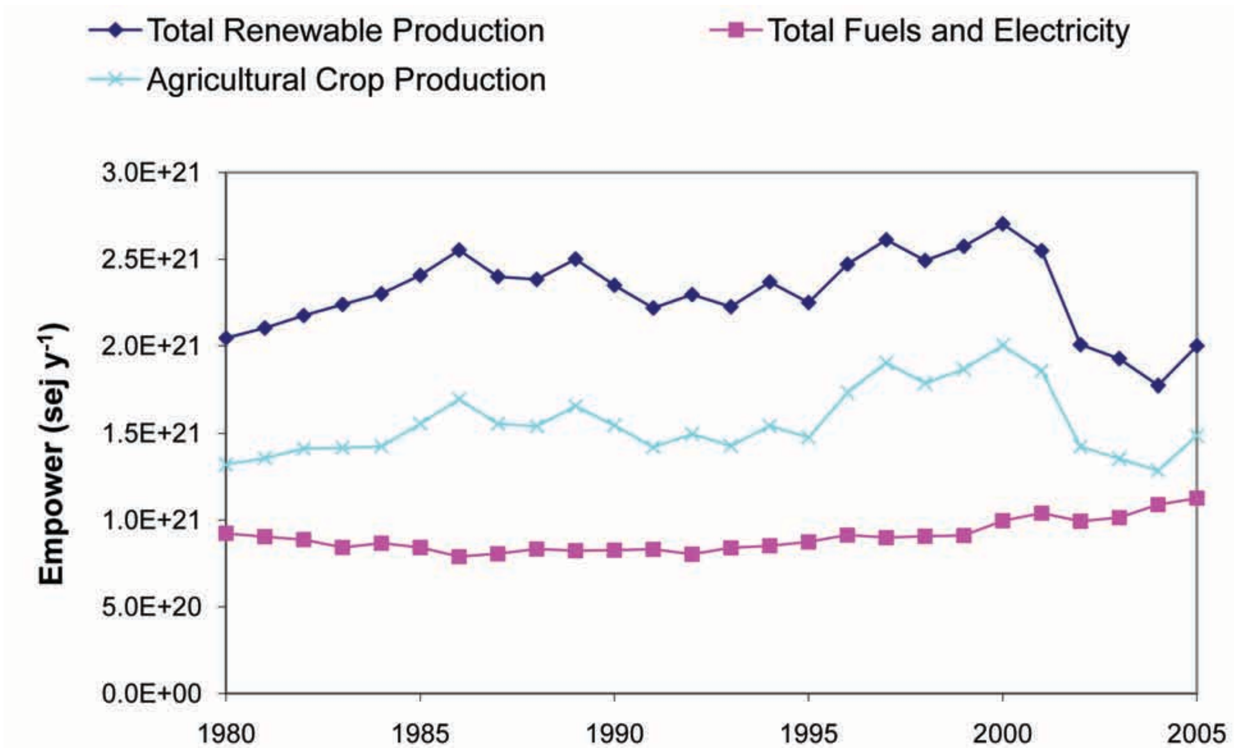

Figure 5-E.1 – Renewable production compared to the emergy of fuels and electricity, and the renewable emergy base of the SLB.

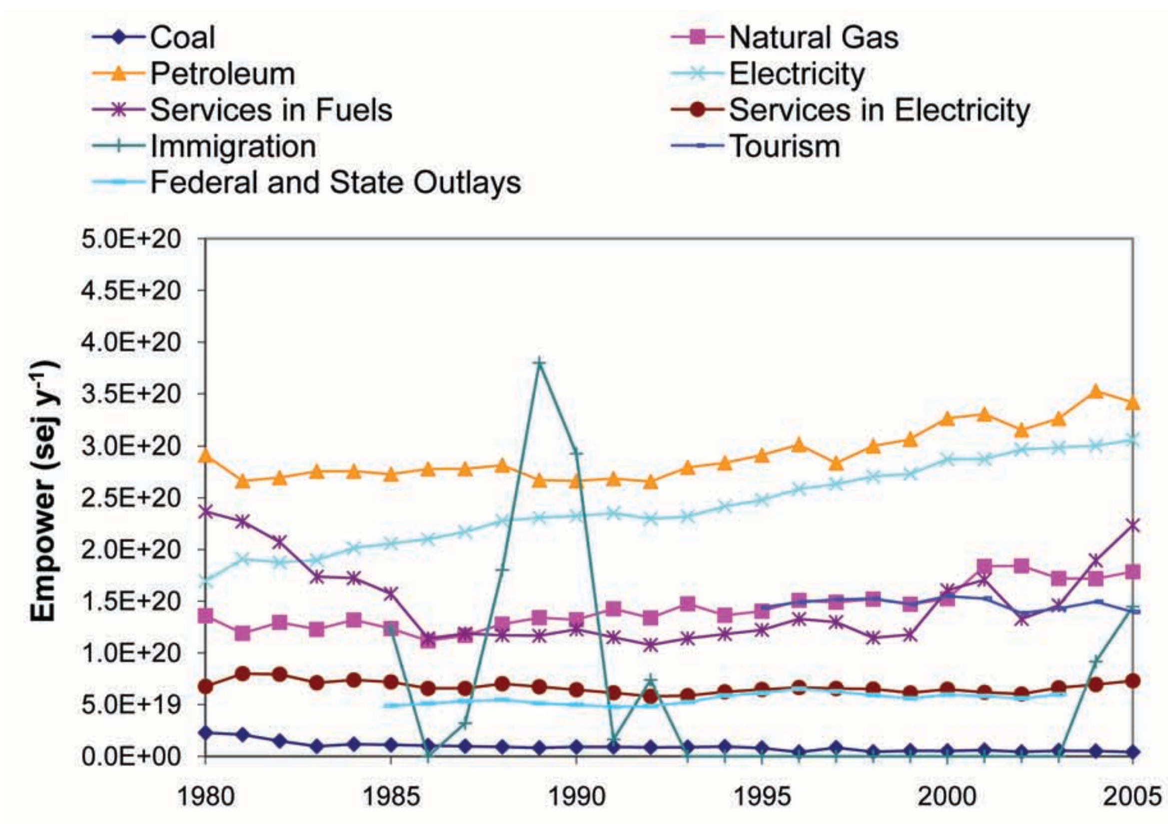

Figure 5-E.2 – Minor components of the emergy input to the San Luis Basin 1980-2005.

Appendix 5-F: Data Quality of the Purchased Data

Global Insight, Inc. (GI) data were important in that they allowed us to apply the revised method (Campbell et al. 2005) for calculating the import and export of emergy to and from a region. The commodity flow data collected by the Bureau of Transportation Statistics (1993, 1997, 2002) met the data quality objectives for measuring commodity movements for the studies of West Virginia and Minnesota (Campbell et al. 2005, Campbell and Ohrt 2009). GI uses their proprietary program, TRANSEARCH, to estimate domestic freight flows by county, commodity, and mode of transportation. They used a variety of public data sources to derive these flows (Global Insight 2006). To verify the accuracy of TRANSEARCH data, GI benchmarks the flows against reported freight volume data using two primary sources: 1) private carrier information that they acquire as part of a data exchange program with railroads and truck carriers; and 2) truck count information released by the state departments of transportation. However, GI does not perform any statistical quantification of this process to estimate the uncertainty inherent in the TRANSEARCH data (Rich Fullenbaum, personal communication). Even though no statistical estimates were made to ascertain this uncertainty, we believe that it is reasonable to assume their methods carry uncertainty comparable to that in the US Census Bureau estimates, because both are based on similar sources. Furthermore, GI crosschecks their estimates with independent information (Rich Fullenbaum, personal communication). Despite the fact the methods reported by GI appear to be logical and deliberate, there is considerable uncertainty associated with some of their measurements. Principally, the export of "nonmetallic minerals, processed" appears to be underestimated, based on conversations with officials of two perlite companies. Both Dicaperl and Harborlite are doing business in Antonito, CO, and stated that almost all of the material that arrives at Antonito is shipped out by rail. At this time we are unable to determine the reason for this apparent error; however, this is a moot point because this commodity class passed through the SLB without local use and therefore we did not include it in our system's import-export balance.

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Appendix 5-G: Miscellaneous Indices and Results

A thorough emergy analysis often consists of several analyses and corresponding results. In an effort to be concise, many of the aspects related to the emergy of this study were not included in the body of the report. Below are the reference notes and tables that contain and the methods and assumptions used for calculating the energy and mass variables used in the emergy evaluation of the SLB. Various figures represent the reference notes and additional aspects of the San Luis Basin. This information makes available the core data needed to calculate the emergy flows of the region for 1995. Information for other years sufficient to reproduce the calculations for that year using the online spreadsheet for 1995 is available at http://www.epa.gov/aed/research/desupp5.html.

Table 5-G.1 – Example calculation of emergy and economic value, assumptions, and data sources used in the emergy evaluation of the San Luis Basin and Upper Rio Grande River Basin for the year 1995.

Note	Variables	Values	Values	Sources
	Areas	**(mi²)**	**(m²)**	
1	Alamosa	722.74	1.87E+09	http://quickfacts.census.gov/qfd/states/08/08003.html
	Conejos	1287.22	3.33E+09	http://quickfacts.census.gov/qfd/states/08/08021.html
	Costilla	1227.1	3.18E+09	http://quickfacts.census.gov/qfd/states/08/08023.html
	Hinsdale	1117.68	2.89E+09	http://quickfacts.census.gov/qfd/states/08/08053.html
	Mineral	875.72	2.27E+09	http://quickfacts.census.gov/qfd/states/08/08079.html
	Rio Grande	911.6	2.36E+09	http://quickfacts.census.gov/qfd/states/08/08105.html
	Saguache	3168.44	8.21E+09	http://quickfacts.census.gov/qfd/states/08/08109.html
	Area of 7 counties	9310.5	2.41E+10	Sum of 7 counties.
	Area counties not in watershed		3.65E+09	By difference between counties
	Area counties in region		8.29E+09	The region consists of 7 counties.
	Area counties in mountains		1.58E+10	All area outside the watershed is mountainous.
	Area of Upper Rio Grande watershed	7900	2.05E+10	http://www.nps.gov/archive/grsa/resources/docs/Trip2023.pdf
	Area of valley Floor	3200	8.29E+09	http://www.nps.gov/archive/grsa/resources/docs/Trip2023.pdf
	Area of mountains	4700	1.22E+10	http://www.nps.gov/archive/grsa/resources/docs/Trip2023.pdf
	Closed Basin watershed (see Figure 5-G.5 [1])		8.05E+09	This study, GIS estimate
	Rio Grande watershed excluding the closed basin (see Figure [1])		1.15E+10	This study, GIS estimate

Note	Variable and formulae	Subsets of the Variable	Value	Units	Sources and additional information
	Renewable Energy Sources				
2	**Solar Energy**				
	Solar radiation absorbed was determined from weather data for two stations from the National Renewable Energy Laboratory (NREL)	Received, watershed	1.2378E+20	J y^{-1}	
	Dataset, Alamosa in the valley and Wolf creek in the mountains.	Absorbed, watershed	9.3062E+19	J y^{-1}	
	Average precipitation and albedo were prorated by area.				
		Received, 7 counties	**1.46E+20**	J y^{-1}	
		Absorbed, 7 counties	**1.10E+20**	J y^{-1}	
		Solar insolation for watershed			NREL Data (1 station, n=46)
		Avg. Insolation (Alamosa)	1.68E+07	J m^{-2} d^{-1}	http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/siteonthefly.cgi?id=724620
		Solar for watershed			
		Solar Energy Received	1.2378E+20	J y^{-1}	Area weighted adjustment by solar fraction for mountains.
		Albedo	3.07181E+19	J y^{-1}	
		Solar Energy Absorbed	9.3062E+19	J y^{-1}	
		Solar Insolation for Counties			
		Solar Energy Received	1.45697E+20	J y^{-1}	
		Albedo	3.60751E+19	J y^{-1}	
		Solar Energy Absorbed	1.09622E+20	J y^{-1}	

Note	Variable and formulae	Subsets of the Variable	Value	Units	Sources and additional information
	Solar Insolation (Wolf Creek/Alamosa)		0.979775281	dimen-sionless	These are dimensionless numbers
		Albedo	Fraction reflected		http://eosweb.larc.nasa.gov/sse/
		Alamosa	0.25417	dimen-sionless	
		Wolf Creek	0.24417	dimen-sionless	
3	**Kinetic Energy of Wind Used at the Surface**		**1.89E+17**	**$J\ y^{-1}$**	http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?WWDI~StnSrch
	(density)(drag coefficient)(geostrophic velocity)3(area)(seconds/year)				
	Calculated in Odum (1999) "Evaluating Landscape Use of Wind Kinetic Energy."				
		Wind Speed, @ 10 m	2.5	$m\ s^{-1}$	
		Air Density	1.3	$kg\ m^{-3}$	
		Geostrophic Velocity	4.166666667	$m\ s^{-1}$	
		Drag Coefficient (area weighted)	0.002656302		
		Area, 7 counties	24114195000	m^2	
		sec / year	31400000		
		Drag coefficient flat land	0.002		
		Drag coefficient mountains	0.003		
4	**Earth Cycle Energy**		**6.81E+16**	**$J\ y^{-1}$**	http://smu.edu/geothermal/georesou/resource.htm
	(land area)(heat flow/area)				
		Area	24114195000	m^2	
		Heat flow/area	89.53571429	$mW\ m^{-2}$	Heatflow is the same for all years.
		Heat flow per m^2/year	2823598.286	$J\ m^{-2}\ y^{-1}$	
5	**Rain, Chemical Potential**		**5.83E+16**	**$J\ y^{-1}$**	
	(area)(rainfall)(density water)(Gibbs Free Energy water relative to seawater)				
	The chemical potential of rain was determined by a GIS analysis performed for this study.				
	Rainfall was averaged for each county and the counties were summed to get the total for the SLB.				
	Detailed data on the chemical potential of rainfall is found in the Geo and Chemical Potential spread sheet [1]				
		Area	24114195000	m^2	
		Rainfall	variable by county	$m\ y^{-1}$	
		Gibbs Energy	4.74	$J\ g^{-1}$	
		Density	1000000	$g\ m^{-3}$	

Note	Variable and formulae	Subsets of the Variable	Value	Units	Sources and additional information
6	**Rain, Geopotential Received on the Land**	**1.76E+17**	**J/yr**	**J y^{-1}**	
	Received: (area)(mean elevation)(precipitation)(density)(gravity)				
	We estimated that 1/2 the precipitation falls as rain over a year.				
		Total Area	24114195000	m^2	
		elevation	variable by county	m	
		(State location of station)			
		rain/yr	variable by county	m y^{-1}	
		Density	1000	kg m^{-3}	
		Gravity	9.81	m s^{-2}	
7	**Rain, Geopotential Energy Absorbed from Runoff**	**9.04E+15**	**J/yr**	**J y^{-1}**	
	Rain Geopotential used, Rain Runoff				
	Absorbed: (area)(mean elevation-minimum elevation)(runoff)(density)(gravity)				
	The geopotential energy absorbed from the rain runoff was determined from GIS calculations made for this study.				
	The closed basin and the Rio Grande drainage were handled separately, because the low points, average elevations, and rainfall of the two watersheds were not the same (see Geochemical Potential Table online). http://www.epa.gov/aed/research/desupp5.html				
		Area			
		Closed Basin	8047770000	m^2	
		Rio Grande Drainage	11502440000	m^2	
		Average Elevation			
		Closed Basin	2679	m	
		Rio Grande Drainage	2836	m	
		Minimum Elevation			
		Closed Basin	2289	m	
		Rio Grande Drainage	2252	m	
		Rainfall			
		Closed Basin	0.377	m y^{-1}	
		Rio Grande Drainage	0.553	m y^{-1}	
		Density	1000	kg m^{-3}	
		Gravity	9.81	m s^{-2}	

Note	Variable and formulae	Subsets of the Variable	Value	Units	Sources and additional information
8	**Snow, Geopotential Received on the Land**	**1.76E+17**	**J/yr**	**J y^{-1}**	
	Received: (area)(mean elevation)(precipitation)(density)(gravity)				
	We estimated that 1/2 the precipitation falls as rain over a year.				
		Total Area	24114195000	m^2	
		elevation	variable by county	m	
		(State location of station)			
		rain/yr	variable by county	m y^{-1}	
		Density	1000	kg m^{-3}	
		Gravity	9.81	m s^{-2}	
9	**Snow, Geopotential Energy Absorbed from Runoff**	**2.04E+16**	**J/yr**	**J y^{-1}**	
	Snow Geopotential used, Snow Runoff				
	Absorbed= (area)*(mean elevation-minimum elevation)*(runoff)*(density)*(gravity)				
	The geopotential energy absorbed from the snow runoff was determined from GIS calculations made for this study.				
	The closed basin and the Rio Grande drainage were handled separately, because the low points, averages elevation, and rainfall of the two watersheds were not the same (see Geo chemical Potential Table online).				
		Area			
		Closed Basin	8047770000	m^2	
		Rio Grande Drainage	11502440000	m^2	
		Average Elevation			
		Closed Basin	2679	m	
		Rio Grande Drainage	2836	m	
		Minimum Elevation			
		Closed Basin	2289	m	
		Rio Grande Drainage	2252	m	
		Rainfall			
		Closed Basin	0.377	m y^{-1}	
		Rio Grande Drainage	0.553	m y^{-1}	
		Density	1000	kg m^{-3}	
		Gravity	9.81	m s^{-2}	

Note	Variable and formulae	Subsets of the Variable	Value	Units	Sources and additional information
	Assumptions for snow				
	Assume all snow runs off into closed basin except for 8% sublimation (Campbell and Ohrt 2009)				
	Assume all snow runs off into Rio Grande Drainage except for 8% sublimation and 10% infiltration (calculated from Emery 1996).				
10	**Chemical and Geopotential of Rivers entering form Outside**				
	Colorado is at the topographic high point for the Nation; therefore, all rivers flow out of Colorado to the east or to the West.				
11	**Chemical Potential Energy of Evapotranspiration**	**3.34E+16**	**J/yr**	**J y^{-1}**	
	(Area)(Evapotranspiration)(density) (Gibbs Free Energy per gram)				
		Forest land Area	8820852711	m^2	
		Avg. Forest Transpiration	0.30	m y^{-1}	An average of 4 values for the ET of three species found in the area was used to
		Density water	1000000	g m^{-3}	Estimated evapotranspiration. Lodgepole pine (Knight et al. 1981), large and small, Ponderosa pine (Ryan et al. 2000) and cottonwood (Gazal et al. 2006) were used.
		Gibb's Free Energy, Rainwater	4.74	J g^{-1}	
		ET Forests	1.23698E+16	J y^{-1}	See the online table for Forests, ET, and GW [1]
		Arable land Area	2379884072	m^2	
		Avg. Crop Transpiration	0.69	m y^{-1}	Average transpiration for crops was taken from (Campbell et al. 2005)
		Density water	1000000	g m^{-3}	
		Gibb's Free Energy, Rainwater	4.74	J g^{-1}	
		ET Crops	7.82877E+15	J y^{-1}	
		Pasture land Area	3818083936	m^2	
		Avg. Pasture Transpiration	0.73	m y^{-1}	Average transpiration for pasture was taken from (Campbell et al. 2005)
		Density water	1000000	g m^{-3}	
		Gibb's Free Energy, Rainwater	4.74	J g^{-1}	
		ET Pasture	1.31932E+16	J y^{-1}	

Note	Variable and formulae	Subsets of the Variable	Value	Units	Sources and additional information
	Renewable Production				
12		**Total Agricultural Crops**	**2.11E+12**	**g y^{-1}**	Data on crop production is from Colorado Agricultural Statistics (2006).
		(amount sold)(energy/unit)			
			Mass		
		Hay	8.44E+11	g y^{-1}	
		Barley	6.01E+10	g y^{-1}	
		Oats	3.41E+10	g y^{-1}	
		Potatoes	1.08097E+12	g y^{-1}	
		Wheat	8.89E+10	g y^{-1}	
13		**Livestock**	**1.2769E+15**	**J y^{-1}**	
		(annual production mass)(energy/mass)			
		Cows			
		# sold	190249		(Animal production data from Colorado Agricultural Statistics (2006).
		wt	551065.2	g/animal	
		Energy /unit	12180	J g^{-1}	Energy content from US Dept of Agriculture Handbook
14		**Fish Production**	**3.7158E+11**	**J y^{-1}**	Fish production was estimated by a survey of 3 local producers
		(mass)(energy/mass)			Carried out by Fred Bunch of the National Parks Service.
		Mass	190,000	lbs y^{-1}	
			453.59	g lb^{-1}	
		Energy/mass	4311.58	J g^{-1}	
15		**Timber Harvest**	**9.7388E+14**	**J y^{-1}**	
		(vol. forest harvested)(dry wt)(J/g)			
		Volume harvested	3582538.96	ft^3	Estimate made in the Ecological Footprint section of this study,
			1.01446E+11	cm^3	Using harvest records of the Rio Grande National Forest and other federal lands.
		dry wt	0.5	g cm^{-3}	
		Forest mass	50723103070	g/yr	
		J/g	19200		
	Nonrenewable Use				
16	Coal Used	**2.10E+14**	**J/yr**	**J y^{-1}**	
	Assume that all coal imported is consumed.				
	Corrected for coal used to generate electricity.		8572	Short tons/yr	
			907200	g/short ton	
			27000	J g^{-1}	

Note	Variable and formulae	Subsets of the Variable	Value	Units	Sources and additional information
17	Natural Gas Used	**3.22E+15**	**J/yr**	**J y^{-1}**	
	Assume that all natural gas imported is consumed.	Amount	3055602.64	Thousand ft^3	
	Corrected for natural gas used to generate electricity.		1055000000	J/thousand ft^3	
18	Petroleum Used	**4.43E+15**	**J/yr**	**J y^{-1}**	
	Assume that all petroleum imported is consumed.		811314.00	barrels	
			5.46E+09	J/barrel	http://bioenergy.ornl.gov/papers/misc/energy_conv.html
19	Electricity Used	**1.46E+15**	**J/yr**	**J y^{-1}**	
		Amount	404174975.10	kW-hr	
	Renewables Used in a Nonrenewable Manner				
20	Groundwater use in some years	**2.57E+15**	**J/yr**	**J y^{-1}**	
	(vol.)(density)(Gibbs free energy)	Volume used	5.49E+08	m^3 y^{-1}	Based on the volume of ground water withdrawn as estimated in the GNRP section.
		Density	1000000	g m^3	
		Gibbs	4.9	J g^{-1}	
21	Soil Erosion	**1.70E+15**	**J/yr**	**J y^{-1}**	
	(area)(erosion rate)(organic fraction)(energy)	Soil mass eroded	2.71E+12	g y^{-1}	Appendix 4-A
		Organic fraction	0.03		
		Energy per gram	20930	J g^{-1}	
	Nonrenewable Production				
	Nonrenewable production is based on the excess of imports over	Crude Oil Produced	**1.35E+11**	**J y^{-1}**	See Imports-exports worksheet[1] for calculation of the nonrenewable
	Exports for those nonrenewables known to be produced in the SLB.	Metallic Ores Produced	**8.40E+08**	g y^{-1}	Materials produced based on the import-export balance.
		Broken Stone, Rip Rap Produced	**2.30E+12**	g y^{-1}	Assume 10% of crushed stone remains within the SLB.
		Sand and Gravel Produced	**2.52E+12**	g y^{-1}	Assume 10% of sand and gravel remains within the SLB.
		Non-metallic Minerals Produced	**9.26E+10**	g y^{-1}	
	Imports				
22	**Fuels**				
	All fuels and electricity used in the SLB were imported during the time of this study	Coal	**2.10E+14**	**J y^{-1}**	
		Petroleum	**4.43E+15**	**J y^{-1}**	
		Natural Gas	**3.22E+15**	**J y^{-1}**	
		Electricity	**1.46E+15**	**J y^{-1}**	

Note	Variable and formulae	Subsets of the Variable	Value	Units	Sources and additional information
23	**Other goods (without nonmetallic minerals processed) and services**				
		Materials other than fuels	**2.87E+11**	$g\ y^{-1}$	See Imports-Exports worksheet [1]
		Services in materials other than fuels	**2.41E+08**	$\$\ y^{-1}$	See Imports-Exports worksheet [1]
		Services in Fuels	**4.56E+07**	$\$\ y^{-1}$	See Energy Consumption worksheet [1]
		Services in Electricity	**2.48E+07**	$\$\ y^{-1}$	
24	**People**				
		Net Immigration	**0**	**individuals** y^{-1}	See the Population worksheet [1]
		Tourism	**5.53E+07**	$\$\ y^{-1}$	Dean Runyon Associates, Colorado Travel Impacts (1996-2003), Colorado Tourism Office
25	**Government**				
		Federal and State Outlays	**2.35E+07**	$\$\ y^{-1}$	See Government Worksheet [1]
	Exports				
26	Exports by Category				
		Agricultural Crops			
		Potatoes	**1.08E+12**	$g\ y^{-1}$	See Imports-Exports worksheet [1]
		Grain, Wheat, Barley, Oats	**1.83E+11**	$g\ y^{-1}$	See Imports-Exports worksheet [1]
		Vegetables, Fruit, Nuts, Seeds	**2.18E+09**	$g\ y^{-1}$	See Imports-Exports worksheet [1]
		Horticultural Specialties	**7.02E+09**	$g\ y^{-1}$	See Imports-Exports worksheet [1]
		Livestock	**1.28E+15**	**J** y^{-1}	see Livestock worksheet
		Minerals			
		Metallic Ores	**8.40E+08**	$g\ y^{-1}$	See Imports-Exports worksheet [1]
		Crude Petroleum	**3.10E+06**	$g\ y^{-1}$	See Imports-Exports worksheet [1]
		Broken Stone Or Riprap	**2.30E+12**	$g\ y^{-1}$	See Imports-Exports worksheet [1]
		Gravel Or Sand	**2.52E+12**	$g\ y^{-1}$	See Imports-Exports worksheet [1]
		Misc Nonmetallic Minerals, Nec	**9.26E+10**	$g\ y^{-1}$	See Imports-Exports worksheet [1]
		Forest Products			
		Primary Forest Products, Logs	**2.96E+10**	$g\ y^{-1}$	See Imports-Exports worksheet [1]
		Lumber and dimension stock	**1.05E+11**	$g\ y^{-1}$	See Imports-Exports worksheet [1]
		Wood Products	**2.82E+10**	$g\ y^{-1}$	See Imports-Exports worksheet [1]
	(without nonmetallic minerals processed)	All other materials	**8.21E+10**	$g\ y^{-1}$	See Imports-Exports worksheet [1]

Note	Variable and formulae	Subsets of the Variable	Value	Units	Sources and additional information
27	**Services**				
	Services in Agricultural Products		**8.83E+07**	**$** y^{-1}	See Imports-Exports worksheet [1]
	Services in Minerals		**9.01E+07**	**$** y^{-1}	See Imports-Exports worksheet [1]
	Services in Forest Products		**2.59E+08**	**$** y^{-1}	See Imports-Exports worksheet [1]
	Services in All Other materials (without nonmetallic minerals processed)		**3.60E+08**	$ y^{-1}	See Imports-Exports worksheet [1]
	Services		**N.A.**	**$** y^{-1}	We have not yet calculated exported services.
	Gross Regional Product			**$** y^{-1}	Used data from Chapter 4 and estimated for this Chapter[10]
28	**People**				
	Emigration by age		**9.70E+02**	**individuals** $\mathbf{y^{-1}}$	See Population worksheet[1]
29	**Government**				
	Federal Taxes			**$** y^{-1}	Data on federal and state taxes are only available for 2004. http://www.taxfoundation.org/files/fedtaxburden bycounty-20070321.pdf
	State Taxes			**$** y^{-1}	

[1] http://www.epa.gov/aed/research/desupp5.html

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[10] Chapter 4 did not specifically estimate Gross Regional Product (GRP). To estimate GRP for this chapter, we used Gross Domestic Product (GDP) for Colorado and New Mexico and population for the two states. We multiplied population for the SLB by the average per capita GDP from both states to estimate GRP. This approach requires numerous assumptions. However, the main assumption depends on whether the average per capita GDP for both Colorado and New Mexico represents consumption in the SLB. If this assumption is not sound, we may have overestimated or under-estimated GRP.

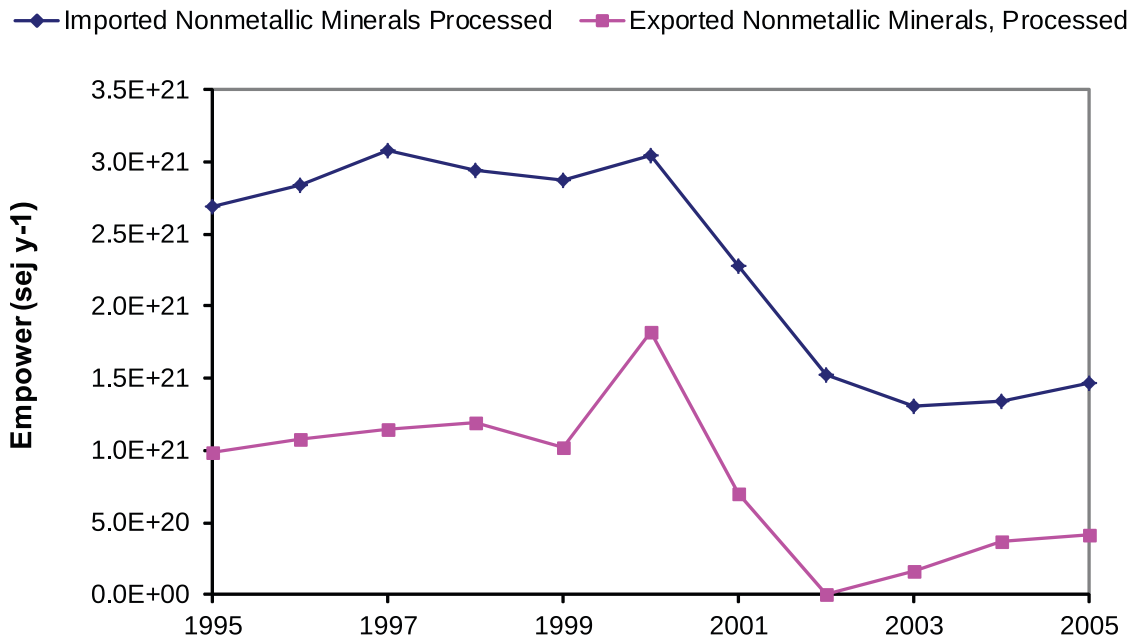

Figure 5-G.1 – The emergy of processed non-metallic minerals (i.e., perlite and scoria) imported into the San Luis Basin and the emergy exported in that category.

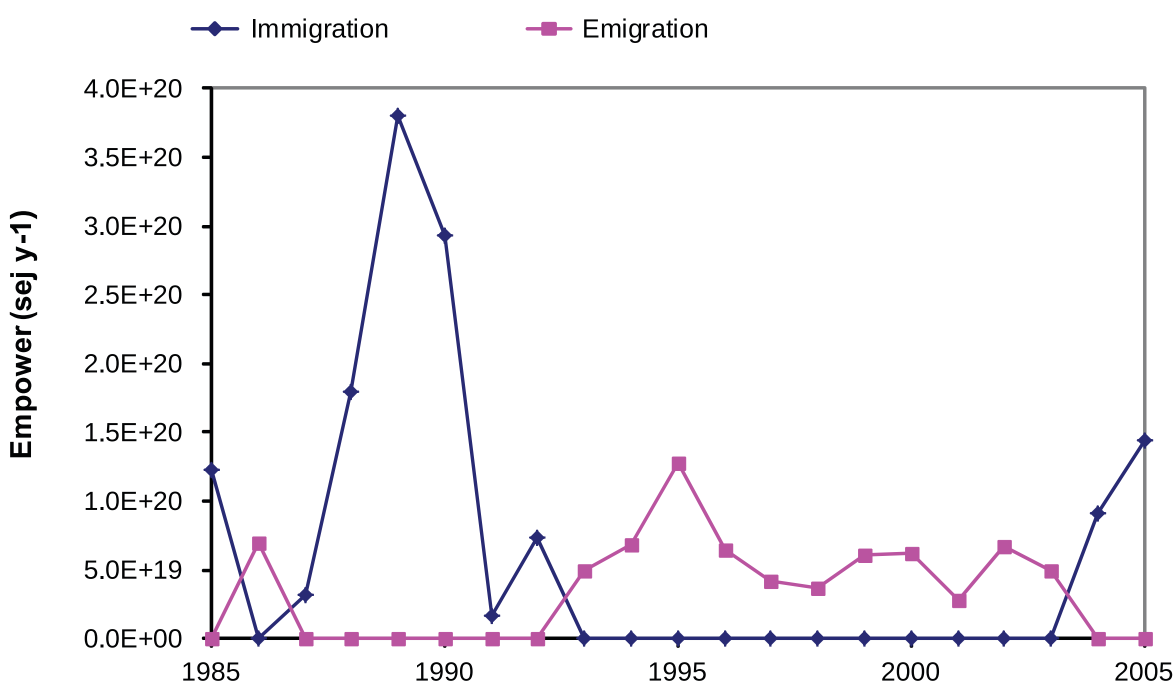

Figure 5-G.2 – The change in annual empower from net immigration or emigration from 1985 to 2005.

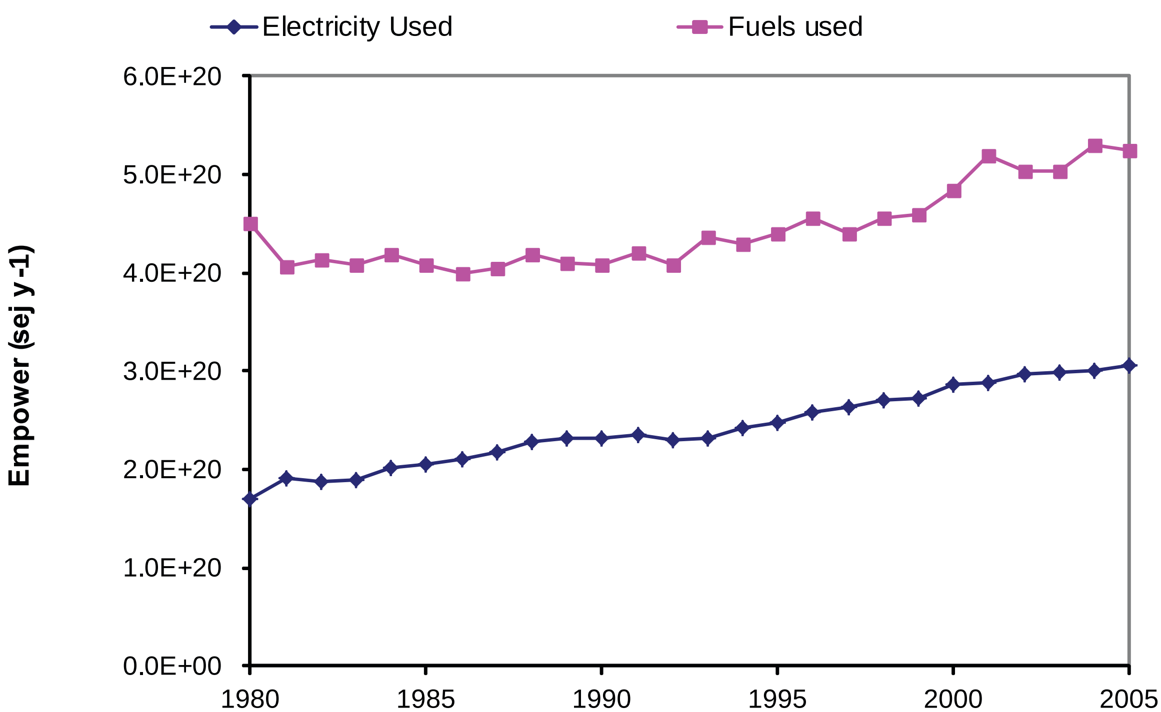

Figure 5-G.3 – The emergy of fuels and electricity used per year in the San Luis Basin from 1980 to 2005.

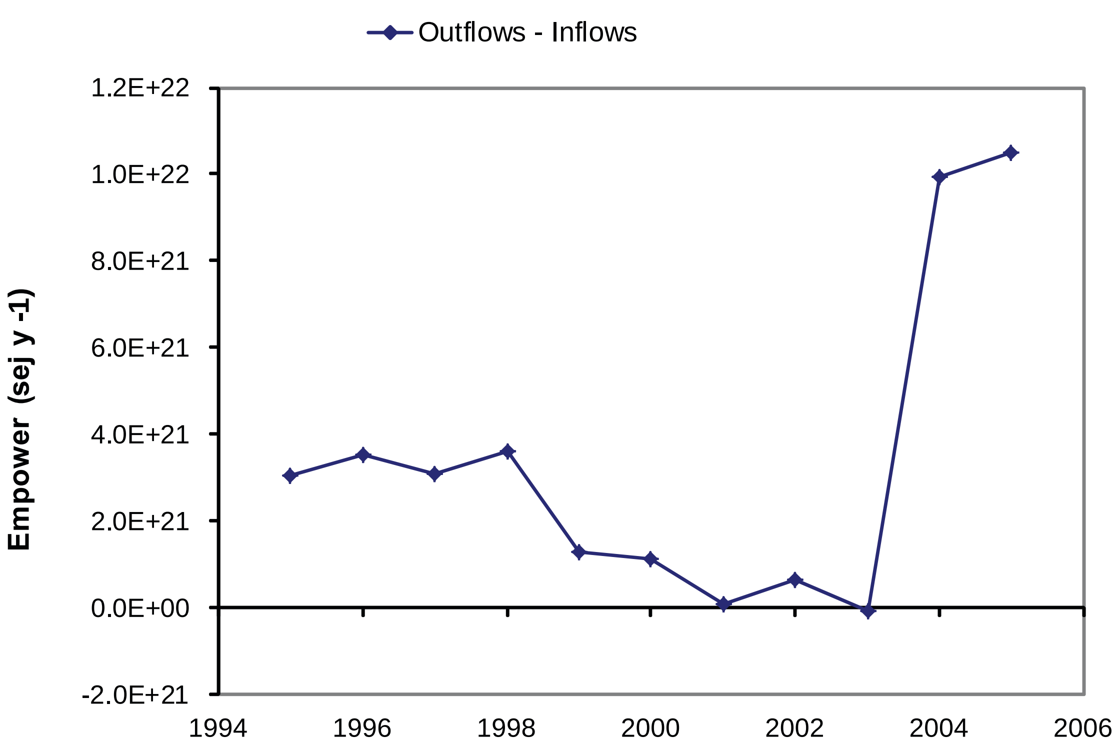

Figure 5-G.4 – The difference between the total emergy outflows ($B+P_2E+N_2$) and total emergy inflows ($R+F+G+P_2I$).

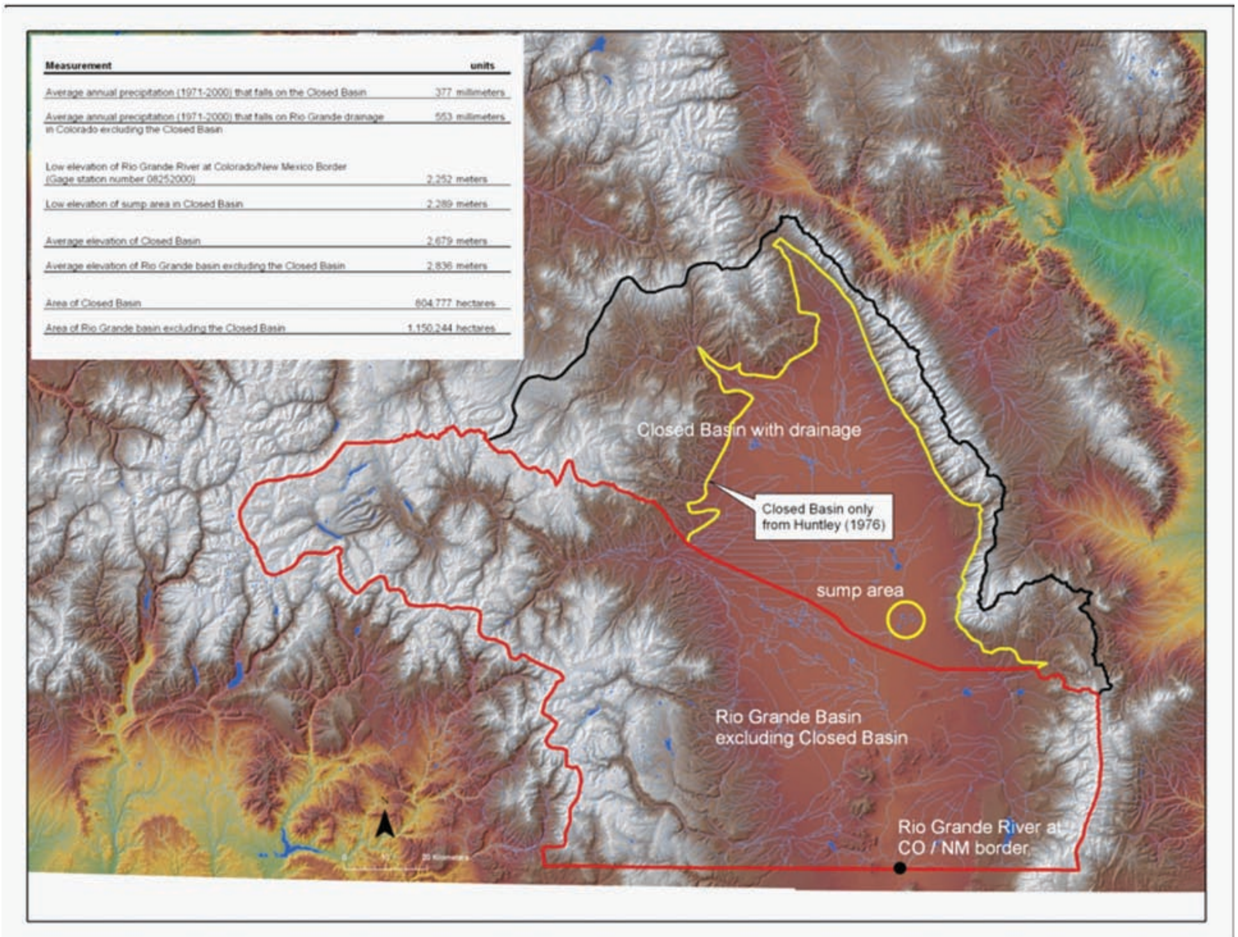

Figure 5-G.5 – Digital elevation model of the Upper Rio Grande River Basin showing the boundaries of the closed and open basins.

6.0
Fisher Information and Order

6.1 Introduction

This chapter presents the theory, data, and methodology for using Fisher information (FI) to assess the dynamic order and overall stability of the San Luis Basin (SLB) regional system. In this chapter we provide background on the method, details of the numerical approach, and include a simple example demonstrating the computation method. Further, we delineate the data used to compute FI for the SLB, present results from the FI analysis and discuss the strengths and weaknesses of the approach.

Fisher information is a key method used in information theory and provides a means of monitoring a broad range of system variables to characterize the dynamic order of a system, to include its regimes, and identify regime shifts (Cabezas et al. 2003). Fisher information has not traditionally been used as a metric of sustainability, and its application to sustainability is, in fact, a relatively new concept. However, its usefulness as a measure of sustainability has been documented in the peer-reviewed scientific literature (Cabezas and Fath 2002, Cabezas et al. 2003, Fath et al. 2003, Karunanithi et al. 2008, Mayer et al. 2007) over a wide array of applications ranging from real and modeled ecosystems to climate.

We have used FI as a metric in the SLB project because it captures a critical aspect of the system that the other metrics do not. Well-functioning economic, ecological, and social systems may be necessary to preserve the self-organization and resilience of an environmental system and FI captures these aspects. Conceptually, the repeatability of observations denotes order in dynamic systems (Karunanithi et al. 2008). Therefore, a dynamic system is said to be well functioning and orderly when its behavior over time follows characteristic, regular, and nearly predictable patterns. FI captures organization and resilience by assessing the dynamic behavior of systems.

To illustrate this point, we offer three examples. First, consider that biological systems have elaborate mechanisms that allow them to maintain a specific degree of organization (Kauffman, 1993). The fact that an ecosystem can be identified as such is itself evidence that it has observable properties that, although variable, are still sufficiently stable to define the system. Indeed, the properties do vary, but they do so in a characteristically orderly and almost predictable manner. Further, as a system experiences a regime shift (i.e., loss of characteristic properties), the variation of key properties generally increase (Carpenter and Brock 2006) which causes a loss of order. Second, similar arguments can be made for markets that are left to operate freely. The observable properties of the markets follow regular patterns, which indicate order. Movement toward market equilibrium helps to predict how prices will change (Maurice and Phillips 1992). The existence of patterns in the markets (i.e., prices as rationing and signaling devices) allows consumers and producers to make decisions with the expectation of particular results (Mankiw 2009; Maurice and Phillips 1992). Finally, consider that the four seasons of the year constitute an orderly dynamic system because the seasons succeed each other in regular, although not exactly precise, timing year after year (Houghton 2002). Indeed, autumn may sometimes come late and climatic fluctuations can occur; however, the seasons follow a pattern.

In summary, ecosystems and social systems follow very complex but real patterns of change over time. Many processes in ecosystems cycle and change along relatively orderly patterns often driven by the daily and yearly cycles of light, tides and seasons along with longer term decadal, centurial, and other temporal and spatial variations. These cycles, although complex, are sufficiently regular to be studied and understood (Odum 1971). Markets likewise follow complex but orderly patterns and they are sufficiently regular to be studied and understood (Maurice and Phillips 1992). In brief, many systems, when functioning well, show regular characteristic behavior, which is an indication of dynamic order. Accordingly, order, or more specifically dynamic order, is an important and very fundamental indicator of the state or condition of the system (Mayer et al. 2007). It is for this reason that FI has been incorporated into the suite of metrics used to assess sustainability in the SLB project.

6.1.1 Capturing Dynamic Shifts with Fisher Information

When any system, including the aforementioned ones, undergoes a change from one characteristic pattern or set of behaviors to another, the change is generally termed a regime shift. Because no two regimes have the same observable patterns, a regime shift is typically accompanied by corresponding changes in dynamic order, which can be tracked by FI. To illustrate this point, consider the very simple case where a system is represented by one variable (e.g., temperature) which is being measured over time. Keeping in mind that the system here is represented by its temperature only, if the temperature is the same (i.e., within measurement error) every time it is measured, then the system can be said to exist in one state only. This system has as much order as it can possibly have, and the FI associated with the temperature is at a maximum. On the other hand, if the temperature is different every time a measurement is made, even after accounting for measurement error, say the temperature is rising linearly with time, then the system can be said to exist in many different states and the FI is at a minimum. Hence, a system with a well-defined pattern (i.e., constant properties) has high dynamic order and high FI, and a system that has no defined patterns (i.e., constantly changing properties) has low order and low FI. Although these two examples represent extreme behavior, real systems typically function between these extremes.

Further exploring this idea, consider a situation where the aforementioned system is cooled, allowed to remain at a constant low temperature, within measurement error, for a period of time, and then heated to a constant temperature with larger variability, perhaps very small amounts of heat are added or removed randomly. In this case, when the temperature is decreasing, the FI will be very small or zero. Once it reaches a constant low temperature, the FI will be very high. As the system is heated and the temperature increases, the FI will again be very small or zero (during the change), and then increases to a relatively steady FI. However, the final "steady" FI value will be less than the original due to the higher variability in the temperature. The system described here experienced a dynamic regime shift, as there was a noted drop in FI between two stable regimes, one with higher order than the other. From these explorations, it is evident that FI tracks the order and stability of the system. Although we used simple examples to illustrate the very basic relationship between system dynamics and FI, as discussed later, the FI method has been adapted to assess the dynamic changes in complex systems described by multiple and disparate variables.

6.2 Methods

6.2.1 Theory

Fisher information was formally developed by statistician Ronald Fisher as the information obtainable from data when estimating the value of a parameter (Fath et al. 2003, Fisher 1922). It has since been adapted as a measure of dynamic order. Details on the derivation of FI from its original form are provided in Fath et al. (2003), Mayer et al. (2007), Karunanithi et al. (2008), and Appendix 6-A.1. From the derivation, we obtain a representation of FI (denoted here as *I* to preserve the historical context; Fisher 1922, Frieden, 1998, 2004, Karunanithi et al. 2008, Mayer et al. 2007) based upon the probability of a system p(s) being in a particular state (s):

$$I = \int \frac{ds}{p(s)} \left[\frac{dp(s)}{ds} \right]^2 \tag{6.1}$$

From this expression, an approach was developed that affords the ability to assess the dynamic order of real systems and is derived as follows. In order to minimize calculation errors from very small probability values, we replace p(s) in Equation 6.1 with its amplitude, which is defined, by $q^2(s) \equiv p(s)$, such that:

$$\frac{dp(s)}{ds} = 2q(s)\frac{dq(s)}{ds} \therefore \left(\frac{dp(s)}{ds}\right)^2 = 4q(s)^2\left(\frac{dq(s)}{ds}\right)^2 \tag{6.2a}$$

Substituting Equation 6.2a into Equation 6.1, the expression becomes:

$$I = 4\int \left[\frac{dq(s)}{ds} \right]^2 ds \tag{6.2b}$$

Equation 6.2b is adapted for use with discrete data by using a summation to approximate the integral and replacing ds and dq(s) with $\Delta s = s_i - s_{i+1}$ and $\Delta q = q_i - q_{i+1}$, such that:

$$I \approx 4\sum_{i=1}^{m} \left[\frac{q_i - q_{i+1}}{s_i - s_{i+1}} \right]^2 (s_i - s_{i+1}) \tag{6.2c}$$

In Equation 6.2c, m is the number of states and s_i is merely an index denoting a particular state of the system (e.g., s_1 is state 1, s_2 is state 2, etc.). Accordingly, $s_i - s_{i+1} = 1$ and Fisher information is then:

$$I \approx 4\sum_{i=1}^{m} [q_i - q_{i+1}]^2 \tag{6.3}$$

Equation 6.3 is our working expression for computing the FI metric.

6.2.2 Calculation Methodology

The basis of computing FI is assessing changes in the probability of observing different states of the system through time. Therefore, we must obtain information on its condition (state) over time. Borrowing from standard statistical mechanics approaches, we define a system by n measurable variables (x_i) that characterize the system and its state at any point in time (Mayer et al. 2007). Note that the correlation structure of the variable time series is not critical, because our goal is to assess changes in dynamic order and not to develop a predictive model of system behavior. By describing a dynamic system in this way, it is said to have a trajectory in a phase space representing all possible states of the system in n-dimensions and time. In the absence of measurement error, each point in phase space is defined by specifying a value for each of the variables at a point in time, pt_i: ($x_1(t_i)$, $x_2(t_i)$ $x_3(t_i)$…x_n (t_i)). However, because measurements of real system parameters contain error (i.e., uncertainty), the state s of the system is delineated by a region rather than a point. In other words, two points that differ from each other by less than the measurement error are indistinguishable and can be thought of as two measurements within the same state. Conversely, two points that differ from each other by more than the measurement error are, in fact, two legitimately different points and consequently, exist in two distinct states of the system. From this conceptual description, we have a foundation for understanding the process of characterizing a dynamic system and assessing changes in its state over time.

In order to capture the dynamic behavior of a system, once the variables characterizing its state have been gathered, the time period is divided into time windows. We achieve this by first defining a parameter (*hwin*) that denotes the size (in time steps) of each window and then determining the amount of overlap (in time steps) desired for each window (*winspace*). The parameters *hwin* and *winspace* denote the integration window parameters used to move through the time series data by creating a sequence of overlapping windows such that *hwin* > *winspace* as shown in Fig. 6.1. This convention affords the ability to compensate for changes in dynamic behavior that may extend beyond the boundary of each window. The probability densities p(s) and corresponding FI are computed within each of these windows. Whereas *hwin* is selected based upon the amount of data available, we have empirically found that it should be at least eight time steps. The next step in the procedure is "binning" each point within the time windows into discrete states of the system. Estimating the uncertainty of the variables is key to defining the states of the system.

As previously mentioned, inherent in any measurement is a level of uncertainty. Accordingly, we define a parameter Δx_i as the measurement uncertainty for each variable (x_i) such that, if the condition:

$$\left| x_i(t_i) - x_i(t_j) \right| \leq \Delta x_i \tag{6.4}$$

is true for all variables at time t_i and t_j then the two points are indistinguishable and subsequently, grouped in the same state (i.e., binned together). Because multiple variables are used to characterize a system and each variable has a distinct measure of uncertainty, a state is represented as an n-dimensional hyper-rectangle where each side is defined by an uncertainty (Δx_i) for each variable. Therefore, this Δx_i is the size of the states for the system.

Typically, knowledge of the measurement uncertainty of underlying state variables is unknown; therefore, we have developed approaches for estimating Δx_i. One tactic is to find a relatively stable time period within the system trajectory, calculate the variation in each variable in this period, and assume this to be the measurement uncertainty. This approach is implemented by calculating the standard deviation (SD) for each variable in the "stable" period and applying Chebyshev's inequality, which is defined by:

$$P(\left| X - \mu \right| < kSD) \geq \left(1 - \frac{1}{k^2} \right) \tag{6.5}$$

and indicates that independent of the type or form of the probability distribution, "The proportion of the observations falling within k standard deviations of the [population] mean is at least $1\text{-}1/k^2$" (Lapin 1975: 58). Therefore, we define the *size of states* parameter (Δx_i) as a function of SD, such that $\Delta x_i = \pm kSD_i$. By setting k = 2, $\Delta x_i = \pm 2SD_i$ at least 75% of the data would occur within this level of uncertainty. This provides a lower bound for the probability of values being k standard deviations from the mean. However, the probability could be much higher (>95% at k=2) if, for instance, the data are normally distributed. Given that each variable has a unique measure of uncertainty, the *size of states* then is noted as a row vector $\Delta x_i = [kSD_1, kSD_2 \ldots kSD_n]$, where k is a scalar constant. Another method of defining the *size of states* is by locating a similar system that exhibits stability and using the variation within this system as a measure of uncertainty for the system under study.

Once the integration window parameters (*hwin* and *winspace*) and *size of states* (Δx_i) are determined, the data may be distributed (binned) into different states of the system. The binning process begins with the first point within the time window taken as the center of the first state. A hyper-rectangle with the side lengths defined by Δx_i for each variable is established around the point, such that all of the points falling within its boundaries are considered to be in the same state. Then, the next unbinned point in the window is assumed to be the center of a new state, a new hyper-rectangle is constructed around it, and all the points within its boundaries are binned into that state. The process continues until all of the points within the first window are binned and is repeated for the remaining time windows until all of the points in each window are binned into states of the system and the data are exhausted.

When measurement uncertainty of the underlying state variables is known and independent, the binning process alone would work well in defining states of the system. Unfortunately, data collected from public sources, as in this project, often do not report the uncertainty associated with their data. Accordingly, an additional step is implemented to mitigate the effect of data error by applying a tightening level parameter (Karunanithi et al. 2008). The tightening level (TL) adjusts the binning criteria such that a point can be declared to be within a given hyper-rectangle (particular state of the system) when at least a certain percentage of the variables meet the *size of states* criteria (Equation 6.4). The percentage itself is the tightening level. For example, if a system is characterized by 100 variables and 95 of the variables indicate that a particular point fits within the state being evaluated, then the two points would be binned together at a 95% tightening level. Therefore, points may be binned into a particular state of the system if the *size of states* criteria is true for all variables in particular time steps or the number of variables that satisfies the *size of states* criteria is greater than the product of the tightening level (TL) and the total number of variables (Fig. 6.2). When all of the points in a window are binned into states at a given tightening level, a probability distribution (p_i) is generated for each window using:

$$P_i = \frac{\#\ points\ in\ state}{total\ \#\ points\ in\ time\ window} \tag{6.6}$$

Next the amplitude, q ($q_i = \sqrt{p_i}$) is calculated for each state and FI for the time window is computed using Equation 6.3. The computed FI value itself is assigned to the middle of each time window (see example in Fig. 6.1). Because there are no rigorous criteria for setting the tightening level, FI is computed for multiple tightening levels between strict and relaxed tightening. Rather than establishing an arbitrary lower bound for the tightening level, relaxed tightening is set as the lowest tightening level at which more than one state is observed in the window and FI is calculated by taking the arithmetic average of FI between strict tightening (TL=100%) and lower bound (relaxed tightening level). Note that this results in multiple p_i and FI values for each window (Karunanithi et al. 2008). The final FI reported in each window is again an average over the tightening levels from strict to relaxed tightening. Finally, in accordance with the Sustainable Regimes Hypothesis (see section 6.2.3), a regime is denoted as sustainable when the dynamic order does not change with time (i.e., ($d\langle FI\rangle / dt \approx 0$) where <FI> indicates a mean FI value). The <FI> is calculated by computing the mean of neighboring FI values. This convention affords the ability to focus on trends in dynamic order and not fluctuations. As such, Equation 6.7 is used to compute a three-point mean, $<\mathrm{FI}>_j$ for window *j*:

$$<\mathrm{FI}>_j = \frac{1}{3}\left(FI_{j+1} + FI_j + FI_{j-1}\right)$$

$$j = w\text{-}1,\ w\text{-}3,\ w\text{-}5,\ w\text{-}7,\ldots \tag{6.7}$$

where *w* is the year corresponding to the last window of the original FI computation. Based on our experience, the three-point mean tends to preserve trends and deemphasize short fluctuations. The $<\mathrm{FI}>_j$ is computed in reverse order to ensure that the more recent period is not omitted when <FI> is evaluated. However, given that a true measurement of uncertainty is unknown for the metrics or underlying variables, we can visually inspect the trends, but we cannot test for statistical significance.

6.2.3 Interpreting Fisher Information

The Sustainable Regimes Hypothesis encompasses conceptual ideas governing the use and interpretation of FI as a metric for assessing sustainability (Cabezas and Fath 2002, Karunanithi et al. 2008). In summary, the hypothesis states that: 1) well functioning systems exist within an orderly dynamic regime with non-zero FI that does not change with time (i.e., ($d\langle FI\rangle / dt \approx 0$); 2) steadily decreasing FI signifies a progressive loss of dynamic order and denotes a system that is becoming disorganized and losing functionality; 3) steadily increasing FI indicates that the system that is becoming more ordered (although, not necessarily more desirable by humans); and 4) a steep decrease in FI between two dynamic regimes denotes a regime shift (Karunanithi et al. 2008). As a note, both conditions of statement 1 must be true for a system to be considered sustainable. In other words, a completely disorganized system has no order over time; therefore, a system with <FI> ≈ 0 is not sustainable even if $d\langle FI\rangle / dt \approx 0$.

Important elements in regime shift detection are determining the occurrence, pervasiveness, and intensity of a shift (Karunanithi et al. 2008). The fourth statement of the Sustainable Regimes Hypothesis indicates that a regime shift has occurred when there is a significant drop in FI between two dynamic regimes. Once a regime shift has been detected, the intensity simply relates to the level of the drop in FI (e.g., a more severe shift has a steeper drop). The pervasiveness of the shift relates to the number of system variables affected by the shift and is characterized by varying the tightening level and noting the lowest tightening level at which a particular shift can be detected. Recall, that the tightening level relates to the number of variables that must meet the *size of states* criteria for binning. Accordingly, the more relaxed (lower) the tightening level at which the regime shift is recognized, the more pervasive the shift.

6.2.4 Computing Fisher Information: A Simple Example

Below a simple example is used to demonstrate the procedure for computing FI. From Section 6.2.2, the basic algorithm is as follows: (1) establish the size of the time windows (*hwin*), (2) determine the time increment that the window will be moved forward (*winspace*) to create overlapping windows, (3) set a tightening level (TL), (4) bin all of the points into states within each window, (5) compute the probability density for each state in each time window – the result at this point will be a sequence of probability densities p_i for each time window, (6) calculate FI from the q_i in each time window, (7) set a new tightening level, (8) repeat steps 4 through 7 until all the computations have been done from strict tightening (TL = 100%) to relaxed tightening (the lowest TL at which more than one state is present in the window), (9) compute an average FI for each window over the tightening levels from strict to relaxed tightening and (10) calculate <FI> (mean FI) values for the system.

For the sake of simplicity, we used two demographic variables (population and personal income) from the SLB data (Fig. 6.3). Because the goal of this exercise is simply to step through the computation algorithm, we used the guidelines for the integration window parameters (see section 6.2.2) and selected values for *hwin* and *winspace* that met the criteria. Recall that the parameters should be set such that *hwin* ≥ 8 and *winspace < hwin.* Accordingly, we set *hwin* to eight time steps (years) and *winspace* to three time steps to ensure we ended up with a manageable number of windows for this computation demonstration. To provide insight into how the integration window parameter settings may affect the computation result, we performed a sensitivity analysis to examine the impact changes in these parameters have on FI (Appendix 6-B). However, the sensitivity analysis is not a requirement for setting *hwin* and *winspace*. The only specific parameter guidelines are provided in section 6.2.2.

Following the basic algorithm already described, we used the *hwin* and *winspace* values to partition the data into over lapping windows (Table 6.1). Next, we set the tightening level (TL) at 100% to include all variables in the computation and then binned the points into states of system within each window (Fig. 6.2). The purpose of binning is to determine the state of the system over time and the basis of this process is grouping points (e.g., $pt_1=(x_1(t_1), x_2(t_1))$ within an established boundary of uncertainty. As explained in section 6.2.2, if the level of uncertainty for the variables under study is unknown, it may be estimated. In this case, it was estimated by assuming a measurement uncertainty by computing the standard deviation (SD) of each variable over the first five time steps. Each SD was then multiplied by two in accordance with Chebyshev's theorem (Lapin 1975: 58), such that the level of uncertainty (Δx_i) defined as $\pm kSD_t$, is a 1×2 vector: $\Delta x_i = [2\times SD_1, 2\times SD_2]$ = [86285.39, 1639.83]. From Fig. 6.2 and Equation 6.4, if the tightening level multiplied by the total number of variables in the time series meet the *size of states* criteria (i.e., $|x_i(t_i) - x_i(t_j)| \le \Delta x_i$) then the two points at t_i and t_j are binned in the same state. The differences were computed by subtracting the value of the variables at each time step starting with the first point in the window (Table 6.2). For example, the difference between variable x_1 at time =1 and time = 2, i.e.,$|x_1(t_2) - x_1(t_1)|$ = |314914-310352| = 4562.

A "bulls-eye" (radar) plot of the differences provides a visual depiction of point binning (Fig. 6.4). The first binning pass starts with assessing the distance from pt_1, accordingly, pt_1 is the center of this figure with an absolute difference value of (0, 0) and the remaining absolute differences are plotted on the corresponding axis (e.g., 2-1 = ($|x_1(t_2) - x_1(t_1)|$, $|x_2(t_2) - x_2(t_1)|$) = (4562, 511)). The red and blue lines represent the boundary of uncertainty (i.e., *size of states* = Δx_1 and Δx_2) around the center for each variable. Points 1, 2, and 3 are binned into state 1, because pt_2 and pt_3 are within the boundary of uncertainty (i.e., less than Δx_i from pt_1). The process then moves to the next "un-binned" point (pt_4), establishes it as the center of state 2 and then bounds state 2 as Δx_i from pt_4, such that points 4-8 are binned into state 2. The binning procedure continues to the next window until all points have been binned into a state of the system. Once all the points have been binned, then probability densities are computed for each window using Equation 6.6. In window 1, there were three points binned into state 1 and five in state 2 resulting in a 37.5% chance (p(1)=3/8) that the system is in state 1 and a 62.5% chance that it is in state 2. This process was repeated for each window, resulting in probability densities for each window (Fig. 6.5). Next, the amplitude ($q(s) = \sqrt{p(s)}$) was computed for each state (Table 6.3). To compute FI for each time window, the gradients of the amplitude ($q_i - q_{i+1}$) were used as in Equation 6.3 (see Fig. 6.6). At this point, the tightening level may be decremented (i.e., TL = TL-1) and the computation steps repeated as articulated in section 6.2.2. This produces FI values for the time series for TL ranging from strict to relaxed tightening. An average FI result is calculated by taking the average of all FI values computed within TL range. For this exercise, we only computed FI at TL = 100% and then used Equation 6.7 to calculate a three-point <FI> to smooth any fluctuations in the result and focus on the general trend of the metric (Fig. 6.7). Further details for using the code and graphical user interface (GUI) to compute FI are provided in Appendices 6-C and 6-D. The procedure for computing FI has been automated in MATLAB (Release 2009a; Mathworks, Inc.) so that only time series data that characterize the system, *size of states*, *hwin*, and *winspace* need to be provided by the user to perform the analysis. The code is provided in Appendix 6-E.

6.3 Computing FI for the San Luis Basin: Data and Sources

To assess dynamic order in the SLB, we needed data that characterized the state of the system. Accordingly, it was necessary to gather data that represent environmental, social, and economic aspects of the region. Because the variables used to compute the other metrics satisfied this criterion, data for this project were selected from the datasets used to calculate EFA, GNRP and EmA (Chapters 3, 4, and 5, respectively). However, any data that adequately characterize a system may be used to calculate FI. Further, we selected variables that contained data for the entire 26 years of the study (1980 - 2005). Each of the variables was assigned to one of six categories for computing FI and encompassed information on consumption (food and forest), environment, and demographic characteristics, as well as, the energy consumption, land use, and agricultural production aspects of the SLB (Table 6.4). Details on each variable are provided in the corresponding chapters (Chapters 3-5).

6.4 Calculation Methodology

Following the approach described in sections 6.2.2 and 6.2.4, as well as, the guidelines for computing FI using MATLAB (Appendices 6-C and 6-D), the GUI (Main_Fisher_data_proc.m) was used to compute both FI and <FI>. The file containing data for the 53 variables over 26 years, the time file which indicates the years examined (i.e., 1980, 1981, 1982,… 2005), and the file containing the *size of states* were selected. Following the guidelines in Section 6.2.2, the *size of states* for the SLB was determined using a small number of years where data were relatively stable. Thus, the *size of states* was defined by calculating the SD of the first five data points (years) for each variable and then (in accordance with Chebyshev's inequality) multiplying the result by 2 (k = 2).

Given the amount of data and the results of the sensitivity analysis (Appendix 6-B), the time window was set to be eight time steps (*hwin* = 8) and the window increment was set to one time step (*winspace* = 1). Thus, FI was integrated over an eight-year window that was moved in one-year increments. The FI value reported represents the FI computed over a specific period and is reported in the center of that window (i.e., FI for 1984 = 1980-1987, FI for 1985 = 1981-1988, FI for 1986 = 1982-1989, etc). The <FI> (for each window *j*) was calculated using Equation 6.7, such that the $\langle FI \rangle_j$ reported is a mean placed in the center of the three points used to calculate it (e.g., $\langle FI \rangle_{2001} = (FI_{2000} + FI_{2001} + FI_{2002})/3$). Further, in order to explore drivers potentially responsible for changes in dynamic order of the system overall, we compared FI of the overall system (included all 53 variables) to that of the variables grouped by categories (e.g., energy consumption). Spearman's rank correlation coefficient analysis was used to assess the relationship between the dynamic order of the system and the variables by category. The statistical significance level established was $P \leq 0.05$.

6.5 Results

FI was computed for the SLB over the 26 years of the study and ranged in value from 2.92 in the period centering 2001 to 4.37 in the period centering 1996 (Fig. 6.8). <FI> ranged from 3.22 in the period centering 1986 to 3.89 in the period centering 1995 (Fig. 6.9; Table 6.5). The system <FI> increased initially, peaked in the period centering 1995, and then decreased slightly thereafter.

The minimum <FI> in the system in 1986 corresponded (visually) to a minimum <FI> in the consumption (food and forest) and agricultural production categories (Fig. 6.10). The peak in the system <FI> in 1995 corresponds (visually) to a peak in the <FI> of the environmental and energy categories, as well as, agricultural production which increases up to 1992 and essentially remains steady until 1998 (Table 6.5; Figs. 6.9 and 6.10). Although the <FI> of consumption (food and forest) category remains relatively steady, the <FI> of the other categories exhibit larger changes over time.

Similar to the overall system, dynamic order of the agricultural production category rose from 1989 to 1992, was relatively steady until 1998, and decreased thereafter (Fig. 6.10). The opposite was true of the demographic variables as the <FI> peaked in 1989, decreased from 1989 to 1995 and increased thereafter. By the end of the study period energy, environment, and demographic categories exhibited an increasing trend (Table 6.5; Fig. 6.10). Further, Spearman's rank analysis indicated a significant, negative correlation between the overall system and the demographic category ($r = -0.88$, $df = 4$, $P = 0.033$).

6.6 Discussion

According to criteria in the Sustainable Regimes Hypothesis (Section 6.2.3), the results of this <FI> assessment indicated that although there were changes in <FI> over time, <FI> was relatively steady during the period and there was no indication of an overall system regime shift (i.e., no sharp drop between two regimes). The dynamic order of the system increased up to 1995 and exhibited a small decrease thereafter. Although the demographic, energy, and environmental categories showed an increase in dynamic order at the end of the 26 years, the overall system, consumption (food and forest), land use, and agricultural production categories indicated a decreasing trend in <FI> which may denote some movement away from sustainability (i.e., decreasing dynamic order). There was, however, no sharp drop in <FI> that could indicate a regime shift.

Spearman's rank analysis indicated that there is an inverse relationship between the demographic category and that of the overall system. Toward the goal of policy setting and decision making, variables within a category may be explored to uncover possible drivers of dynamic behavior. As an illustration, a closer look at the FI of the demographic category revealed that changes in dynamic order seem to correspond to changes in the underlying variables (e.g., population and personal income). Because FI is a measure of system order, increases in variability of the system variables generally result in decreasing FI. As a simple exploration to see if we could identify such variables, we computed the annual percent change in the demographic variables as a measure of variability. While population generally increased during the period examined, the percent change varied during the 26 years (e.g., +1.6% from 1982 to 1983 and +0.9% from 1983 to 1984 graphically is a decrease). Further, unlike the percent change in personal income over time, the percent change in population decreased initially, peaked in 1995, and decreased thereafter. A visual comparison of these patterns and demographic FI suggests, the variation in population (as described by percent change) appears to be inversely proportional to demographic FI (i.e., low variation in demographic data corresponds to high FI values). For that reason, changes in annual percent change of population seem to correspond to changes in dynamic order of the demographic category (Fig. 6.11). From this simplified approach, there appears to be a relationship; however, other techniques (e.g., sensitivity analysis) to explore the effect of changes in underlying variables on FI may help determine which variables drive changes in dynamic order.

In summary, there was no indication of a regime shift in the overall system. Although, the system exhibited small changes in dynamic order during the 26 years, we conclude the SLB is relatively stable with a slight indication of possible movement away from sustainability near the end of the period.

6.7 Strengths and Weaknesses

One of the key strengths of FI is the ability to collapse data from complex, multivariate systems into a fundamental metric that can be computed over time and used to evaluate the dynamic behavior of systems. This is important because the characterization of complex, integrated systems for sustainability (social, ecological, and economic systems) often requires a large number of disparate variables. Traditional approaches to assessing regime shifts and system dynamics (e.g., variance) have typically only been demonstrated on simple model systems and work must be done to determine whether these methods can be used to evaluate real, complex systems (Scheffer et al. 2009). However, the calculation of dynamic order using FI is insightful, theoretically sound, and provides a means of evaluating both model and real systems that are characterized by multiple, disparate variables.

As is the case for many methods used to analyze complex systems, the computation of FI has its challenges. Some of the challenges include establishing the integration window parameters (i.e., *hwin* and *winspace*), the need for determining the measurement error for each variable (used to set the *size of states*), and the availability and quality of data to characterize the system. The integration window parameters are used to traverse through the time series data and establish overlapping windows for the FI computations. These parameters must be carefully selected based on amount of data available and knowledge of the system. The *size of states* is a key parameter used for binning points into states of the system and is based on estimating the amount of error present in the data. Strategic recommendations for determining the *size of states* and the integration window parameters were provided in sections 6.2.2 and Appendix 6-B, respectively. Data availability and quality issues are discussed in Chapter 7.

Another challenge is that because PDFs are used to calculate FI, one FI value is provided in each time window and reported in the center of that period. Accordingly, there is a unique FI for each time window and not each time step. Hence, FI values tend to come several years behind the latest data point (e.g., the last data were for 2005, but the last FI value was for 2001). Moreover, according to the Sustainable Regimes

Hypothesis, in order to capture the trends (and not fluctuations) in the dynamic order, a <FI> is calculated. We therefore use a three-point <FI> to evaluate trends in dynamic order over time. Based on our experience with these calculations, three points seem to smooth the result, while maintaining the characteristic changes in dynamic order associated with trends.

Further, the methodology can identify if a system is either maintaining its current order (i.e., $(d\langle FI\rangle / dt \approx 0)$or losing dynamic order $(d\langle FI\rangle / dt < 0)$ and heading toward or already experiencing a regime shift (i.e., a sharp drop in <FI> between two stable regimes). The loss of dynamic order, and certainly a regime shift, indicates the system is moving away from sustainability. However, an increase in <FI> indicates the system is gaining order, yet does not necessarily mean the system is moving toward a more preferable state (i.e., sustainability) in terms of human wants and needs (Karunanithi et al. 2008). Hence, FI is a one-sided test of sustainability and care must be taken on interpreting changes in dynamic order with reference to human preferences.

Lastly, we acknowledge that the details of the conceptual underpinning of FI analysis can be quite abstract and, perhaps, difficult for many potential users to understand. However, we also believe that anyone with a good grounding in science or engineering can understand the fundamental concept sufficiently to apply the method and interpret the results appropriately. We note that practical and effective end users of methods and technologies in many professions are not necessarily experts in the theory behind the tool being used. For example, most physicians are not experts in Quantum Mechanics, yet they can effectively use Magnetic Resonance Imaging (MRI) and interpret the results. Use of MRI may involve a medical technologist who serves as a bridge between those who designed the MRI and the physicians that interpret and use the results. The point here is that it should be possible to make the benefits of otherwise abstract concepts (such as FI) available to non-expert end users through software and/or individuals that act as intermediaries. To help make the concept more accessible, we provided an example of the computation and interpretation of FI using a simple example of dynamic order (Section 6.2.4). Further, we provided the MATLAB code necessary to compute FI and stand-alone software with a GUI to simplify calculating FI. The GUI improves the usability of the metric by automating the computation process.

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Table 6.1 – Data were divided into a sequence of overlapping time windows. The eighth window was removed because there were not enough data in the time series to place in it. Therefore, all data were accounted for within seven windows. t = time (i.e., 1980-2005), x_1 = Population and x_2 = Personal income (in thousands). Point 1 (pt_1) was defined by $(x_1(t_1), x_2(t_1))$ and is highlighted as 310352, 38469.

$pt_1 = (x_1(t_1), x_2(t1)) =$ (310352, 38469)

	Window 1				Window 2				Window 3		
#	t	x_1	x_2	#	t	x_1	x_2	#	t	x_1	x_2
1	1980	310352	38469	4	1983	384256	40112	7	1986	431318	40804
2	1981	314914	38980	5	1984	400888	40490	8	1987	436775	41104
3	1982	318946	39467	6	1985	424601	40369	9	1988	448738	41289
4	1983	384256	40112	7	1986	431318	40804	10	1989	504014	40903
5	1984	400888	40490	8	1987	436775	41104	11	1990	551552	40682
6	1985	424601	40369	9	1988	448738	41289	12	1991	549641	41283
7	1986	431318	40804	10	1989	504014	40903	13	1992	562981	41120
8	1987	436775	41104	11	1990	551552	40682	14	1993	625715	41466
	Window 4				Window 5				Window 6		
	t	x_1	x_2		t	x_1	x_2		t	x_1	x_2
10	1989	504014	40903	13	1992	562981	41120	16	1995	715547	43793
11	1990	551552	40682	14	1993	625715	41466	17	1996	754872	44566
12	1991	549641	41283	15	1994	661317	42564	18	1997	781542	45289
13	1992	562981	41120	16	1995	715547	43793	19	1998	839246	45902
14	1993	625715	41466	17	1996	754872	44566	20	1999	892574	46377
15	1994	661317	42564	18	1997	781542	45289	21	2000	910329	47097
16	1995	715547	43793	19	1998	839246	45902	22	2001	967522	46907
17	1996	754872	44566	20	1999	892574	46377	23	2002	1042786	47404
	Window 7				Window 8						
	t	x_1	x_2		t	x_1	x_2				
19	1998	839246	45902	22	2001	967522	46907				
20	1999	892574	46377	23	2002	1042786	47404				
21	2000	910329	47097	24	2003	1042145	47598				
22	2001	967522	46907	25	2004	1048231	48207				
23	2002	1042786	47404	26	2005	1097044	48101				
24	2003	1042145	47598	0	0	0	0				
25	2004	1048231	48207	0	0	0	0				
26	2005	1097044	48101	0	0	0	0				

Table 6.2 – Absolute difference of variables x_1 (population) and x_2 (personal income) in each window using the first point as the center. For example, the absolute difference of $x_1(t_1)$ and $x_1(t_2)$ (i.e., $|x_1(t_1) - x_1(t_2)|$ is 4562 as highlighted here in blue and the absolute difference of point 2 from point 1 (i.e., 2-1) is 4562 and 511).

	Window 1			Window 2			Window 3			Window 4	
points	**x_1**	**x_2**	**points**	**x_1**	**x_2**	**points**	**x_1**	**x_2**	**points**	**x_1**	**x2**
2-1	4562	511	5-4	16632	378	8-7	5457	300	11-10	47538	221
3-1	8594	998	6-4	40345	257	9-7	17420	485	12-10	45627	380
4-1	73904	1643	7-4	47062	692	10-7	72696	99	13-10	58967	217
5-1	90536	2021	8-4	52519	992	11-7	120234	122	14-10	121701	563
6-1	114249	1900	9-4	64482	1177	12-7	118323	479	15-10	157303	1661
7-1	120966	2335	10-4	119758	791	13-7	131663	316	16-10	211533	2890
8-1	126423	2635	11-4	167296	570	14-7	194397	662	17-10	250858	3663

	Window 5			Window 6			Window 7	
points	**x_1**	**x_2**	**points**	**x_1**	**x_2**	**points**	**x_1**	**x_2**
14-13	62734	346	17-16	39325	773	20-19	53328	475
15-13	98336	1444	18-16	65995	1496	21-19	71083	1195
16-13	152566	2673	19-16	123699	2109	22-19	128276	1005
17-13	191891	3446	20-16	177027	2584	23-19	203540	1502
18-13	218561	4169	21-16	194782	3304	24-19	202899	1696
19-13	276265	4782	22-16	251975	3114	25-19	208985	2305
20-13	329593	5257	23-16	327239	3611	26-19	257798	2199

Table 6.3 – Amplitude (q(s)) for each window. These values were computed by first counting the number of points in each state within each window, computing a probability for each state in each window (p(s)) and calculating the amplitude, $q(s) = \sqrt{p(s)}$ for each state in each window.

		q(s)			
		1	**2**	**3**	**4**
Window	**1**	0.6124	0.7906		
	2	0.8660	0.5000		
	3	0.7071	0.7071		
	4	0.7071	0.5000	0.5000	
	5	0.5000	0.5000	0.6124	0.3536
	6	0.6124	0.6124	0.5000	
	7	0.6124	0.7071	0.3536	

Table 6.4 – Variables used to calculate FI for the San Luis Basin. These variables were selected from data used to compute EFA, GNRP, and EmA. The data and their sources are discussed in Chapters 3, 4, and 5, respectively. The variables include demographic, energy, land use, food and forest consumption, environmental and agricultural production categories for the system.

Category	**Variable**
Demographic	
	Personal income (thousands of dollars)
	Population (persons)
Energy	
	Coal consumption (short tons)
	Natural Gas Consumption (billion cubic feet)
	Petroleum Consumption (thousand barrels)
	Hydro-electric Consumption (million kilowatt hours; kWh)
	Wood and waste Consumption (trillion British thermal units; BTU)
	Solar Energy Absorbed (Joules per year; J/yr)
	Rain Chemical Potential (J/yr)
	Rain Geopotential on the Land (J/yr)
	Snow Geopotential on Land (J/yr)
	Rain Geopotential as Runoff (J/yr)
	Snow Geopotential as Runoff (J/yr)
Land type	
	Built-up land (hectares; ha)
	Arable land (ha)
	Pasture (ha)
	Forest including deforestation (ha)
Food and forest consumption	
	bovine, buffalo (pounds per capita; lbs/ca)
	sheep, goat (lbs/ca)
	non-bovine (lbs/ca)
	milk (gal/ca)
	cheese (lbs/ca)
	eggs (lbs/ca)
	fish (lbs/ca)
	cereals (lbs/ca)
	wheat (lbs/ca)
	vegetables (lbs/ca)
	maize (lbs/ca)
	fruit (lbs/ca)
	roots and tubers (lbs/ca)
	pulses (lbs/ca)
	coffee and tea (lbs/ca)
	cocoa (lbs/ca)
	oil seed (lbs/ca)
	fats (lbs/ca)
	sweetener consumption (lbs/ca)
	forest harvest (million board feet, MBF)

Category	Variable
Environmental	
	mean precipitation (centimeters; cm)
	Change in ground water storage (acre-feet)
	Change in surface water storage (acre-feet)
	SLB CO_2 emissions
	Evapotranspiration (J/yr)
	Soil Erosion (tons/year)
Food production	
	bovine, buffalo production (kilograms; kg)
	cereal production (kg)
	wheat production (kg)
	animal feed production (kg)
	roots and tubers production (kg)
	Potatoes All (Planted) (unit:acre)
	Wheat Other Spring (Planted) (unit:acre)
	Barley All (Planted) (unit:acre)
	Hay Alfalfa (Dry) (Harvested) (unit:acre)
	Oats (unit:acre)

Table 6.5 – Three-point mean Fisher information (<FI>) for the overall system and the variables grouped by the categories defined in Table 6.4.

Year	System	Consumption	Demographic	Energy	Environment	Land	Production
1986	3.22	3.34	5.02	4.59	3.86	4.82	4.56
1989	3.51	3.93	6.04	4.03	3.39	5.58	4.79
1992	3.64	3.66	4.14	4.63	4.61	6.32	5.99
1995	3.89	4.13	2.77	4.63	4.85	5.12	5.94
1998	3.88	4.48	2.81	3.82	4.32	6.00	6.02
2001	3.58	4.28	3.32	3.93	4.42	4.73	5.03

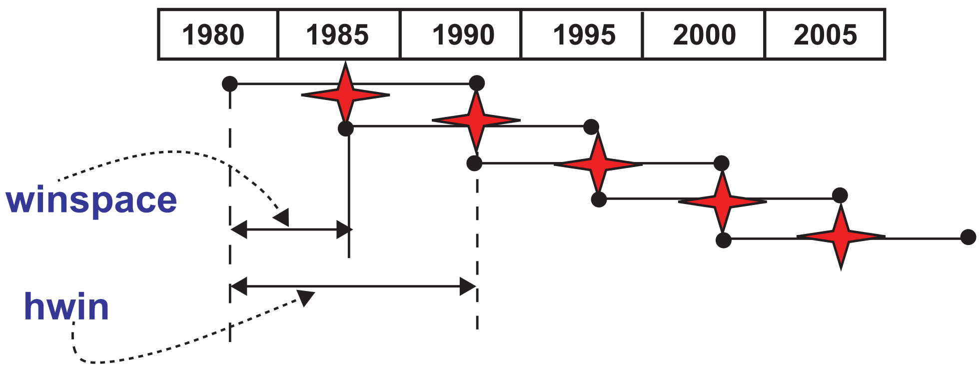

Figure 6.1 – Graphical representation of the sample settings for the Fisher information (FI) computation indicating the size of the integration window (*hwin*) and window increment (*winspace*) in time steps used to move through the data. In this example, *hwin* =10 and *winspace* = 5. The red star indicates the center point of the window denoting the placement of FI.

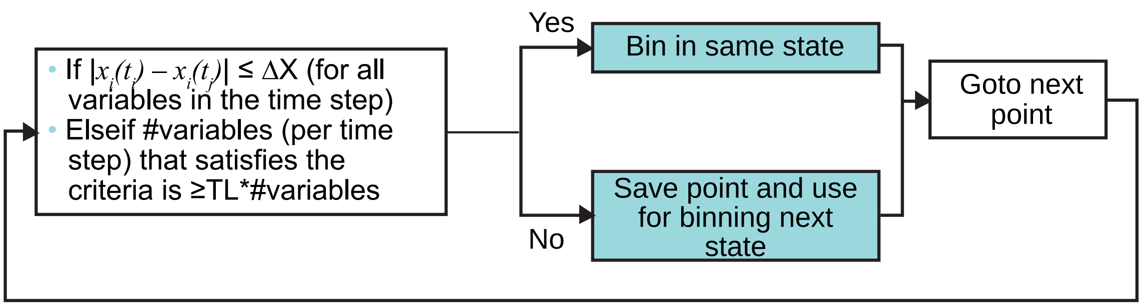

Figure 6.2 – Flow diagram of the binning algorithm in the Fisher information computation. According to Equation 6.4, if each variable $|x_i(t_i) - x_i(t_j)|$ is less than the *size of states* (Δx_i), then the two points at time *i* and *j* are indistinguishable and are grouped (binned) in the same state.

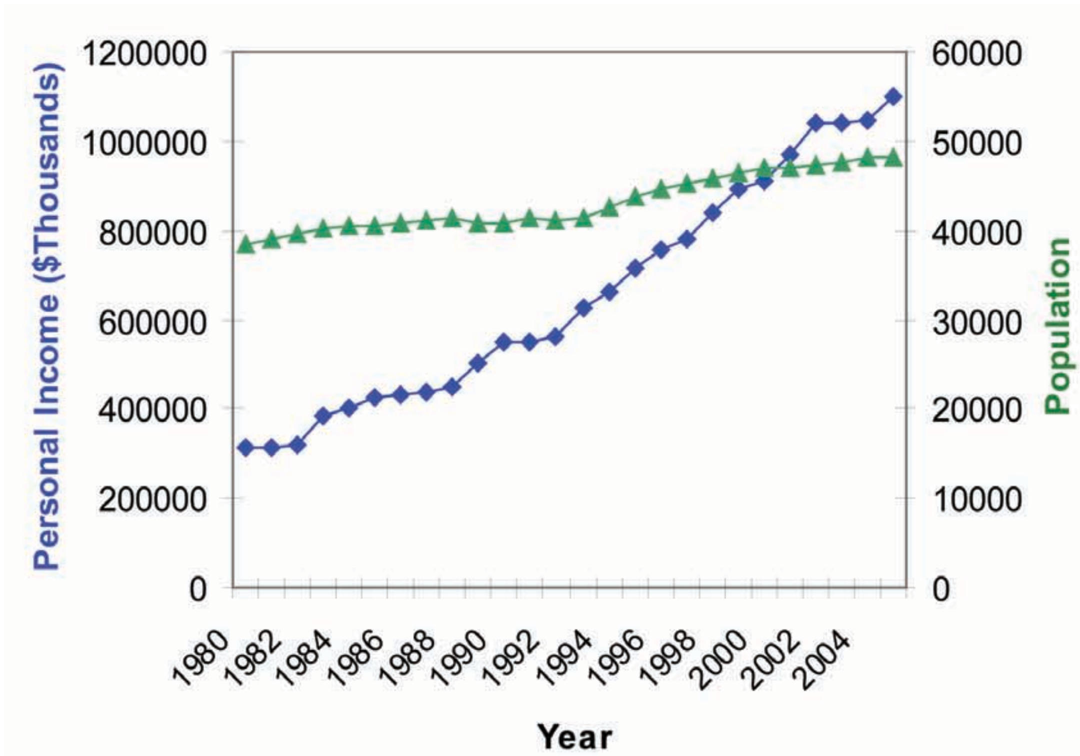

Figure 6.3 – Population (x_1, green triangles) and Personal Income (x_2, blue diamonds) values for the San Luis Basin from 1980 to 2005. These variables were used as data for the example FI computation exercise provided in Section 6.2.4.

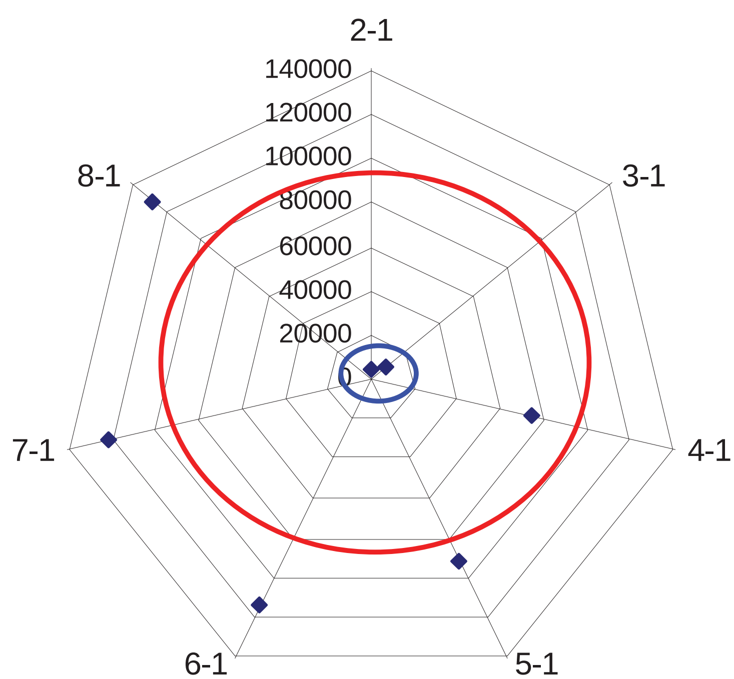

Figure 6.4 – Bulls-eye plot of binning points in state 1 for the simple example. Point 1 (pt_1: $(x_1(t_1), x_2(t_1))$ = (310352, 38469)) is the center of this figure and the absolute difference from pt_1 are plotted on the corresponding axis, e.g., absolute difference 2-1 = (4562, 511). The values plotted are from Table 6.2. As described in Section 6.2.2, the level of uncertainty (i.e., *size of states* (Δx_i)) was computed for each variable such that in this plot Δx_1 and Δx_2 correspond to the red and blue line, respectively. The points are binned in a state when the difference is less than the level of uncertainty (i.e., *size of states*).

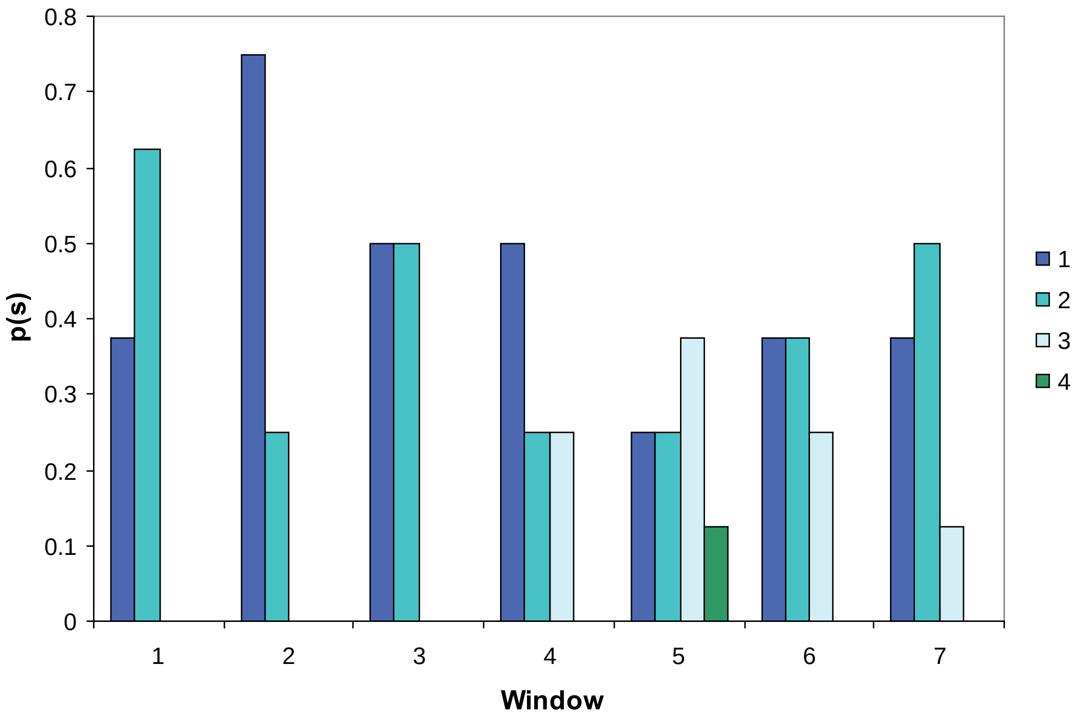

Figure 6.5 – Probability density (p(s)) for each window in the simple example (Section 6.2.4). These values were computed by first counting the number of points in each state within each window and then computing a probability for each state in each window. In window 3, four points were binned in both state 1 and state 2; therefore, the probability was 50% for each state.

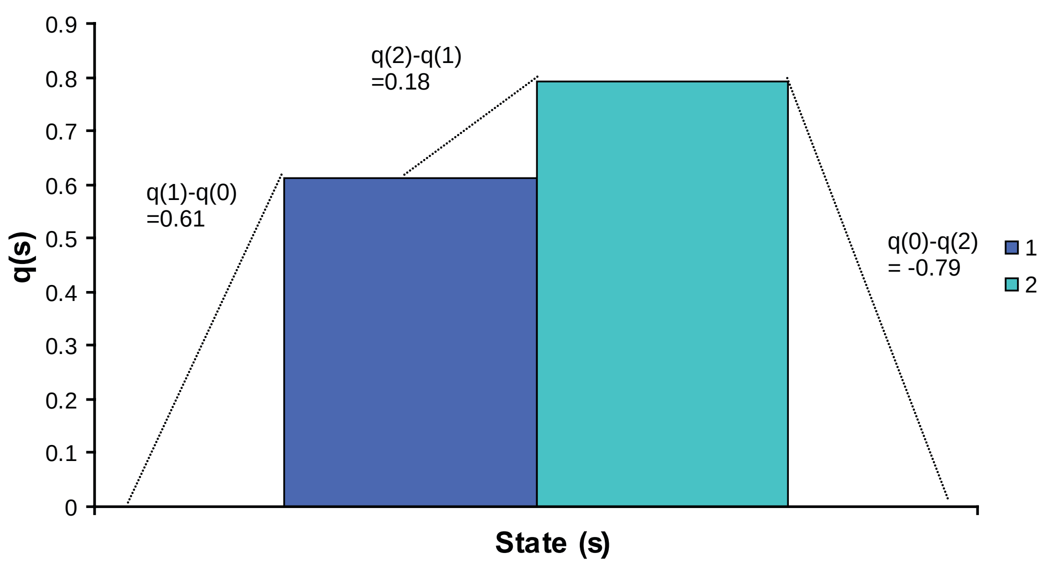

Figure 6.6 – Calculating gradients of the amplitude (q(s)) in window 1 of the simple example (Section 6.2.4). Gradients were used as a convention for mimicking a discrete density function and were computed as q_i-$q_{i+1,}$ where *i* is the state. These values used in Equation 6.3 to compute FI.

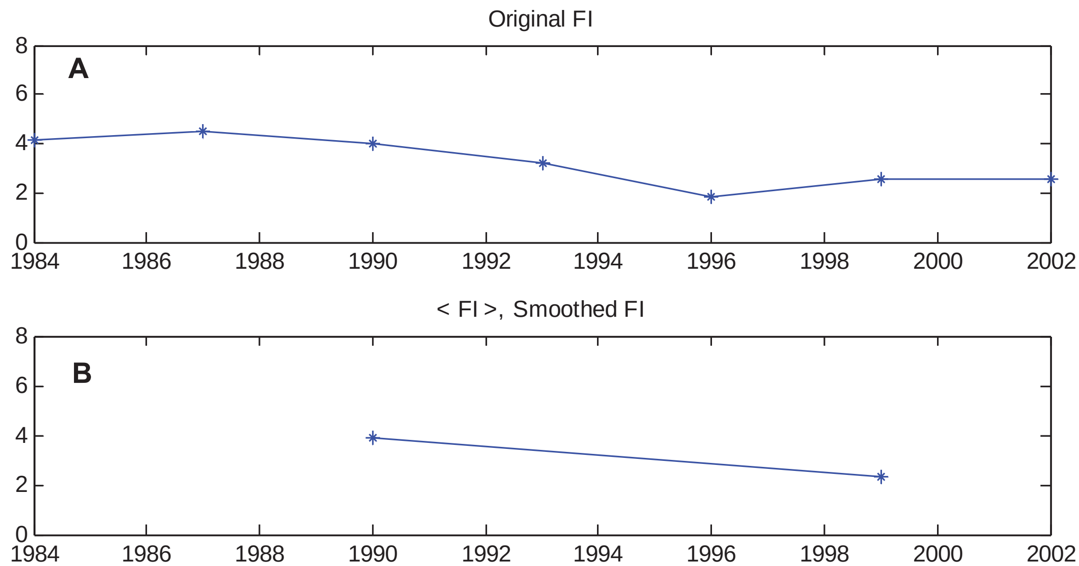

Figure 6.7 – Fisher information for each window from the simple example: (A) Fisher information (FI) and (B) Smoothed FI using three-point mean (<FI>), i.e., $\langle FI \rangle_{1999} = (FI_{2002} + FI_{1999} + FI_{1996})/3$ and $\langle FI \rangle_{1990} = (FI_{1993} + FI_{1990} + FI_{1987})/3$.

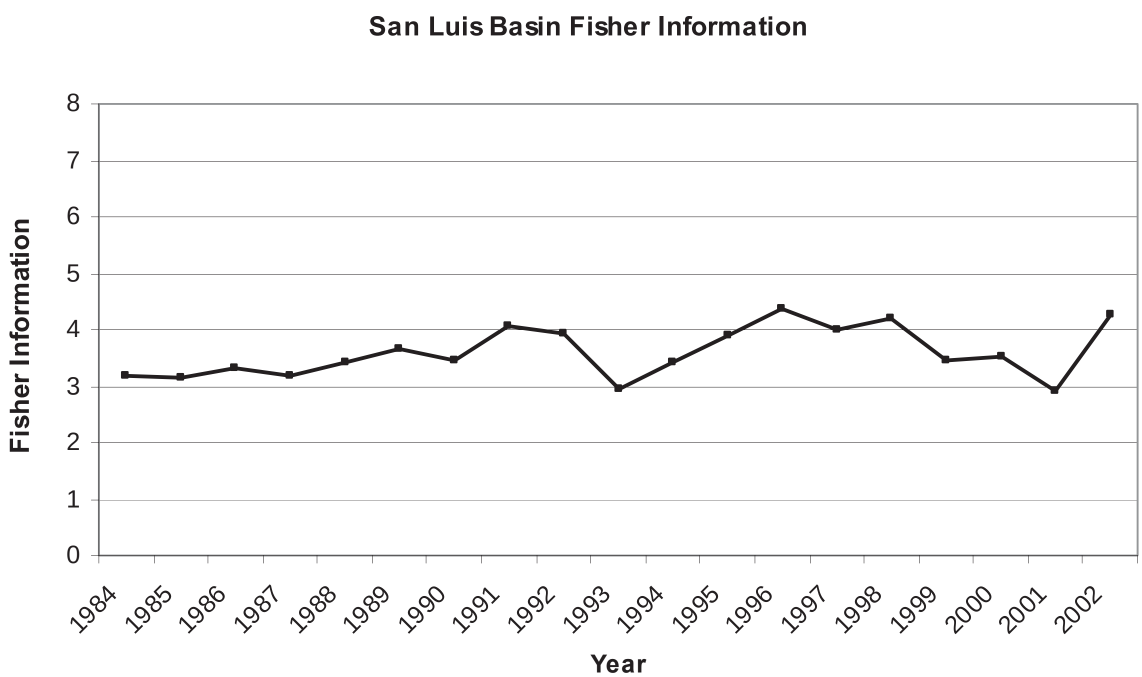

Figure 6.8 – Fisher information calculated for the San Luis Basin over a 26-year period (1980-2006). Each point represents the FI computed in each window and is reported in the center of that period (i.e., FI; 1984 = 1980-1987, 1985 = 1981-1988, 1986 = 1982-1989, etc.).

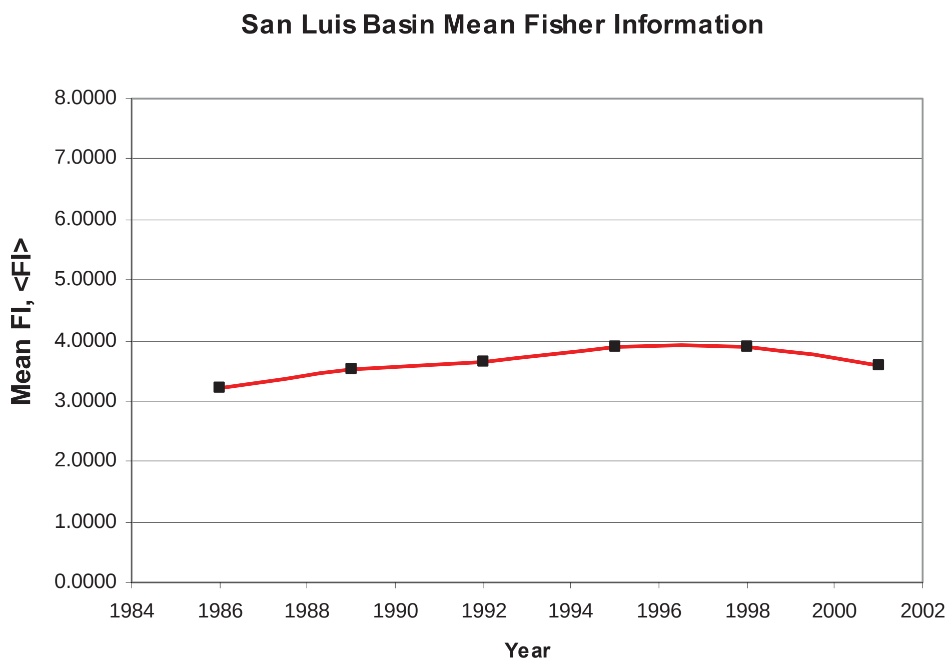

Figure 6.9 – Mean Fisher information (<FI>) for the San Luis Basin. <FI> was computed as a three-point average of the FI (Fig. 6.8) in order to smooth out short-term fluctuations and highlight trends, rather than fluctuations. The <FI> is reported in the center of the three points (i.e., <FI>; 2001 = 2002-2000, 1998 = 1999-1997, etc.).

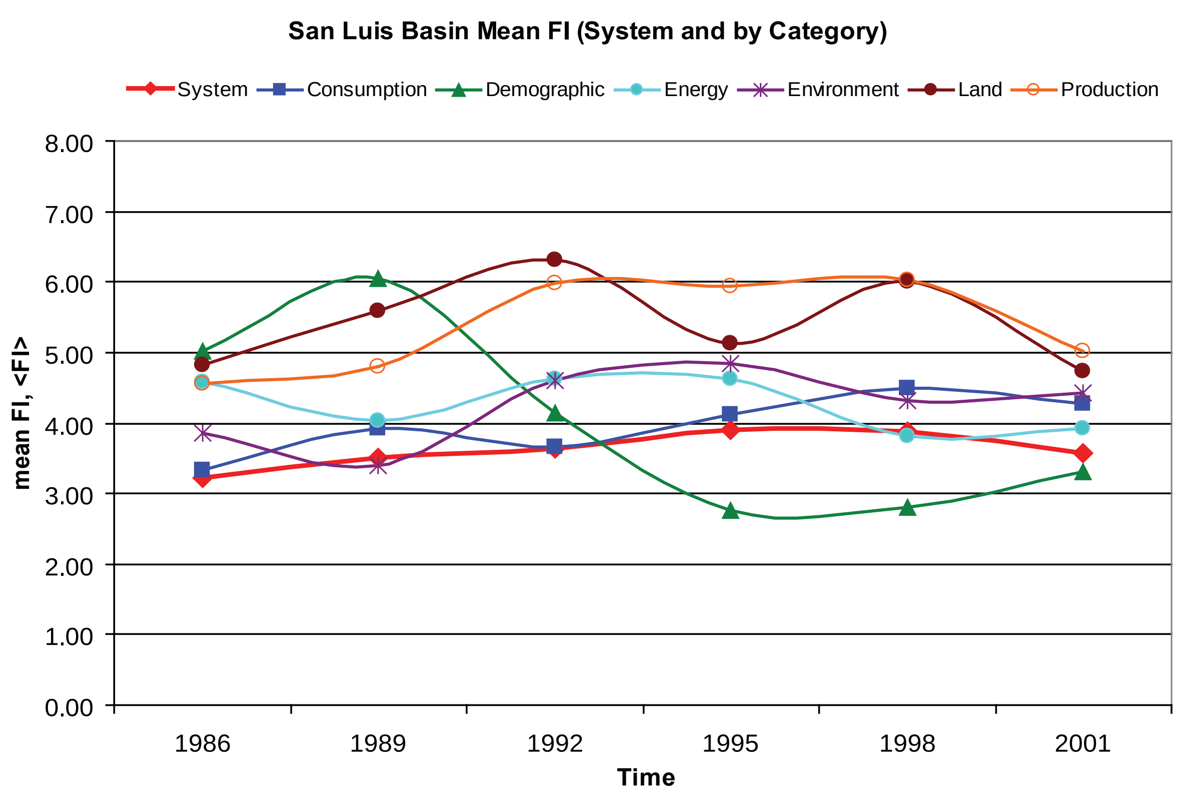

Figure 6.10 – Mean Fisher information of the San Luis Basin for the overall system and by category. Using this plot, we compared changes in system mean FI (<FI>) to the <FI> the variables grouped in categories. The <FI> is reported in the center of the three points (e.g., $\langle FI \rangle_{2001} = (FI_{2000} + FI_{2001} + FI_{2002})/3$).

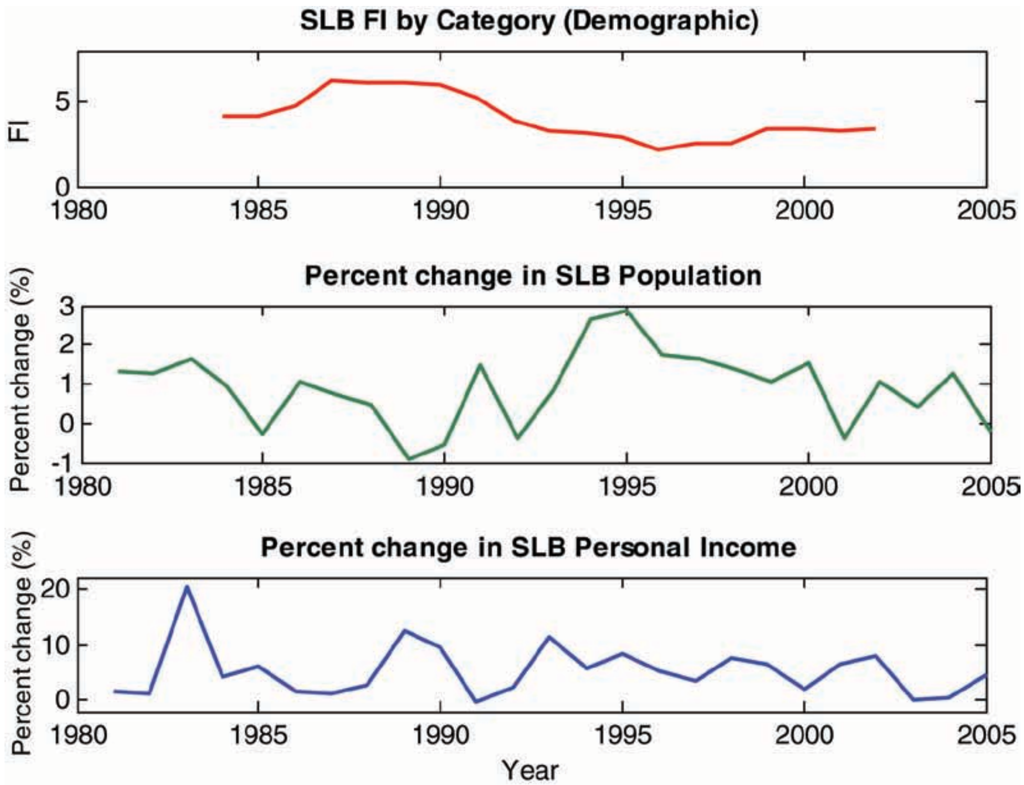

Figure 6.11 – Percent change in the San Luis Basin demographic variables. The percent change in population corresponded to the changes in dynamic order of the demographic category. The change in population decreased initially, peaked in 1995, and decreased thereafter which corresponds to the changes in dynamic order for the demographic category.

Appendix 6-A: Derivation Of Fisher Information

Fisher information was developed by the statistician Ronald Fisher as a statistical measure of information in data being used to fit a parameter (Fisher 1922). It is formally defined by Frieden (1998, 2004) as:

$$I(\theta) \equiv \int \frac{dy}{p(y\,|\,\theta)}\left[\frac{dp(y\,|\,\theta)}{d\theta}\right]^2 \qquad (6\text{-A.1})$$

where, *I* is Fisher information and *p(y|θ)* is the probability density of observing a particular measured value of a variable *y* in the presence of a parameter *θ*. From this equation, *I* is a measure of the amount of information about *θ* that is obtainable from the measurement of *y* (we use *I* here to preserve the historical context; Fisher 1922, Frieden, 1998, 2004, Karunanithi et al. 2008, Mayer et al. 2007). For example, if *y* has no information about *θ*, then the derivative in Equation 6-A.1 is zero and *I* is zero as well. The parameter *θ* can represent many items. With that in mind, in order to transform this equation into a measure of order for complex dynamic systems, let the parameter *θ* be the mean <*y*> of *y* over a particular period of time, T:

$$< y > \equiv \frac{1}{T}\int_0^T y(t)dt \qquad (6\text{-A.2})$$

where T is the integration period for all observations of *y*. By substituting Equation 6-A.2 into (6-A.1), we have:

$$I(< y >) = \int \frac{dy}{p(y\,|< y >)}\left[\frac{dp(y\,|< y >)}{d < y >}\right]^2 \qquad (6\text{-A.3})$$

Next, to represent the fluctuations in *y* around the mean <*y*>, we define a new variable *s*, such that *s* ≡ *y* - <*y*>. According to elementary statistics, systems where the variation around the mean is independent of the value of the mean are said to be shift-invariant (Frieden, 2004)

$$p(y\,|< y >) \equiv p(y - < y > | < y >) = p(s - < s >) = p_0(s) \qquad (6.A.4a)$$

indicating that the probability distribution does not depend on the value of the mean. Using the results of Equation 6-A.4a and incorporating the chain rule (6-A.4b):

$$\frac{dp}{d < y >} = \frac{dp}{ds}\frac{ds}{d < y >} = \frac{dp}{ds} \qquad (6\text{-A.4b})$$

where we have tacitly dropped the subscript "0" on *p(s)*, and Equation 6.A.1 becomes:

$$I = \int \frac{ds}{p(s)}\left[\frac{dp(s)}{ds}\right]^2 \qquad (6\text{-A.5})$$

where *p(s)* is the probability density finding a particular value of *s*. This is Equation 6.1 found in the main text of Chapter 6. Now let *s* be a state of the system in a Euclidean (linear) space defined by the observable variables of the system and time. That is, a particular state *s* is a region in a space, (i.e., linear phase space where the dimensions are the observable variables of the system and time). Then, *p(s)* is the likelihood of observing a particular state, *s*.

From Equation 6-A.5, we note that *I* is proportional to *dp / ds*. In the context of order, systems can exist within two idealized extremes, perfect disorder and perfect order, as discussed in the main text within a different context. The perfect disorder case occurs when a system is unbiased toward any particular state. In other words, it has the same probability of being in one state as any other state of the system (s=1: n), i.e., p(s) = p(1) = p(2) =…p(n) and the probability density function (PDF) is flat (Fig. 6-A.1a) so that *dp / ds* →0. Accordingly, the system lacks order (which in some contexts can be thought of as predictability) and the resulting Fisher information approaches zero (i.e., *I*→0) (Fath et al. 2003). Perfect order occurs when repeated measurements of the system result in the same state over time. This more structured system has high order, is more predictable, and is biased toward a particular state or states. Accordingly, the PDF has a steep slope, *dp / ds* →∞ and Fisher information approaches infinity (i.e., *I*→∞) (Fig. 6-A.1b). However, real systems typically function between these two system extremes (e.g., Fig. 6-A.1c).

For completeness, we would like to point out that one reasonably elegant means of evaluating Equation 6-A.5 is by adapting a statistical mechanics approach and representing the system in its phase space. Here the space coordinates are again the measurable system variables, and the probability density for observing a particular state (*s*) is proportional to the time the system spends in state *s*, i.e., p(*s*) ∞ Δt(*s*). This method provides us with a resulting expression that is a function of the velocity (*R'*(*t*)) and acceleration (*R"*(*t*)) tangential to the system path in its phase space (Mayer et al. 2007). The expression used to compute the Fisher information under this theory is:

$$I = \frac{1}{T}\int_0^T \frac{(R''(t))^2}{(R'(t))^4}dt \qquad (6\text{-A.6})$$

However, Equation 6.A-6 requires the evaluation of the first and second order derivatives tangential to the system path defined by the system variables (Cabezas et al. 2005, Fath et al. 2003, Mayer et al. 2006). Although this approach is appropriate for model systems for which smooth data are readily available, the challenge is that it is extremely difficult to obtain high quality second order derivatives from the noisy, sparse data sets characteristic of real systems (Karunanithi et al. 2008). Accordingly, the numerical approach (derived and discussed in Chapter 6) was developed for calculating *I* to assess the dynamic order of real systems without the need to compute second derivatives. Further details of the analytical and numerical derivation of *I* can be found in Mayer et al. (2007) and Karunanithi et al. (2008).

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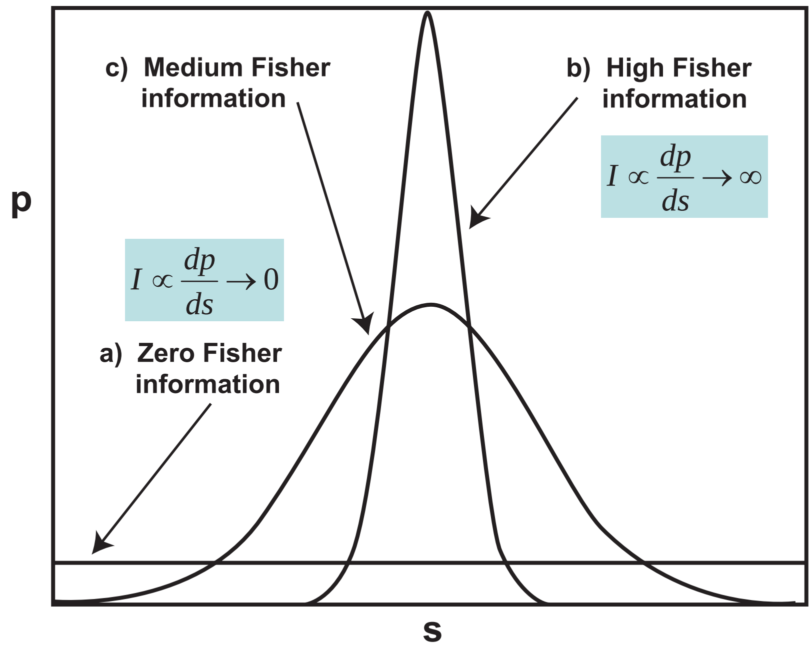

Figure 6-A.1 – Fisher information is proportional to the probability of system states (Pawlowski and Cabezas 2008). (a) Zero I results when a system has an equal probability of being in one state as any other state, resulting in a uniform probability density function (PDF), such that $dp / ds \to 0$ and $I \to 0$. (b) High I occurs when repeated measurements of the system result in the same state over time (i.e., the system is more predictable resulting in high predictability), a PDF with a steep slope, $dp / ds \to \infty$ and Fisher information approaching infinity (i.e., $I \to \infty$). (c) However, real systems typically function between these two extremes and exhibit medium I.

Appendix 6-B: Sensitivity Analysis On Integration Window Parameters

In section 6.2.4, we used a simple example to demonstrate the FI computation steps. The FI result was calculated using the integration window parameters selected in accordance with the basic criteria (section 6.2.2) and contained seven values (one for each time window) which were limited by the amount of data available, *hwin,* and *winspace* (Table 6.1). However, one of the challenges in computing FI is determining optimal settings for the integration window parameters. Accordingly, this appendix provides an exploration of the effect of changing the value of *hwin* and *winspace* on both the FI results and the resolution of results (number of FI results produced from a computation) for the data from the simple example. This exercise is not meant to cover every possibility; however, it is intended to (1) underscore the fact that care should be taken when selecting the integration window parameters and (2) provide key insights on the impact of the parameters on the FI result.

The basic guidelines for setting the integration window parameters are *hwin* ≥ 8 and *winspace* < *hwin* (section 6.2.2). For this exercise, we used the data from the simple example and examined four different values for *hwin* (ranging from 8 to 11 time steps) and *winspace* (ranging from 1 to 4 time steps). Graphing FI computed from these settings provide some sense of the effect changes in *winspace* and *hwin* on FI (Fig. 6-B.1). Each panel of Fig. 6-B.1 reflects the FI result with *hwin* constant and a different *winspace* for each computation. For example, panel A contains the FI results given *hwin* = 8 and *winspace* ranging from 1 to 4. The average value of FI (avgFI) and standard deviation (SD) of FI reported were computed from all the FI results in each panel as a summary statistic. For example, the avgFI and SD reported in panel A are the average value and standard deviation of FI given *hwin* = 8 and *winspace* from 1 to 4. In general, smaller *winspace* values resulted in more fluctuations in FI, yet, the overall impact of *winspace* on the value of FI was relatively minor. However, looking at avgFI for each panel, as *hwin* increased avgFI decreased. We performed similar analysis on the data by holding *winspace* constant and found that when assessing the variability of avgFI, the standard deviation is 0.11 as *winspace* changes and 0.44 as *hwin* changes. Therefore, it appears that the selection of *hwin* is the primary factor affecting FI. However, this only just begins to answer the question of the impact of the parameters on the FI result and provides minimal insight regarding optimal settings for *hwin* or *winspace* for this system.

One of the common approaches to assessing the impact of controllable (independent) variables on output responses includes evaluating the system one factor at a time (OFAT). Not only is this approach time consuming and costly, factor interactions are not considered (Anderson 2005, Montgomery 1997). In lieu of an OFAT approach, we opted to perform a sensitivity analysis by designing a factorial experiment using *hwin* and *winspace* as controllable factors and the average value of FI (avgFI) and resolution of FI results (Npts) as output response variables. A designed experiment affords the ability to determine critical factors by assessing the impact of controlled variable changes (and their interactions) on output responses. Using Design Expert 8 (StatEase, Inc., Minneapolis, MN) we created a design matrix for the 4^2 full factorial design showing the factor combinations and responses for each experiment (Table 6-B.1). An analysis of variance (at $\alpha = 0.05$) of avgFI revealed that both *hwin* ($F (3, 9) = 77.56$, $P \ll 0.05$) and *winspace* ($F (3, 9) = 4.64$, $P < 0.05$) are statistically significant factors (Table 6-B.2). However, note that the sum of squares (SS) and mean squares (MS) summarizes the amount of variability accounted for by each factor and random error (Montgomery 1997; NIST/SEMANTECH 2006). Accordingly, the results indicate that more of the variation in avgFI comes from changes in *hwin*. Similarly, we found that both factors have a statistically significant impact on the resolution of the FI results (number of FI results produced from a computation); however, *winspace* is dominant (Table 6-B.3). Further, there was a strong negative correlation ($r = -0.9934$, $P = 0.0066$, $df = 2$) between the avgFI and *hwin* (i.e., as *hwin* increases, avgFI decreases) and although *hwin* has little effect on the resolution of FI results, smaller *winspace* values produce a higher resolution of FI results (Figs. 6-B.2 and 6-B.3). From the analysis, it appears that *hwin* is the primary factor affecting the variability and amplitude of the avgFI result and *winspace* is the key parameter affecting the number of FI results produced from a computation (Npts). The challenge at this point is determining optimal settings for the integration window parameters such that the deviation in the avgFI result is minimized and the number of FI data points is maximized. In order to determine the optimal settings, we sought a solution to the multiple objective problem of (a) minimizing the standard deviation of FI, the standard error of the mean value of FI and standard error of the Npts and (b) maximizing Npts (Table 6-B.4). Using the optimization function within Design Expert 8 by StatEase, Inc., an optimal solution was found at *hwin* = 8 and *winspace* = 1 (Fig. 6-B.4). Using the solution from the sensitivity analysis and numerical optimization, we calculated FI and the three-point mean FI result, <FI> (Fig. 6-B.5). These parameter settings were also used to compute FI for the SLB system.

References

Montgomery, D.C. 1997. Design and Analysis of Experiments. John Wiley and Sons, Inc., New York, NY.

NIST/SEMATECH. 2006. e-Handbook of Statistical Methods. Available online at http://www.itl.nist.gov/div898/handbook/toolaids/pff/1-eda.pdf. Last Accessed August 26, 2010.

Table 6-B.1 – Design matrix for the sensitivity analysis of the simple example data: Determining the impact of controllable factors, *hwin* and *winspace* on the response variables, average value of FI (avgFI) and the number of FI results (Npts) for computation.

	Factors		**Response**	
Run	***hwin***	***winspace***	**avgFI**	**Npts**
1	8	2	3.13511	10
2	9	2	2.74041	9
3	9	1	2.87719	18
4	11	1	2.22149	16
5	10	1	2.44636	17
6	11	2	2.13994	8
7	9	3	3.16116	6
8	8	1	3.18285	19
9	8	3	3.24848	7
10	10	2	2.3549	9
11	11	3	2.15498	6
12	9	4	2.90048	5
13	10	3	2.75425	6
14	10	4	2.44245	5
15	8	4	2.99323	5
16	11	4	2.12815	4

Table 6-B.2 – Analysis of Variance (ANOVA) for the average value of FI (avgFI). The results reveal that both *hwin* ($F(3, 9) = 77.56$, $P<<0.05$) and *winspace* ($F(3, 9) = 4.64$, $P< 0.05$) were significant factors affecting avgFI. Moreover, as an indicator of the amount of variability that is accounted for by factor effects (e.g., *hwin* or *winspace*) and random error (i.e., residual), the MS values reflect that more of the variability was determined by *hwin*.

Source	**Sum of Squares (SS)**	**df**	**Mean Square (MS)**	**F value**	**p-value Prob > F**	
Model	2.4199	6	0.4033	41.1021	< 0.0001	significant
A-hwin	2.2833	3	0.7611	77.5644	< 0.0001	significant
B-winspace	0.1366	3	0.0455	4.6397	0.0317	significant
Residual	0.0883	9	0.0098			
Cor Total	2.5082	15				

Table 6-B.3 – ANOVA for the resolution of Fisher information results (Npts). Like the ANOVA for avgFI, both *hwin* (F (3,9) = 8.33, *P* <0.05) and *winspace* (F(3,9) = 519, *P* <<0.05) were statistically significant factors affecting Npts. However, the mean square (MS) values indicate that majority of the variability in Npts was due to *winspace*.

Source	Sum of Squares (SS)	df	Mean Square (MS)	F Value	p-value Prob > F	
Model	395.5	6	65.92	263.67	< 0.0001	significant
A-hwin	6.25	3	2.08	8.33	0.0058	significant
B-winspace	389.25	3	129.75	519	< 0.0001	significant
Residual	2.25	9	0.25			
Cor Total	397.75	15				

Table 6-B.4 – Criteria for determining the optimal value for *hwin* and *winspace* for the sample exercise. The goal of the numerical optimization was to minimize the deviation in avgFI and maximize Npts, subject to (a) minimizing the standard deviation of FI, the standard error of the mean value of FI and standard error of the Npts and (b) maximize Npts. The highest importance was placed on maximizing Npts and minimizing the standard error of avgFI and Npts. The optimization was performed in Design Expert 8 (StatEase, Inc.).

		Constraints		
Name	Goal	Lower Limit	Upper Limit	Importance
A:hwin	is in range	8	11	3
B:winspace	is in range	1	4	3
StdErr(mFI)	minimize	0.065521169	0.065521169	4
Npts	maximize	4	19	5
StdErr(Npts)	minimize	0.330718914	0.330718914	4
std mFI	minimize	0.421906393	1.178581952	3

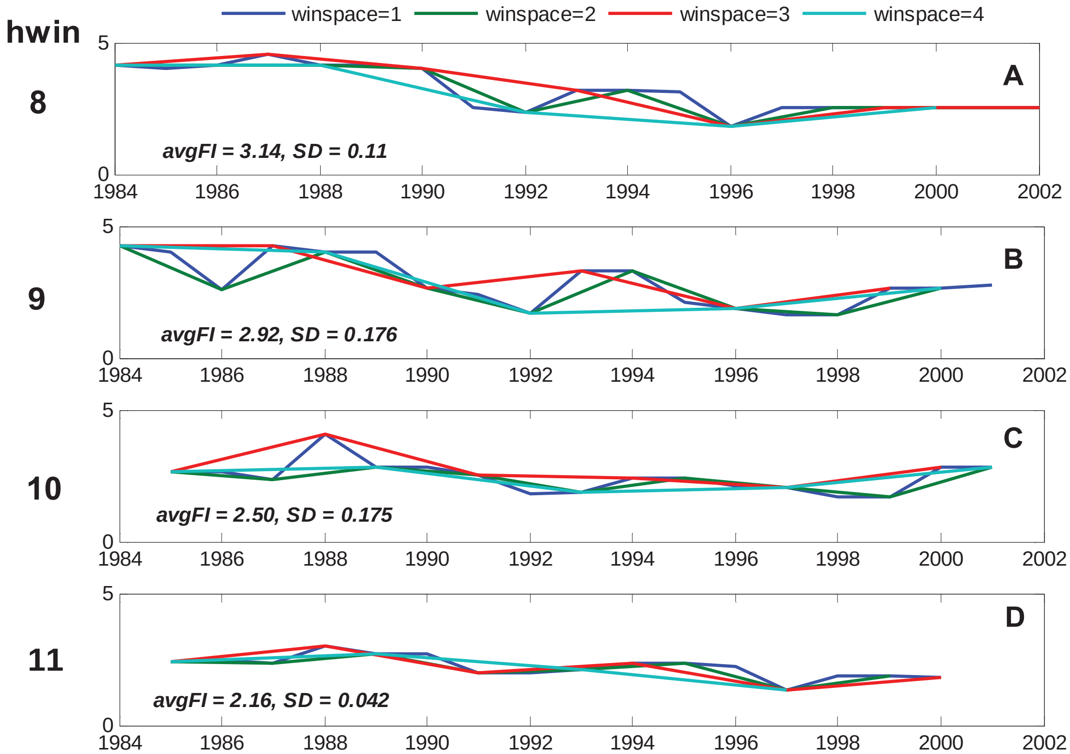

Figure 6-B.1 – The effect of changing *hwin* on the FI result. The value of *hwin* changes from panel to panel (A-D), while *winspace* varies within each panel. Therefore, each panel reflects the Fisher information result over time with *hwin* constant and a different *winspace* for each computation: (A) *hwin* =8, *winspace* =1 to 4, (B) *hwin* =9, *winspace* =1 to 4, (C) *hwin* =10, *winspace* =1 to 4, (D) *hwin* =10, *winspace* =1 to 4. The average value (avgFI) and standard deviation (SD) reported of FI in each panel were computed from all the FI results in each panel as a summary statistic. For example, avgFI and SD in panel A are the mean and standard deviation of the FI values given *hwin* = 8 and *winspace* = 1 to 4. Note that avgFI decreases as *hwin* increases and small *winspace* values result in more fluctuations (e.g., *winspace* =1 is represented by the blue line).

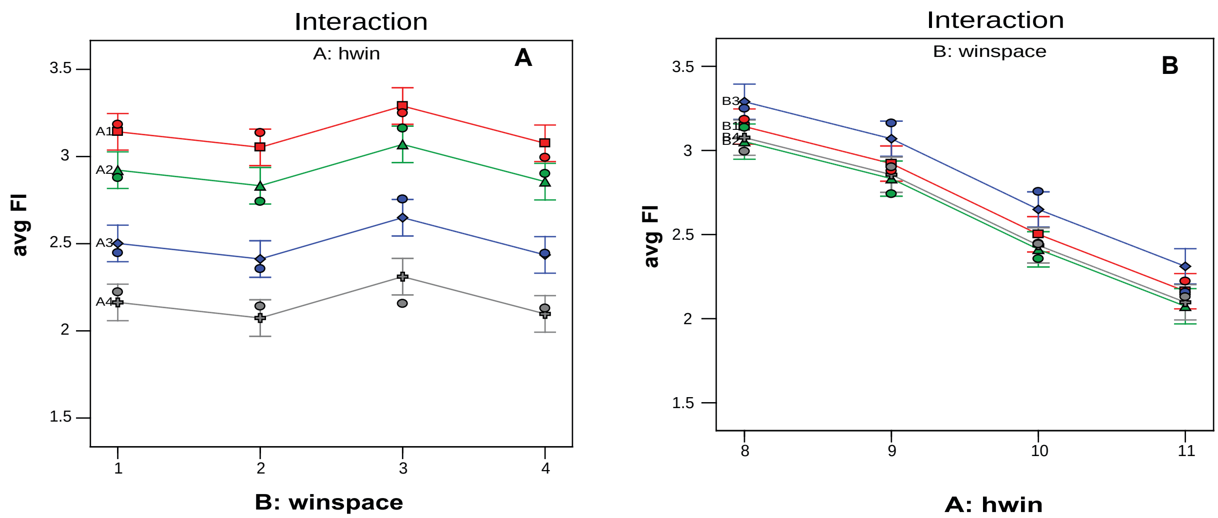

Figure 6-B.2 – Interaction plots for the average value of FI (avgFI). Plotting the value of avgFI as a function of *hwin* and *winspace* affords the ability to evaluate the impact of both parameters on avgFI. (A) Each *hwin* value is represented by a different color plot. With *winspace* varying along the x-axis, there is little variability in avgFI as *winspace* increases. Conversely, note that as *hwin* increases (e.g., A1: *hwin* = 8, A4: *hwin* = 11), the value of avgFI decreases. (B) The strong relationship between *hwin* and avgFI is also shown as *hwin* increases along the x-axis.

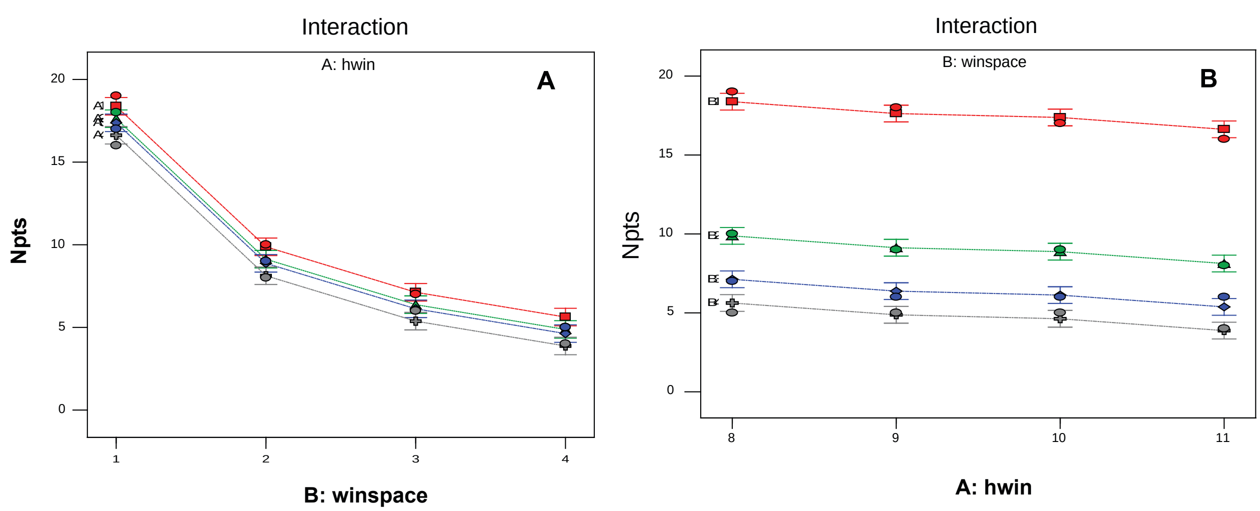

Figure 6-B.3 – Interaction plots for the number of FI results (Npts). Plotting the value of Npts as a function of *hwin* and *winspace* affords the ability to evaluate the impact of both parameters on Npts. (A) Each computation with a particular *hwin* value is represented by a different color plot. With *winspace* varying along the x-axis, there was a great deal of variability in Npts. (B) However, as *hwin* increases along the x-axis, there are minor changes in Npts. Further, there is a greater decrease in Npts as *winspace* goes from 1 to 2, than from 2 to 3 or 3 to 4.

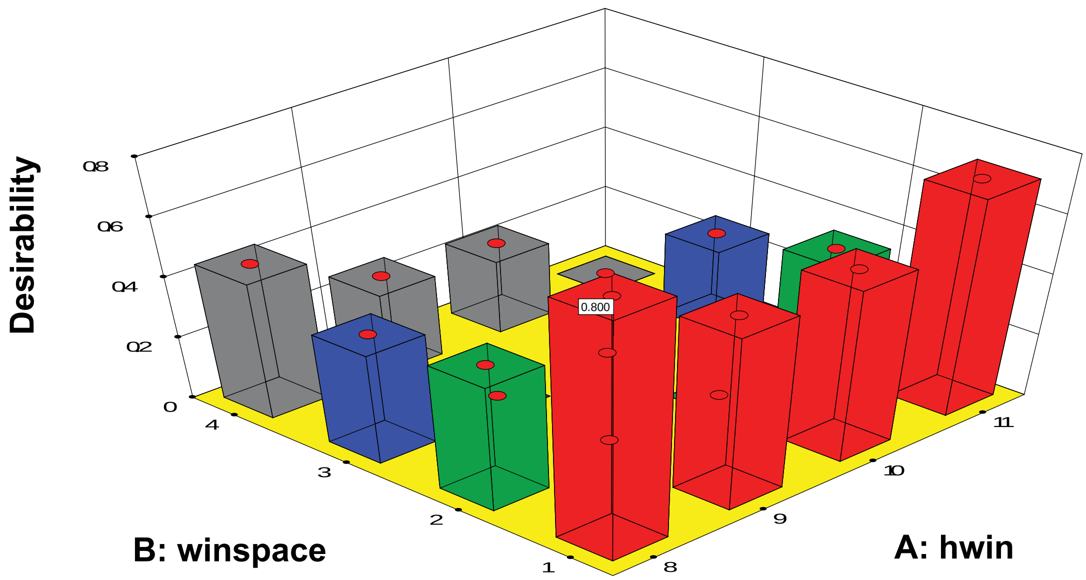

Figure 6-B.4 – Results of the numerical optimization of *hwin* and *winspace* using data from the simple example. Based on the optimization criteria of maximizing Npts and minimizing the deviation in avgFI, the optimal solution was found (using Design Expert 8) with integration window parameter settings of *hwin* = 8 and *winspace* = 1.

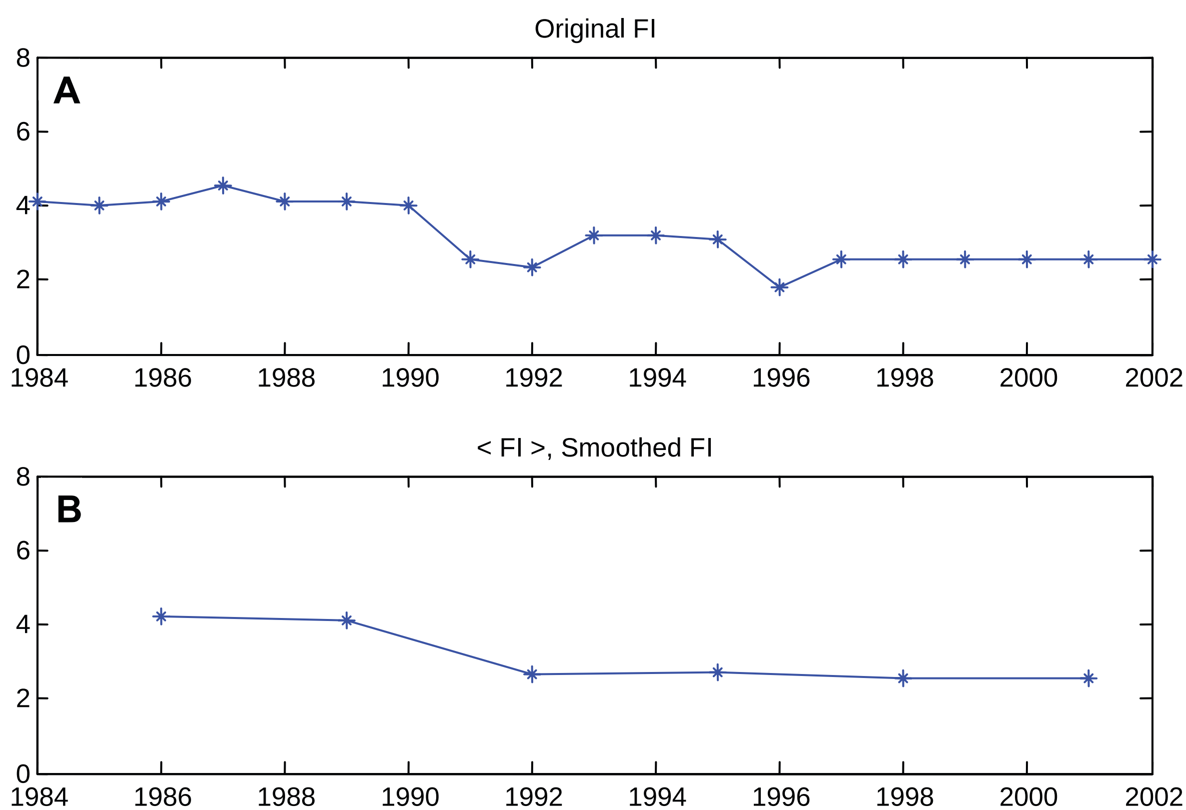

Figure 6-B.5 – Final Fisher information (FI) result from the simple example. (A) FI result from the optimal parameter settings (*hwin* = 8 and *winspace* =1). (B) Smoothed result: <FI>, three-point mean Fisher information.

Appendix 6-C: San Luis Basin Fisher Code User Manual – Utilizing MATLAB Files (Gfisher.m and CalcFishMean.m) to Calculate Fisher Information

Appendix 6-C.1: Using MATLAB Files to Calculate Fisher Information via Command Line: (GFisher.m, CalcAvgFish.m, and SmoothFI.m)

The primary MATLAB files developed for this project include GFisher.m, CalcAvgFish.m and Main_Fisher_data_proc.m (GUI) and AdvancedFishGUI.m (GUI). Other supporting files are Nfisherpdf.m, round2.m, CloseGUI.m and SmoothFI.m. In this section, we present a general description for using MATLAB to execute the functions (e.g., GFisher.m, CalcAvgFish.m) via command line to compute FI. Using the functions in this way requires some knowledge of MATLAB; however, this manual is not intended to be a MATLAB tutorial. Conversely, the GUIs (i.e., Main_Fisher_data_proc.m and Advanced FishGUI.m) are not command line functions and are the most user-friendly means of computing FI. They will be described in Appendix 6-C.2:

The file GFisher.m contains the code developed in conjunction with the ongoing research within the US EPA's Sustainable Environments Branch for implementing the numerical approach to computing FI. Given that m=number of time steps (e.g., years) and n=number of characteristic variables, the command line for this code is:

[FI,midt_win] = GFisher (t,data,sost,hwin,winspace,TL,IP) where the required inputs into the function are:

t:	the time data for study of size m × 1
data:	the time series data of variables characterizing the state of the system of size m × n
sost:	a row vector of the *size of states* for each variable, size = 1× n
hwin:	the size of the time window
winspace:	the moving window increment
TL:	the tightening level (%)
IP:	a toggle on or off (1 or 0) for requesting an automatic plot of the FI result

The function outputs are:

FI:	Fisher information for each time window
midt_win:	Midpoint of each time window corresponding to the FI result

Prior to executing the code, the user must gather the input data as described above, to include: time series data of the variables that characterize the state of the system (data), the time period (e.g., 1980-2005) that the data represent time (t), the integration window parameters (*hwin* and *winspace*) and the *size of states* (sost) for each variable. Please refer to sections 6.2.2 and 6.2.4 for information on determining and gathering this information.

Once the data are compiled, they may be entered into MATLAB directly via command line or imported from a saved file of a supported type (e.g., csv, Excel). The data entry method is not critical when executing the command line functions; however, data must be in a particular format:

- The time series data of the variables characterizing the system (data) should be configured such that data for each variable are listed in one column with each row containing the variable values for a particular time step, producing a m× n matrix. For example, if there are 5 variables and 20 time steps. The data will be entered into a 20 × 5 matrix.
- The time data (time, t) should be formatted such that one time step value is entered in each row producing a m ×1 column vector with each time period corresponding to a datum point.
- The *size of states* (sost) data should be formatted such that there is a *size of states* value for each variable in each column, producing a 1 × n row vector (see 6.2.2 for computing *size of states*). For example, the 20 × 5 matrix mentioned above contains 5 variables and would have 5 *size of states* values, one for each variable (i.e., 1 × 5 row vector).

All of these inputs must be loaded into the workspace prior to executing the function. In other words, properly formatted data must be loaded into the workspace and parameter values must be defined in the MATLAB command window before entering the command.

While GFisher.m provides the FI result for one specified tightening level (e.g., 100% = 100), CalcAvgFish.m calls GFisher.m to compute FI by incrementally changing the tightening level and calculating the average of the FI from the strict (TL = 100%) to relaxed tightening (see Section 6.2.2). The command line for this file is:

[AvgFish,PO_TL,mY]= CalcAvgFish (t,data,hwin,winspace,sost)

The function inputs are similar to GFisher and outputs are:

AvgFish: Average Fisher for each time window

PO_TL: Tightening Level the system is in perfect order. When there is a regime shift, it is an indication of pervasiveness

mY: Mean year for each time window

The SmoothFI.m file is used to compute the mean FI <FI>, a *m* point mean which smoothes the FI results to focus the analysis on trends and not fluctuations. The command line is: [FIm]=SmoothFI(m,t,FI), where *m* is the number of points to be used in calculating the average, t is the time vector and FI is the computed FI result from GFisher.m, CalcAvgFish.m or Main_Fisher_data_proc.m GUI. The output is 2 columns containing the mean time and mean FI computed. In the SLB project, *m* was set to a default of three in order to provide a three-point mean FI.

Appendix 6-C.2: Graphical User Interfaces (GUI) for Calculating Fisher Information: (Main_Fisher_data_proc.m and AdvFishGUI.m)

To simplify the calculation of FI and enhance user-friendliness, a GUI was developed as an extension to the *San Luis Basin Sustainability Metrics Project* (Fig. 6-C.1). The GUI is an interface for data entry, executing code to compute FI, as well as, displaying and saving results from an FI analysis (Fig. 6-C.1). It is designed to simplify the procedure by allowing the user to select pre-formatted data files, alter pre-set parameter values and process data to calculate FI over numerous tightening levels (from strict to relaxed tightening). The computed FI is plotted in the GUI and the user is able to save the FI computations and plot for further use.

Although MATLAB can import multiple file types, the code for the GUI was setup to accept data specifically in Excel format. Accordingly, although the data files are created using the data formatting guidelines (see Appendix 6-C.1), there are a few caveats:

- The Excel file containing the variable time series data should be formatted as an m×n matrix with a descriptive name that ends in *data.xls* (e.g., *SLBdata.xls*).
- The time data should be saved in a separate Excel file whose descriptive name ends in time.xls (e.g., *SLBtime.xls*) and contains the m ×1 time data, where m is the number of time steps
- The *size of states* data should be saved in a separate Excel file whose descriptive name ends in *sost.xls* (e.g., *SLBsost.xls*) and contains the data in a 1× n row vector, where n is the number of variables.
- There should be no column headings in these files.

Navigating through the GUI, the [Add/Remove Files] menu tab contains controls that allow the user to select the data files for computing FI. The [Add Files] button is used to identify the location and add the pre-formatted files. Note that because there is one evaluation done at a time, only one time series, one *size of states,* and one time series data file (e.g., *SLBdata.xls*, *SLBtime.xls*, *SLBsost.xls*) should be loaded at a time. The [Delete Files] button may be used to remove unnecessary files. Once the data, time, and *size of state* files have been selected, the user inputs the *hwin* and *winspace* parameters, as well as, the number of points for the smoothing the FI results. The values for these parameters are preset to 8, 1, and 3 (respectively) for this project. The [START] button executes the function to perform the FI computation. Once this button is selected, all buttons and figures are disabled until the computation is complete and then a graph of the result (FI and smoothed FI (<FI>)) is displayed in the Plot Window. The [Save Plot] and [Save Calculations] buttons are used to save the FI plot and numerical result for further use. The [Save Calculations] button saves the FI values, date and time of calculation, as well as the smoothed mean FI results into an Excel file in the following format:

Row1 Col1: Date

Row2 Col1: Time (military)

Row3 Col1: Perfect order tightening level: PO_TL

Row4 Col2: Average FI results: [Year FI]

The smoothed <FI> results follow the average FI results

The [Reset] button allows the user to clear the figure and parameter settings and the [Help] button hyperlinks to a help file, which provides instructions on using the Main GUI. The [Advanced] button opens the Advanced Fisher GUI, which allows the user to assess the pervasiveness, and intensity of a regime shift, if one exists (see Section 6.2.2 and Fig. 6-C.2). Such an examination is pertinent only if a regime shift has been identified.

Given the same data and parameter settings that were established in the Main GUI (Main_Fisher_data_proc.m), clicking [Study] in the Advanced Fisher GUI executes the computation of the FI for multiple tightening levels and plots the result on two axes (axis1: TL=100%-60% and axis2: 50%-10%) along with the mean FI within the GUI interface. Through these plots, the user is able to study the pervasiveness and intensity of the regime shift as described in Section 6.2.2 and Karunanithi et al. (2008). Pervasiveness indicates the number of variables affected by the shift and is estimated by determining the lowest level in which the drop in FI is still present. This is based on finding the TL value at which the system is perfectly ordered (i.e., FI = 8) for the entire period. The pervasiveness is calculated by subtracting the perfect order tightening level (POTL) from 100 and denotes the percentage of variables that are impacted by the shift. The intensity relates to the amplitude of the shift and is determined by how far the FI drops between two stable regimes. A system with a more intense shift would have a lower drop in FI before settling into a new dynamic regime.

The main benefit of the graphical interface is that it requires minimal user input and simplifies the evaluation process for FI computation. In conjunction with this project, MATLAB files for the GUIs were made into executable files using the MATLAB Compiler. This provides portability to locations where the MATLAB software is not readily available; thereby making the GUIs available for use on any desktop. However, these executable files are not modifiable.

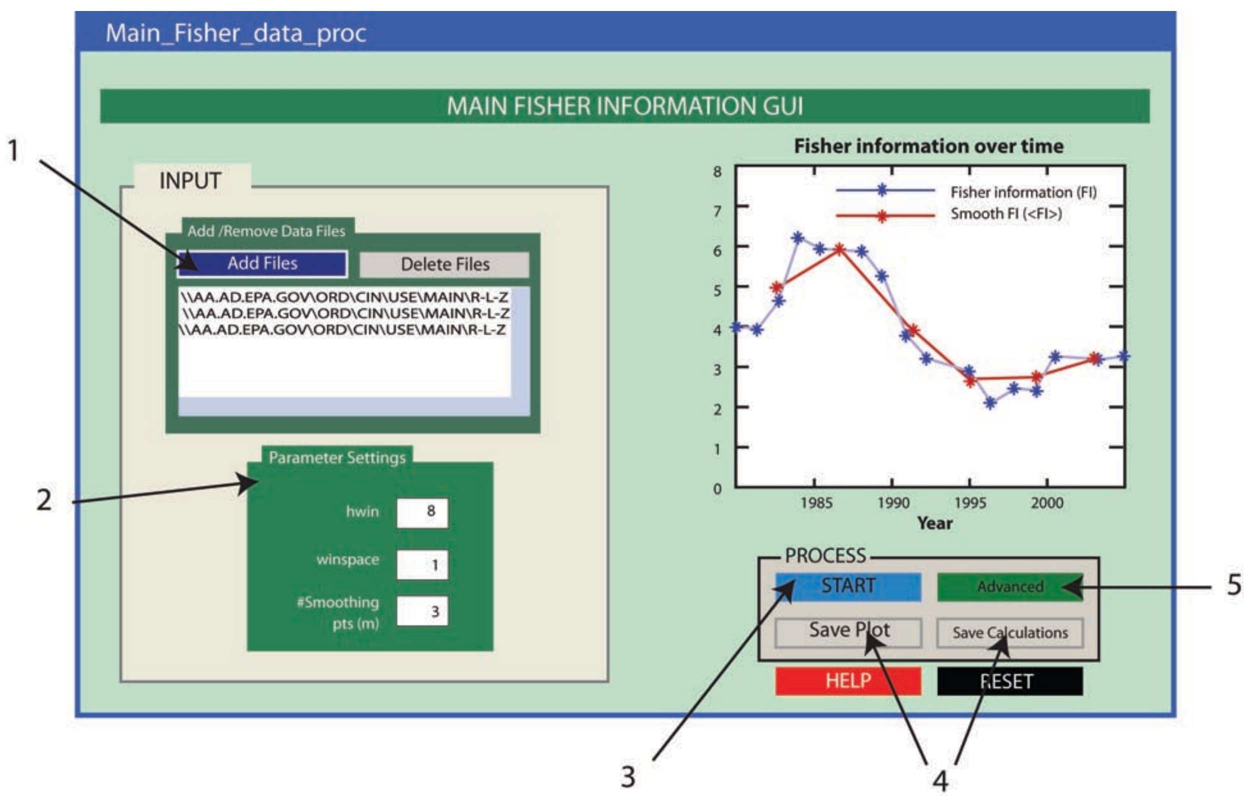

Figure 6-C.1 – GUI interface developed to compute FI from system data. The GUI is used for (1) importing pre-formatted data files, (2) choosing parameter settings (3) computing and plotting FI, (4) saving the FI results and (5) further study of regime shifts. The results plotted in this figure are from the simple example in Appendix 6-D.

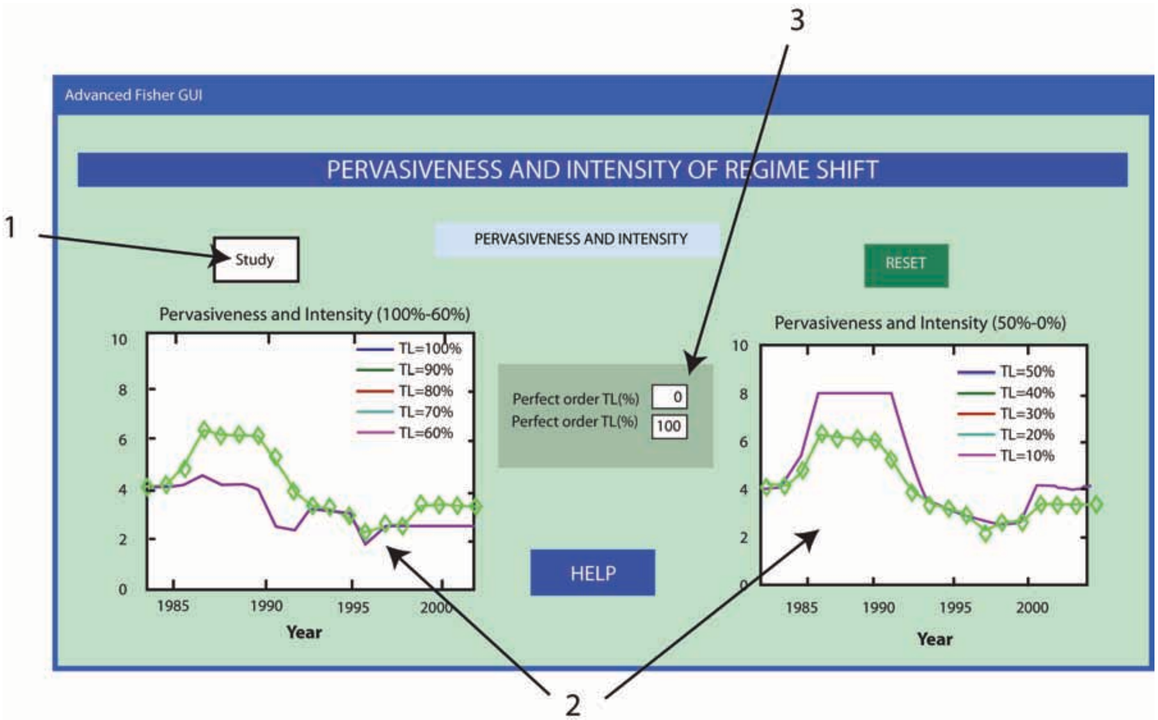

Figure 6-C.2 – The Advanced GUI was developed to study the pervasiveness and intensity of ecosystem regime shifts by (1) evaluating and (2) plotting the FI at various tightening levels. (3) The perfect order tightening level and pervasiveness are computed and shown in the text boxes. The results plotted are from the simple example as computed in Appendix 6-D. Using this simple example, note that the pervasiveness is 100% and there is one regime shift between two stable regimes.

Appendix 6-D: Using MATLAB to Compute FI for the Simple Example

In this section, we describe the steps involved in using the MATLAB GUI to analyze the data from the simple example. The first step was to save the time series, time, and *size of states* data into separate Excel files. In accordance with the guidelines in Appendix 6-C.2, the time series of the variables characterizing the system and the time data (i.e., 1980 to 2005) plotted in Fig. 6.3 were saved as *SLBExdata.xls* and *SLBExtime.xls* (Tables 6-D.1 and 6-D.2). The *size of states* for each variable as computed in section 6.2.4 (i.e., [86285.39 1639.83]) were saved in *SLBExsost.xls* (Table 6-D.3). Once the data files were set up, we opened the Main_data_proc GUI and clicked the [Add files] button to select the formatted data files (*SLBExtime.xls*, *SLBExdata.xls* and *SLBExsost.xls*) for computing FI. We left the default settings for the integration window parameters, *hwin* = 8, *winspace* = 1 and the number of smoothing points = 3 and pressed [START] to process the data and generate a plot of the FI and smoothed FI (<FI>) results (see Fig. 6-D.1). After the data were processed, the plot and FI calculations were saved using the [Save Plot] and [Save Calculations] buttons.

Although, the data used in this example do not fully characterize the sustainability aspects of the region (contains only two demographic variables), for the sake of this exercise, we assumed that these variables characterize the system under study. Looking at Fig. 6-C.1, we noted a drop in FI "bookended" by two stable regimes indicating the existence of a regime shift. Thus, in order to study the pervasiveness and intensity of the shift, we clicked the [Advanced] button to open the AdvancedFish GUI (Fig. 6-C.2). After clicking the [Study] button, the FI (green plot), as well as FI at various tightening levels from strict (TL = 100%) to completely relaxed tightening (TL=0%) are computed and plotted. In addition, the perfect order tightening level (POTL) and pervasiveness for the system were shown in the textboxes. Typically, the POTL may be observed graphically by noting the lowest tightening level at which the features of the shift (drop in FI) are still present. Note that there are only a few plots visible because there are only two variables in this study. At any rate, because the features of the shift remain intact for the plots, the POTL = 0 and pervasiveness = 100%, both variables are impacted by the shift.

Table 6-D.1 – Excel file containing the time series of the variables characterizing the system for the simple example (*SLBExdata.xls*). In this exercise, there are two variables (x_1 and x_2) such that each column contains the time series data for one variable. As described in Appendix 6-C.1, the data file is displayed as an $m \times n$ matrix with m = the number of time steps and n = the number of variables.

x_1	x_2
310352	38469
314914	38980
318946	39467
384256	40112
400888	40490
424601	40369
431318	40804
436775	41104
448738	41289
504014	40903
551552	40682
549641	41283
562981	41120
625715	41466
661317	42564
715547	43793
754872	44566
781542	45289
839246	45902
892574	46377
910329	47097
967522	46907
1042786	47404
1042145	47598
1048231	48207
1097044	48101

Table 6-D.2 – Excel file containing time data for simple example (*SLBExtime.xls*). In this exercise, the time period was from 1980 to 2005 and represents 26 time steps. Accordingly, as described in Appendix 6-C.1, the time file is displayed as an m × 1 matrix with m = the number of time steps.

Year
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005

Table 6-D.3 – Excel file containing the *size of state* (sost) data for simple example (*SLBExsost.xls*). In this exercise, there were two variables (x_1 and x_2) and the *size of states* was computed for each variable (Δx_1 and Δx_2). The values are exhibited as a 1 × n matrix with n = the number of variables.

x_1	x_2
86285.39	1639.83

Appendix 6-E: Fisher Information MATLAB Code

Code is available for download in the zipped file named "Appendix 6E - Fisher Information code.zip"

Gfisher.m

```
function [FI,midt_win,t_win]=GFisher(t,data,sost,hwin,winspace,TL,IP) %used with GUI
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%
%This program calculates FI as a measure of dynamic order.
%It is one of the products of an on-going effort within the US
%Environmental Protection Agency's Sustainable
%Environments Branch under the direction of Heriberto Cabezas.
%Key contributors to this effort include:
%Theory, methodology and direction from Heriberto Cabezas as adapted from
%Ronald Fisher's work in theoretical statistics(1922); Chris Palowski for
%the initial coding and framework: recurnumFI4.m (6/17/2004).
%Methodology enhancements and corresponding source code
%implementation by Arunprakash Karunanithi (3/13/2006) and additional
%modifications by Tarsha Eason (2008-2009).
%Further details on the methodology may be found in:
%Karunanithi, AT. Cabezas H, Frieden BR and Pawlowski CW. 2008. Detection
%and Assessment of ecosystem regime shifts from FI. Ecology
%& Society. 13(1): 22.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%
%This program calculates the FI from time series data.
%Pertinent parameters include:
%   FI          :   Fisher information
%   midt_win    :   mid point of each time window
%   t_win       :   time within each window
%   t           :   time data
%   data        :   Input data (matrix), size (#time steps, #variables)
%   sost        :   size of states
%   hwin        :   window size(number of points in each calculation)
%   winspace    :   number of time steps we move the window (<hwin)
%   TL          :   tightening Level
%   IP          :   Toggles the internal plots (IP=1==>on)
 %profile on
 FI=[];
t_win=[];
window=0;
for i=1:winspace:size(data,1) %start big loop to go through all the data
   %Revised Method: #pts=hwin
   lmin=min(i,size(data,1));
   lmax=min(i+hwin-1,size(data,1));
   NP=size(data(lmin:lmax,1),1);
if NP== hwin
   window=window+1;
   [pdf,neighbour]=Nfisherpdf(data,lmin,lmax,sost,TL/100); %calculate pdf for data
   %pdf
   %neighbour
   q=sqrt(pdf(:,1));  %convert to amplitude of the pdf
%modification
  counter=0;
  Q=0;
```

```
  neighbourQ=[];
  for j=1:size(q,1)
      if q(j,1)~=0
         counter=counter+1;
         Q(counter,1)=q(j,1);
         neighbourQ(counter,:)=neighbour(j,:);
       end
  end
%neighbourQ
%Q
%%%%%%%
%This portion of code re-arranges the states by assessing proximity.  As
%such, it calculates the Euclidean distance (zz) of the points in the state,
%finds the smallest distance and orders the q vector by the Euclidean
%distance.  This ensures that the states are indeed ordered by distance.
if size(neighbourQ,1)>2
minimumneighbourQ=0;
tempneighbourQ=0;
tempQ=0;
z=[];
for ii=1:(size(neighbourQ,1)-1)
    for jj=1:size(neighbourQ,1)
        if jj>ii
            z(ii,jj)=sqrt(sum(neighbourQ(ii,:)-neighbourQ(jj,:))^2);
        else
            z(ii,jj)=5000000000;
        end
    end
minimumneighbourQ=min(z(ii,:));
    for kk=2:size(neighbourQ,1)
        if kk>ii
            if z(ii,kk)==minimumneighbourQ
                tempneighbourQ=neighbourQ(ii+1,:);
                tempQ=Q(ii+1);
                neighbourQ(ii+1,:)=neighbourQ(kk,:);
                Q(ii+1)=Q(kk);
                neighbourQ(kk,:)=tempneighbourQ;
                Q(kk)=tempQ;
            end
        end
    end
end
end
 QQ=[0;Q(1:end);0]; %adding points (beginning and end) for edge gradients
 dq=diff(QQ)./1;  %calculating dqs
 %Calculates fisher for each window and places it in the middle of the %window
 if (i+(hwin-winspace))<=size(data,1)
   t_win(lmin:lmax,window)=[t(lmin:lmax)]; %time within each window
    FI(window)=[4*sum(dq.^2*1,1)]; %One fisher for each window
    midt_win(window)=ceil(mean(nonzeros(t_win(:,window))));
    %midt_win(window)= mean(nonzeros(t_win(:,window)));  %for ode calc
end
end
```

```
end
%FI
if IP==1  %plot outputs

subplot(2,1,1), plot(t,data) %plots data
%subplot(2,1,1), plot(data(:,1),data(:,2)) %plots data for ode
title('Time series data');
subplot(2,1,2),plot(midt_win,FI,'-b*')
title('Fisher information for each time window');
axis([min(t) max(t) 0 8]);
xlabel(‚Time'); ylabel(‚Fisher information');
end
```

NFisherpdf.m

```
function [pdf,neighbour]=NFisherpdf(data,lmin,lmax,sizeofstates,TL)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%
%The methodolgy for calculating FI as a sustainability
%indicator as a measure of dynamic order has been an on-going interative
%effort within the US Environmental Protection Agency's Sustainable
%Environments Branch under the direction of Heriberto Cabezas.
%Key contributors to this effort include:
 %Theory, methodology and direction from Heriberto Cabezas as adapted from
%Ronald Fisher's work in theoretical statistics(1922); Chris Palowski for
%the conceptual framework and coding of initial Matlab program, recurnumFI4.m
%(6/17/2004); Methodology enhancements and corresponding source code
%implementation by Arunprakash Karunanithi (3/13/2006)  and additional
%functional and conceptual modifications by Tarsha Eason (2008-2009).
%Further details on the methodology can be found in: Karunanithi AT.
%Cabezas H, Frieden BR and Pawlowski CW. 2008. Detection and Assessment of
%ecosystem regime shifts from FI. Ecology & Society. 13(1): 22.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%
 %The purpose of this program is to bin the points into states by
%calculating the difference (dist) of each variable vector per timestep
%and then counting the variable vector if dist<= size of the state AND the
%percentage of variables in the vector that meets that criteria is over the
%tightening level (TL).  Further, the number of vectors that fit within a
%state are counted(rnum)and then used to calculate the pdf (rum/sum(rum)).

fp_tol=1e-12; %correcting for floating point significant digits
% Initialize the vector which will hold the counter for points in a state
   rnum=zeros(lmax-lmin+1,1);
%Initialize array of points that will be counted in line with lmin and lmax.
%This dummy variable is used to ensure that the rows are not double
%counted.
     pout=zeros(lmax-lmin+1,1);
   %
   % now, find recurrence points about each in window and record their
   % instances, ignoring points that have already been counted

   for j=lmin:lmax   %looping over the window in time steps
       j;
      count=0;
       if pout(abs(j-lmin)+1,1)==0  %no double counting variable vector
           pouttemp=zeros(size(pout));
           for k=lmin:lmax
               k;
            Mcount=0;
             for m=1:size(data,2)    %entire column length(#of variables)
                 m;

                  dist=abs(data(j,m)-data(k,m)); %for each variable 1 by 1
```

```
              %Dealing with floating point error
             r_dist=round2(dist,fp_tol); %rounds it to certain precision
             if r_dist<=(sizeofstates(1,m))

              Mcount=Mcount+1;
          end
          end

%Ensures that the number of variables that have been counted (meet
%the criteria is >= TL*total number of variables and this variable
%vector has not been previously counted

     if
Mcount>=TL*size(data,2))&(pout(abs(lmin-k)+1,1)==0)
                    count=count+1;
                    pouttemp(abs(lmin-k)+1,1)=1;
                end
            end
            rnum(abs(lmin-j)+1,1)=count; %number of points in state
            neighbour(abs(lmin-j)+1,:)=data(j,:);
          end
        pout=pout|pouttemp; %update no double counting using logical OR
       end
    %Calculating pdf
        if sum(rnum,1)==0
        pdf=rnum;
    else
        pdf=rnum/sum(rnum,1);
    end
size1=size(neighbour);
pdf;
```

CalcAvgFish.m

```
function [AvgFish,PO_TL,mY]= CalcMeanFish(t,data,hwin,winspace,sost)

%This code was developed to calculate the mean value of the Fisher
%information by computing FI over various tightening levels to find the
%point above which perfect order is experienced.  And then calculating a
%mean of the values for each time window.  The program returns:

%AvgFish:         Average Fisher information over TL from strict to relaxed
%PO_TL:           Tightening Level the system is in perfect order.  It is
%                 connected to pervasiveness (1-PO_TL)
%mY:              Mean Year for each time window

% The code was developed by Tarsha Eason (2009)

%[AvgFish Y TL t_win]= Availdata(t,data,hwin,winspace,sost)
TL=[]; FisherMat=[];
profile on
display('Working....');
for i=1:100
   Tol=100-(i-1);

[FI,midt_win]=GFisher(t,data,sost,hwin,winspace,Tol,0);

FMat(:,i)=FI;
n=size(FI,2);  %# of Fisher information Calculations

%Calculates average FI for each time window by seeking the tightening
%level at which all resulting fisher calculation for each widow is at its
%max = 8, perfect order.  The average FI is calculated
%from the FisherMat which stores all of the Fisher results from each time
%window less the windows where all of the Fisher results are 8.
    if sum(FMat(:,i))<8*n %Tightening level with all Fishers = 8, perfect order
    % display('Yes');
     FisherMat(:,i)=FMat(:,i);
     TL=Tol; %Final value is lowest tightening level before all Fisher results are 8 (max FI)

   %else
    %    display('End TL Calcs');
   end
end %End Tol loop

if isempty(TL)==1
display('The system is in perfect order for this size of states at all tightening levels.  Please feel free to make an adjustment accordingly!!');
f = warndlg('The system is in perfect order for this size of states at all tightening levels.  Please feel free to make an adjustment accordingly!!', 'Warning Dialog');
  PO_TL=100;
else
PO_TL=TL-1;
end
mY=midt_win;
```

```
%Provides an ouput when the system is competely orderly at all tightening
%levels.  This results in no collection of Fisher values before the system
%is a maximum level.  Accordingly, FisherMat is empty indicates either true
%perfect order or a need to adjust the size of states (smaller)
 if isempty(FisherMat)==1;
   AvgFish=8*ones(size(FI));
else
 %Calculates mean FI for each time window
AvgFish=mean(FisherMat');
  end

%Provides an ouput when the system is competely orderly at all tighten
%levels.  Indicates either true perfect order or a need to adjust the size
%of states (smaller)

%Transposing (aesthetic)
AvgFish=AvgFish';
mY=midt_win';

%%%%%Simple Plots%%%%%%%%%%%%%%%%

subplot(2,1,1), plot(t,data) %plots data
%subplot(2,1,1), plot(data(:,1),data(:,2)) %plots data for ode
title('Time series data');

subplot(2,1,2), plot(mY,AvgFish)

axis([mY(1) mY(end) 0 9])
title('Fisher information over time');
xlabel('Time'); ylabel('Fisher information');
```

SmoothFI.m

```
function [FIm]=SmoothFI(n,t,FI,plot)

% Computes <FI>, a "m" point mean of FI smoothing results to focus on trends
% and not fluctuations.

% The code was developed by Tarsha Eason (2010)

data=[t FI];
A=sortrows(data,-1); FIs=A(:,2);ts=A(:,1);

window=0; I=[];T=[];A=[];B=[]; FIm=[];
for i=1:n:size(FI,1) %loop through FIs
  i

  %Revised Method: #pts=hwin
  lmin=min(i,size(FIs,1));
  lmax=min(i+n-1,size(FIs,1));
  NP=size(FIs(lmin:lmax,1),1);

  if NP== n
  window=window+1;

I(window)= mean(FIs(lmin:lmax));      %<FI>
T(window)=ceil(mean(ts(lmin:lmax)));
end
end

B=[T' I'];

FIm=sortrows(B,1);

if plot==1

subplot(2,1,1),plot(t,FI,'-*');  %plot original FI
title('Original FI'); axis([t(1) t(end) 0 8]);
subplot(2,1,2),plot(FIm(:,1),FIm(:,2),'-*');   %plot <I>
title('Smoothed FI(< FI >)'); axis([t(1) t(end) 0 8]);
end

%%
```

GUI: Main_Fisher_data_proc.m

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%This program  provides a graphical user interface (GUI) for performing
%Fisher information(FI)calculations. It is designed to simplify the
%procedure by allowing the user to select formatted data files, set
%parameter values and process the data which calculates FI over numerous
%tightening levels (from strict to relaxed tightening) providing an average
%FI result. The computed FI is plotted in the GUI, along with a plot of the
%FI results that have been "smoothed" using an "m" point average (<FI>).
%The user is able to save the FI computations and plot for further use.  It %also provides access for the advanced
study of regime shifts, if they exist.

%Procedure for use
%
%Select the formatted data files (*time.xls, *data.xls and *sost.xls; see
%Appendix 6-B.2 for file formatting details) and press the
%'START' button to process the data and generate a plot of the
%time-averaged fisher.  After the data is processed, the plot and
%calculations may be saved by using the 'Save Plot' and 'Save Calculations'
%buttons. The 'Advanced' button calls the AdvancedFisher GUI for further
% Fisher information analysis.

%Main_Fisher_data_proc was developed by Tarsha Eason (2008-2010)as a
%graphical extension to work done from 2004 to 2008 by Cabezas, Pawloski,
%Karunithini and Eason to calculate FI in the Gfisher.m and
%Nfisherpdf.m code.  Please feel free to refer to the source code of those
%files for additional references.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function varargout = Main_Fisher_data_proc(varargin)
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                  'gui_Singleton',   gui_Singleton, ...
                  'gui_OpeningFcn',  @Main_Fisher_data_proc_OpeningFcn, ...
                  'gui_OutputFcn',   @Main_Fisher_data_proc_OutputFcn, ...
                  'gui_LayoutFcn',   [] , ...
                  'gui_Callback',    []);
if nargin && ischar(varargin{1})
   gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
   [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
   gui_mainfcn(gui_State, varargin{:});
end

handles.processDataCompleted = 0; %
%%
function Main_Fisher_data_proc_OpeningFcn(hObject, eventdata, handles, varargin)
 handles.output = hObject;
%set(hObject,'toolbar','figure'); %enables toolbar
%this variable used to prevent users from breaking the GUI
%the variable is set to 1 once the data has been processed
```

```
%this command asks the user to confirm closing of GUI
set(handles.figure1,'CloseRequestFcn','closeGUI');

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes Main_Fisher_data_proc wait for user response (see UIRESUME)
% uiwait(handles.figure1);

%%
% --- Outputs from this function are returned to the command line.
function varargout = Main_Fisher_data_proc_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;


%%
function inputFiles_listbox_Callback(hObject, eventdata, handles)
%no code needed for this callback, the listbox is only used as a visual

%%
function addFiles_pushbutton_Callback(hObject, eventdata, handles)

%gets input file(s) from user
[input_file,pathname] = uigetfile( ...
       {'*.xls', 'Data Files (*.xls)'; ...
        '*.*', 'All Files (*.*)'}, ...
        'Select files', ...
        'MultiSelect', 'on');

%if file selection is cancelled, pathname should be zero
%and nothing should happen
if pathname == 0
   return
end

%gets the current data file names inside the listbox
inputFileNames = get(handles.inputFiles_listbox,'String');
 %if they only select one file, then the data will not be a cell
if iscell(input_file) == 0

   %add the most recent data file selected to the cell containing
   %all the data file names
   inputFileNames{length(inputFileNames)+1} = fullfile(pathname,input_file);
```

```
%else, data will be in cell format
else
    %stores full file path into inputFileNames
    for n = 1:length(input_file)
        inputFileNames{length(inputFileNames)+1} = fullfile(pathname,input_file{n});
    end
end

%updates the gui to display all filenames in the listbox
set(handles.inputFiles_listbox,'String',inputFileNames);

%make sure first file is always selected so it doesn't go out of range
%the GUI will break if this value is out of range
set(handles.inputFiles_listbox,'Value',1);

% Update handles structure
guidata(hObject, handles);

%%
function deleteFiles_pushbutton_Callback(hObject, eventdata, handles)
%this function allows the user to delete files they accidentally
%added to the list box

%get the current list of file names from the listbox
inputFileNames = get(handles.inputFiles_listbox,'String');

%get the values for the selected file names
option = get(handles.inputFiles_listbox,'Value');

%is there is nothing to delete, nothing happens
if (isempty(option) == 1 || option(1) == 0 || isempty(inputFileNames))
    return
end
%erases the contents of highlighted item in data array
inputFileNames(option) = [];

%updates the gui, erasing the selected item from the listbox
set(handles.inputFiles_listbox,'String',inputFileNames);

%moves the highlighted item to an appropriate value or else will get error
if option(end) > length(inputFileNames)
    set(handles.inputFiles_listbox,'Value',length(inputFileNames));
end

% Update handles structure
guidata(hObject, handles);
%%
function edit_hwin_Callback(hObject, eventdata, handles)
% hObject        handle to edit_hwin (see GCBO)
% eventdata      reserved - to be defined in a future version of MATLAB
% handles        structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of inputText_hwin as text
%        str2double(get(hObject,'String')) returns contents of edit_hwin as a double
```

```
HW=str2num(get(hObject,'String'));

%checks to see if input is empty.  If so, default input1_editText to zero
if(isempty(HW))
    set(hObject,'String','0')
end
guidata(hObject,handles);

% --- Executes during object creation, after setting all properties.
function edit_hwin_CreateFcn(hObject, eventdata, handles)
% hObject       handle to edit_hwin (see GCBO)
% eventdata     reserved - to be defined in a future version of MATLAB
% handles       empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
%%
function edit_winspace_Callback(hObject, eventdata, handles)
% hObject       handle to edit_winspace (see GCBO)
% eventdata     reserved - to be defined in a future version of MATLAB
% handles       structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of inputText_winspace as text
%        str2double(get(hObject,'String')) returns contents of inputText_winspace as a double
WS=str2num(get(hObject,'String'));

%checks to see if input is empty.  If so, default input1_editText to zero
if(isempty(WS))
    set(hObject,'String','0')
end

guidata(hObject,handles);

% --- Executes during object creation, after setting all properties.
function edit_winspace_CreateFcn(hObject, eventdata, handles)
% hObject       handle to edit_winspace (see GCBO)
% eventdata     reserved - to be defined in a future version of MATLAB
% handles       empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
%%
function edit_Smoothpts_Callback(hObject, eventdata, handles)
% hObject       handle to edit_winspace (see GCBO)
% eventdata     reserved - to be defined in a future version of MATLAB
% handles       structure with handles and user data (see GUIDATA)
```

```
% Hints: get(hObject,'String') returns contents of inputText_winspace as text
%        str2double(get(hObject,'String')) returns contents of inputText_winspace as a double
nS=str2num(get(hObject,'String'));

%checks to see if input is empty.  If so, default input1_editText to zero
if(isempty(nS))
    set(hObject,'String','0')
end
guidata(hObject,handles);

% --- Executes during object creation, after setting all properties.
function edit_Smoothpts_CreateFcn(hObject, eventdata, handles)
% hObject       handle to edit_winspace (see GCBO)
% eventdata     reserved - to be defined in a future version of MATLAB
% handles       empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
%%
function reset_pushbutton_Callback(hObject, eventdata, handles)
%resets the GUI by clearing all relevant fields
handles.processDataCompleted = 0;
cla(handles.axes1,'reset');

set(handles.edit_hwin,'String','8');
set(handles.edit_winspace,'String','1');
set(handles.edit_Smoothpts,'String','3');
%set(handles.inputFiles_listbox,'String','');
%set(handles.inputFiles_listbox,'Value',0);
guidata(hObject, handles);
%%
function start_pushbutton_Callback(hObject, eventdata, handles)

inputFileNames = get(handles.inputFiles_listbox,'String');
%checks to see if the user selected any input files
%if not, nothing happens
if isempty(inputFileNames)
    return
end

%disables the button while data is processing
disableButtons(handles);
refresh(Main_Fisher_data_proc);

%initialize the cell structures
handles.data = {};
handles.time = {};
sost=[];
%Read input data
```

```
for x=1:length(inputFileNames)
  A=inputFileNames{x};
  a=size(A,2);
  b=a-7;
  if(A(b:a)=='data.xls')
    %display('Loading Variable Data');
    data=xlsread(inputFileNames{x});
    %size(data)

  elseif(A(b:a)=='time.xls')
    %display('Loading Time Data');
    time=xlsread(inputFileNames{x});
    %size(time)
  elseif(A(b:a)=='sost.xls')
    %display('Loading Size of states Data');
    sost=xlsread(inputFileNames{x});
    %size(sost)
  else
    display('Not correct input filename.  See Appendix 6-B.2');
  end
end

%Calculate Fisher information
t=time;
handles.data=data;
handles.t=time;

Flag=isempty(sost); %test to see if *sost.xls file was uploaded

if Flag==1
%display('Since no size of states file was added.  The size of states will be calculated from the first 5 data points')

errordlg('Since no size of states file was added.  The size of states will be calculated from the first 5 data points','File
Error');
sost=2*std(data(1:5,:));
end

handles.sost=sost;
%get hwin and winspace from input form
H=get(handles.edit_hwin,'String');
W=get(handles.edit_winspace,'String');
nS=get(handles.edit_Smoothpts,'String');

hwin=str2num(H);
winspace=str2num(W);
nSpts=str2num(nS);

handles.hwin=hwin;
handles.winspace=winspace;

TL=[]; FisherMat=[];

%Using search algorithm for finding the size of states
%[s_sost,region_year,diff_test]=statesize(4,hwin,winspace,data,time);
%sost=s_sost;
```

```
%Calculating lowest tightening level before all FI results are 8
%(max): PO_TL
for i=1:100
   Tol=100-(i-1);
 [FI, midt_win, t_win]=GFisher(t,data,sost,hwin,winspace,Tol,0);
   %YMat(:,i)=t_win;
   %YMat(:,i)=t_win(i);
   FMat(:,i)=FI';

n=size(FI,2);  %# of FI Calculations

%Calculates FI for each time window by seeking the tightening
%level at which all resulting fisher calculation for each widow is at its
%max = 8, perfect order.  The average fisher is calculated
%from the FisherMat which stores all of the FI results from each time
%window less the windows where all of the FI results are 8.

  if sum(FMat(:,i))<8*n %Tightening level with all FI values = 8, perfect order
   % display('Yes');
    FisherMat(:,i)=FMat(:,i);

    TL=Tol; %Final value is lowest tightening level before all FI results are 8
   else
   %display('End TL Calcs');

  end
end %End Tol loop

if isempty(TL)==1
display('The system is in perfect order for this size of states at all tightening levels.  Please feel free to make an adjustment accordingly!!');
f = warndlg('The system is in perfect order for this size of states at all tightening levels.  Please feel free to make an adjustment accordingly!!', 'Warning Dialog');
  PO_TL=100;

else
PO_TL=TL-1;
end

handles.PO_TL=PO_TL;

%Provides an ouput when the system is competely orderly at all tighten
%levels.  This results in no collection of FI values before the system is a
%maximum level.  Accordingly, FisherMat is empty indicates either true
%perfect order or a need to adjust the size of states (smaller)

if isempty(FisherMat)==1;
   AvgFish=8*ones(size(FI));
else

%Calculates Avg FI for each time window
AvgFish=mean(FisherMat');

end
```

```
T=zeros(size(t_win));
P=T|t_win;

t_win;

   handles.AvgFish=AvgFish;
   %AvgFish

for i=1:size(AvgFish,2)
   AvgFI(:,i)=P(:,i)*AvgFish(i);
end

handles.AvgFI_win=AvgFI;

handles.PO_TL=PO_TL;
%PO_TL
%plot mean FI over time window
axes(handles.axes1)

YMat=t(1:size(handles.AvgFI_win,1)); %time period
handles.YMat=YMat;

%%%%Plot Avg FI over time window%%%%%%%%%%%%%%%%%%
%plot(YMat,handles.AvgFI_win)
%title('Average FI vs. Time');

%%%%%Plot average FI in center of window%%%%%%%%%%%%%%%%%%
for j=1:size(t_win,2)
   R(:,j)=nonzeros(t_win(:,j));
   Z(:,j)=AvgFish(j)*ones(size(R,1),1);
Y(j)=ceil(mean(R(:,j))); %mean year for each time window
end

plot(Y,AvgFish,'*b-')
handles.Year=Y;
title('Average FI over time');
hold
n=nSpts; %n=3;  %make sure to create an edit text to change this value
[FIm]=SmoothFI(n,Y',AvgFish',0);
handles.MnYr=FIm(:,1);
handles.MnFI=FIm(:,2);

plot(FIm(:,1),FIm(:,2),'*r-')

legend('Fisher information(FI)','Smoothed FI (<FI>)')
legend(handles.axes1,'boxoff')
axis([Y(1,1) Y(end) 0 8]); xlabel('Year'); ylabel('Fisher information');

enableButtons(handles);
handles.processDataCompleted = 1;
guidata(hObject, handles);
%%
function savePlot_pushbutton_Callback(hObject, eventdata, handles)
```

```
%if the data hasn't been processed yet,
%nothing happens when this button is pressed

if (handles.processDataCompleted == 0)
    return
end

disableButtons(handles);
refresh(Main_Fisher_data_proc);

savePlot(handles.axes1); %figure out how to save the legend?

enableButtons(handles);
guidata(hObject, handles);
%%
function export_pushbutton_Callback(hObject, eventdata, handles)
%This function saves the mean FI values, date and time of
%calculation, as well as the smoothed mean FI results into an Excel file in
%the format:
%Row1 Col1: Date
%Row2 Col1: Time (military)
%Row3 Col1: Perfect order tightening level: PO_TL
%Row4 to Row4+size(FI) Col2: [Year FI]
%The Smoothed mean FI results follow

%if the data hasn't been processed yet,
%nothing happens when this button is pressed
if (handles.processDataCompleted == 0)
   return
end

calctime=clock;

%stores savepath for results
[filename, pathname] = uiputfile ({'*.xls', 'Data Files (*.xls)'; ...
        '*.*', 'All Files (*.*)'}, ...
        'Save file as','default');

%if user cancels save command, nothing happens
if isequal(filename,0) || isequal(pathname,0)
    return
end

%saves the data
dlmwrite(fullfile(pathname, filename),[calctime(2),calctime(3),calctime(1)],'delimiter','/','-append');
dlmwrite(fullfile(pathname, filename),[calctime(4) calctime(5)],'delimiter',':','precision','%4.2d','-append');
dlmwrite(fullfile(pathname, filename),handles.PO_TL,'-append');
%dlmwrite(fullfile(pathname, filename),'Mean FI','-append')
dlmwrite(fullfile(pathname, filename),[handles.Year',handles.AvgFish'],'-append','delimiter','\t','roffset',1)
dlmwrite(fullfile(pathname, filename),[handles.MnYr,handles.MnFI],'-append','delimiter','\t','roffset',2)
%%
```

```
function disableButtons(handles)
set(handles.figure1,'Pointer','watch');
set(handles.start_pushbutton,'Enable','off');
set(handles.reset_pushbutton,'Enable','off');
set(handles.addFiles_pushbutton,'Enable','off');
set(handles.savePlot_pushbutton,'Enable','off');
set(handles.deleteFiles_pushbutton,'Enable','off');
set(handles.inputFiles_listbox,'Enable','off');
set(handles.export_pushbutton,'Enable','off');
set(handles.Advanceduser_pushbutton,'Enable','off');
set(handles.Help_pushbutton,'Enable','off');
%%
function enableButtons(handles)
set(handles.figure1,'Pointer','arrow');
set(handles.start_pushbutton,'Enable','on');
set(handles.reset_pushbutton,'Enable','on');
set(handles.addFiles_pushbutton,'Enable','on');
set(handles.savePlot_pushbutton,'Enable','on');
set(handles.deleteFiles_pushbutton,'Enable','on');
set(handles.inputFiles_listbox,'Enable','on');
set(handles.export_pushbutton,'Enable','on');
set(handles.Advanceduser_pushbutton,'Enable','on');
set(handles.Help_pushbutton,'Enable','on');
%%
function inputFiles_listbox_CreateFcn(hObject, eventdata, handles)

% Hint: listbox controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% --- Executes on button press in Advanceduser_pushbutton.
function Advanceduser_pushbutton_Callback(hObject, eventdata, handles)
% hObject       handle to Advanceduser_pushbutton (see GCBO)
% eventdata     reserved - to be defined in a future version of MATLAB
% handles       structure with handles and user data (see GUIDATA)

AdvancedFisherGUI()  %Call subGUI for further analysis

guidata(hObject, handles);

function Help_pushbutton_Callback(hObject, eventdata, handles)
% hObject       handle to edit_hwin (see GCBO)
% eventdata     reserved - to be defined in a future version of MATLAB
% handles       structure with handles and user data (see GUIDATA)

%testflag=250000

HelpPath = which('helpMain.html');
web(HelpPath);  %opens GUI help file

guidata(hObject,handles);
```

AdvancedFisherGUI.m

```
function varargout = AdvancedFisherGUI(varargin)

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%
%This program is called from the Fisher_data_proc GUI and provides a
%graphical user interface for studying the pervasiveness and intensity of
%regime shifts by plotting the Fisher information (FI) results for tightening
%levels (TL) from 100%-10% overlaid by the average FI. Pervasiveness indicates
%the number of variables affected by the shift and is determined by finding
%the TL value at which the system is perfectly ordered (i.e. FI is at its
%max (8) for the entire period.  Pervasiveness is computed by subtracting
%the perfect order tightening level (POTL) from 100) and denotes the percentage
%of variables that were impacted. The intensity relates to the amplitude of
%the shift and is determined by how far the FI drops between two stable regimes.

%NOTE: Data files must be selected through the Fisher_data_proc GUI and
%processed prior to doing advanced analysis through this GUI.
%
%AdvancedFisher was developed by Tarsha Eason(2008-2010) as a graphical
%extension to work done from 2004 to 2008 by Cabezas, Pawlowski, Karuninithi
%and Eason to calculate FI in the Revfisher.m, fisherpdf.m code.
%Please feel free to refer to the source code of those files for additional
%references.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%

%Matlab GUIDE information

% ADVANCEDFISHERGUI M-file for AdvancedFisherGUI.fig
% ADVANCEDFISHERGUI, by itself, creates a new ADVANCEDFISHERGUI or raises
% the existing singleton*.
%
% H = ADVANCEDFISHERGUI returns the handle to a new ADVANCEDFISHERGUI or
% the handle to the existing singleton*.
%
%ADVANCEDFISHERGUI('CALLBACK',hObject,eventData,handles,...) calls the
%local function named CALLBACK in ADVANCEDFISHERGUI.M with the given input
%arguments.
%
%ADVANCEDFISHERGUI('Property','Value',...) creates a new ADVANCEDFISHERGUI
%or raises the existing singleton*.  Starting from the left, property value
%pairs are applied to the GUI before AdvancedFisherGUI_OpeningFcn gets
%called.  An unrecognized property name or invalid value makes property
%application stop.  All inputs are passed to AdvancedFisherGUI_OpeningFcn
%via varargin.

 % Last Modified by GUIDE v2.5 17-Jun-2010 12:44:09

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
```

```
                  'gui_OpeningFcn', @AdvancedFisherGUI_OpeningFcn, ...
                  'gui_OutputFcn',  @AdvancedFisherGUI_OutputFcn, ...
                  'gui_LayoutFcn',  [] , ...
                  'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT

 % --- Executes just before AdvancedFisherGUI is made visible.
function AdvancedFisherGUI_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject        handle to figure
% eventdata      reserved - to be defined in a future version of MATLAB
% handles        structure with handles and user data (see GUIDATA)
% varargin       command line arguments to AdvancedFisherGUI (see VARARGIN)

% Choose default command line output for AdvancedFisherGUI
handles.output = hObject;

%this command asks the user to confirm closing of GUI
set(handles.figure1,'CloseRequestFcn','closeGUI');

%set(hObject,'toolbar','figure');  % activates toolbar

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes AdvancedFisherGUI wait for user response (see UIRESUME)
% uiwait(handles.figure1);


% --- Outputs from this function are returned to the command line.
function varargout = AdvancedFisherGUI_OutputFcn(hObject, eventdata, handles)
% varargout      cell array for returning output args (see VARARGOUT);
% hObject        handle to figure
% eventdata      reserved - to be defined in a future version of MATLAB
% handles        structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;

% --- Executes during object creation, after setting all properties.
function inputText_hwin_CreateFcn(hObject, eventdata, handles)
% hObject        handle to inputText_hwin (see GCBO)
% eventdata      reserved - to be defined in a future version of MATLAB
% handles        empty - handles not created until after all CreateFcns called
```

```
% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function inputText_winspace_Callback(hObject, eventdata, handles)
% hObject        handle to inputText_winspace (see GCBO)
% eventdata      reserved - to be defined in a future version of MATLAB
% handles        structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of inputText_winspace as text
%        str2double(get(hObject,'String')) returns contents of inputText_winspace as a double
%WS=str2num(get(hObject,'String'));

%checks to see if input is empty.  If so, default input1_editText to zero
%if(isempty(WS))
%    set(hObject,'String','0')
%end
guidata(hObject,handles);

% --- Executes during object creation, after setting all properties.
function inputText_winspace_CreateFcn(hObject, eventdata, handles)
% hObject        handle to inputText_winspace (see GCBO)
% eventdata      reserved - to be defined in a future version of MATLAB
% handles        empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

function inputText_TL_Callback(hObject, eventdata, handles)
% hObject        handle to inputText_TL (see GCBO)
% eventdata      reserved - to be defined in a future version of MATLAB
% handles        structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of inputText_TL as text
%        str2double(get(hObject,'String')) returns contents of inputText_TL as a double

%Tol=str2num(get(hObject,'String'));

%checks to see if input is empty.  If so, default input1_editText to zero
if(isempty(Tol))
    set(hObject,'String','0')
end
guidata(hObject,handles);

% --- Executes during object creation, after setting all properties.
function inputText_TL_CreateFcn(hObject, eventdata, handles)
% hObject        handle to inputText_TL (see GCBO)
% eventdata      reserved - to be defined in a future version of MATLAB
% handles        empty - handles not created until after all CreateFcns called
```

```
% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

%Calculates and plots FI different tightening levels

% --- Executes on button press in FishTL_pushbutton.
function FishTL_pushbutton_Callback(hObject, eventdata, handles)
% hObject    handle to FishTL_pushbutton (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

YMat=[];FMat=[];
mainFigureHandle=Main_Fisher_data_proc;  %stores the figure handle of main GUI here
mainGUIdata = guidata(mainFigureHandle);

%Pulling data, time, AvgFish, and midyear from Main_Fisher_data_proc.m

t=mainGUIdata.t;
data=mainGUIdata.data;
AvgFish=mainGUIdata.AvgFish;
midyear=mainGUIdata.Year;
PO_TL=mainGUIdata.PO_TL;
SOST=mainGUIdata.sost;
hwin=mainGUIdata.hwin;
winspace=mainGUIdata.winspace;

%Studying Pervasiveness and Intensity from Main_Fisher data_proc parameter
%settings

for i=1:10
    Tol=100-(i-1)*10;

 [FI, midt_win, t_win]=GFisher(t,data,SOST,hwin,winspace,Tol,0);


 FMat(:,i)=FI';
 YMat(:,i)=midt_win;

end

axes(handles.axes3); plot(YMat(:,1),FMat(:,1),YMat(:,2),FMat(:,2),YMat(:,3),FMat(:,3),YMat(:,4),FMat(:,4),YMat(:,
5),FMat(:,5));


% Create legend
legend1 = legend(handles.axes3,'TL=100%','TL=90%','TL=80%','TL=70%','TL=60%');
set(legend1,'YColor',[1 1 1],'XColor',[1 1 1],...
   'Location','NorthEast',...
    'FontSize',8,...
    'FontName','Arial');
```

```
hold

plot(midyear,AvgFish,'-gd','LineWidth',2);

title('Pervasiveness and Intensity (100%-60%)');
axis([YMat(1,1) YMat(size(YMat,1)) 0 10]); xlabel('Year'); ylabel('Fisher information');

hold off

axes(handles.axes4); plot(YMat(:,6),FMat(:,6),YMat(:,7),FMat(:,7),YMat(:,8),FMat(:,8),YMat(:,9),FMat(:,9),YMat(:,
10),FMat(:,10))

% Create legend
legend2 = legend(handles.axes4,'TL=50%','TL=40%','TL=30%','TL=20%','TL=10%');
set(legend2,'YColor',[1 1 1],'XColor',[1 1 1],...
   'Location','NorthEast',...
    'FontSize',8,...
    'FontName','Arial');
 hold
plot(midyear,AvgFish,'-gd','LineWidth',2);

title('Pervasiveness and Intensity (50%-0%)');
axis([YMat(1,1) YMat(size(YMat,1)) 0 10]); xlabel('Year'); ylabel('Fisher information');

hold off

PVL=100-PO_TL;
set(handles.edit_POTL,'String',num2str(PO_TL));
set(handles.edit_Pervasiveness,'String',num2str(PVL))

%Save result of User Analysis

%dlmwrite('Results.xls',[hwin,winspace],'-append');
%dlmwrite('Results.xls',[YMat(:,1) AFish'],'-append','delimiter','\t','precision','%4.4f');
%dlmwrite('Results.xls',[midyear' AvgFish'],'-append','delimiter','\t','precision','%4.4f');
warning off
%%%%%

guidata(hObject, handles); %updates the handles

function edit_Pervasiveness_Callback(hObject, eventdata, handles)
% hObject       handle to edit_Pervasiveness (see GCBO)
% eventdata     reserved - to be defined in a future version of MATLAB
% handles       structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit_Pervasiveness as text
%        str2double(get(hObject,'String')) returns contents of edit_Pervasiveness as a double

 % --- Executes during object creation, after setting all properties.
function edit_Pervasiveness_CreateFcn(hObject, eventdata, handles)
% hObject       handle to edit_Pervasiveness (see GCBO)
% eventdata     reserved - to be defined in a future version of MATLAB
% handles       empty - handles not created until after all CreateFcns called
```

```
% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% --- Executes on button press in RESET_Pushbutton.
function RESET_Pushbutton_Callback(hObject, eventdata, handles)
% hObject      handle to RESET_Pushbutton (see GCBO)
% eventdata    reserved - to be defined in a future version of MATLAB
% handles      structure with handles and user data (see GUIDATA)
cla(handles.axes3,'reset');
cla(handles.axes4,'reset');
set(handles.inputText_TL,'String',100)
set(handles.inputText_hwin,'String',10)
set(handles.inputText_winspace,'String',5)
set(handles.edit_Pervasiveness,'String',0);
set(handles.edit_POTL,'String',0);
%handles.buttonCounter = 0; %reset buttoncounter

guidata(hObject, handles); %updates the handles

function edit_POTL_Callback(hObject, eventdata, handles)
% hObject      handle to edit_POTL (see GCBO)
% eventdata    reserved - to be defined in a future version of MATLAB
% handles      structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of edit_POTL as text
%        str2double(get(hObject,'String')) returns contents of edit_POTL as a double

% --- Executes during object creation, after setting all properties.
function edit_POTL_CreateFcn(hObject, eventdata, handles)
% hObject      handle to edit_POTL (see GCBO)
% eventdata    reserved - to be defined in a future version of MATLAB
% handles      empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end

% --- Executes on button press in Help_pushbutton.
function Help_pushbutton_Callback(hObject, eventdata, handles)
% hObject      handle to Help_pushbutton (see GCBO)
% eventdata    reserved - to be defined in a future version of MATLAB
% handles      structure with handles and user data (see GUIDATA)

HelpPath = which('helpAdvGUI2.html');
web(HelpPath);

guidata(hObject,handles);
```

round2.m : Floating Point Correction

```
function z = round2(x,y)
%ROUND2 rounds number to nearest multiple of arbitrary precision.
%Z = ROUND2(X,Y) rounds X to nearest multiple of Y.
%Floating point work around designed by Robert Bemis 15 Dec 2003 and updated
%(29 Jun 2006): http://www.mathworks.com/matlabcentral/fileexchange/4261

%% defensive programming
error(nargchk(2,2,nargin))
ror(nargoutchk(0,1,nargout))
if prod(size(y))>1
  error('n must be scalar')
end

z = round(x/y)*y;
```

CloseGUI.m

```
function closeGUI

selection = questdlg('Do you want to close the GUI?',...
                     'Close Request Function',...
                     'Yes','No','Yes');
switch selection,
   case 'Yes',
    delete(gcf)
   case 'No'
     return
end
```

7.0
The San Luis Basin Sustainability Metrics Project: Results, Conclusions, and Recommendations

7.1 Introduction

In this report, we have presented the results of a five-year project that estimated four metrics of sustainability for the San Luis Basin (SLB). The SLB is an agricultural region in south-central Colorado, adjacent to New Mexico, with a large portion of land publicly owned. It is a relatively uncomplicated region that has not experienced a substantial amount of change during the 26 years we examined. This lack of change provided an opportunity to develop a methodology for calculating sustainability metrics and to examine a large geographic region with relatively little diversity in land uses (i.e., there are few major industries or land uses to overly complicate the calculation of metrics) and economic drivers. For example, the San Luis Valley Development Resources Group (SLVDRG; 2007) finds the top three land uses in 2002 were: 1) rangeland (43.6%); 2) forest land (39.6%); and 3) agricultural land (11.8%). Urban land is only 0.2% of the area in the six county Valley.[11] Because individual metrics do not capture all aspects of a system, multiple metrics were estimated to examine the SLB's movement toward or away from sustainability. We assembled a detailed dataset that met the three research objectives presented in Chapter 1. We successfully estimated the metrics, even though data for some of the variables were not available at the county level. In the previous four chapters, we described the individual methodologies and presented the metric results. Those chapters will enable the reader to understand each metric in terms of what they capture and the meaning of the results. Even though we chose a less complicated region, we still faced a number of hurdles while developing the methodology. This chapter examines the sustainability metrics together, using the results of the previous four chapters, to decipher whether the SLB is moving toward or away from sustainability. It describes the strengths and limitations of the overall approach (rather than the strengths and limitations of the individual metric approaches, which can be found in Chapters 3-6). We present future research directions generated from this research project and review our research goal.

[11] The San Luis Valley Development Resources Group defines the Valley as the following six counties: Alamosa, Conejos, Costilla, Mineral, Rio Grande, and Saguache. This differs from our definition of the SLB by not including Hinsdale County.

7.2 Summary of Calculations

Based on the results of Ecological Footprint Analysis (EFA), we found that even though there was a surplus in bioproductive land, the ecological remainder was decreasing due to population growth in the SLB (Chapter 3). If the trend continues, the ecological remainder (a reserve in this region) will eventually become an ecological deficit. Hence, we concluded that the SLB is moving away from sustainability based on the EFA. The estimation of Green Net Regional Product (GNRP) provides a one-sided test of sustainability and reveals when a system is not sustainable (see Chapter 4). The results for GNRP provided no definitive evidence that the system was moving away from sustainability. Emergy Analysis (EmA) used the fraction of renewable emergy used to total emergy used as a metric for sustainability, but it was limited by data availability (Chapter 5). Unlike the other metrics, a complete EmA was estimated only for the 11-year period of 1995-2005. Overall, there was a general decrease in the fraction of renewable emergy used to total emergy used. Early in this period, EmA suggested the SLB was moving away from sustainability. More recently, there was an increase in the fraction of renewable emergy used to total emergy used, indicating the SLB has been moving toward sustainability since 2003. Finally, the results of the Fisher information (FI) assessment revealed the system exhibited no regime shifts for the period of the study (Chapter 6). Although the system exhibited small changes in dynamic order during the study period, it was relatively stable. Further, with the slight decreasing trend in dynamic order at the end of the study period, we noted the SLB may be starting to move away from sustainability. These results are summarized in Table 7.1.

7.3 Holistic Results for San Luis Basin

In Chapter 1, we stated that for the SLB to be on a sustainable path, the following criteria must be satisfied: 1) ecological balance (i.e., remainder) is increasing (or the ecological deficit is decreasing) with time and 2) the ratio of renewable emergy used to total emergy used is trending to one. FI and GNRP are one-sided tests and cannot technically show if the system is moving toward sustainability. Criteria for these one-sided tests indicate if the region is moving away from sustainability when: 3) FI is steadily decreasing with time (Karunanithi et al. 2008); and 4) GNRP is decreasing with time (i.e., Pezzey et al. 2006). For this study, we define a system to be moving away from sustainability if ecological balance, GNRP (or human welfare), the ratio of renewable emergy used to total emergy used, or FI are declining over time. Because each metric captures different aspects of a system, and all aspects are vital to the maintenance of a system, losing any one component would result in problems with the system and, we would consider the system to be moving away from sustainability.

Interpretation of these results could be examined statistically (e.g., Bastianoni et al. 2008, Shmelev and Rodríguez-Labajos 2009) or graphically (e.g., Hanley et al. 1999, Lammers et al. 2008, Pezzey et al. 2006). In this case, given the difference in the number of years calculated, interpreting the results statistically is not likely to provide useful conclusions (although FI uses data for the entire 26-year period, it produces only six data points). Furthermore, we cannot satisfactorily account for variation in each of the variables used in any of the metrics. Hence, we lack statistical analyses for trends and uncertainty. To explore further, we graphed the results using a similar scale. The ecological remainder showed a downward trend whereas GNRP was increasing from 1980-2005 (Fig. 7.1). First, we can examine how EFA and GNRP might relate because these metrics were estimated for the entire 26-year period. It is not surprising that GNRP has an inverse relationship with EFA (as represented by ecological remainder) because increased economic activity often accompanies a corresponding increase in the human impact on the environment or resource use. Although GNRP attempts to account for environmental degradation, the effect on human welfare might be mitigated by increases in physical capital. The indirect relationship between GNRP and EFA is consistent with Nourry (2008) who examined the sustainability of France. Other studies have found little relationship between GNRP and EFA (e.g., Hanley et al. 1999, Nourry 2008). This is consistent with our calculation of EFA and GNRP after 1994.

When we only look at 1995-2005 (11 years used for EmA), we find that the fraction of renewable emergy used to total emergy used was declining early in the time period and began to increase again in the last couple of years. Ecological Balance continued to decline during these 11 years. Ecological Balance may be positively correlated to total emergy used. In addition, total emergy used per person, is decreasing slightly (Fig. 5.4). Ecological footprint (*ef*) and total emergy used per person are supposed to lead to comparable results, but similar to Bastianoni et al. (2008), there appears to be no similar trend.

FI is difficult to include in this conversation on a year-by-year basis because the window settings established to capture the dynamic behavior of the system does not result in a FI value for each year. Further, as noted in the Sustainable Regimes Hypothesis, the method requires that a mean FI (<FI>) be computed to capture the trends in the dynamic order. As such, only six <FI> values are reported for the 26 year period. From the analysis, we found the system FI increased slightly until it peaked during the period centering 1995, and decreased slightly thereafter. Although there were changes in the FI over time, it was relatively steady and there was no indication of a regime shift for the period of the study. Upon examining the relationship between the <FI> for the overall system and the variables by category, we found the peak in system's <FI> during the period centering 1995 occurred at the same time as <FI> for the energy and environmental categories. In addition, we found the system had a negative correlation with the demographic category. However, the overall system, consumption (food and forest), land use, and agricultural production categories indicated movement away from sustainability by the end of the study period.

Interpreting the results holistically, we find evidence that the SLB may be moving away from sustainability. All four metrics are capturing different aspects or answering different sustainability questions (e.g., Hanley et al. 1999), and EFA and EmA indicate movement away from sustainability. EFA and EmA helped us reach this conclusion based on the criteria listed above and the graphs just described (Fig 7.1). If, as Neumayer (2010) points out, weak sustainability is an important step in the right direction, then, according to GNRP and FI, the SLB was moving in the right direction. According to the results of EFA and EmA, the region does not meet the requirements of strong sustainability and was moving in the wrong direction. If we correctly identified each metric as strong and weak measures of sustainability, it is interesting to realize the weak measures indicate the region is stable or moving toward sustainability, whereas the strong measures show the region is moving away from sustainability. These results support Neumayer's (2010) idea that, although not a long-term solution, weak sustainability may be a step in the right direction. However, we recognize the estimates are not perfect and have identified the limitations of each metric in their respective chapter. The next sections focus on the strengths and limitations we identified using the SLB project methodology.

7.4 Strengths of Methodology

Knowing if a region is trending toward or away from sustainability is quite useful and interest in this type of information is growing (e.g., Graymore et al. 2008). We believe that our methodology –our first attempt– adequately characterizes and evaluates the movement toward or away from sustainability of a regional system. The methodology suggests the multidisciplinary approach adequately assesses whether a region is moving toward or away from sustainability. Whereas no methodology measures every aspect of the system, we argue that each metric identifies changes to major components of the system and that together these metrics adequately represent the complexity of a regional system.

The metrics are data intensive and the data requirements are often prohibitive and lead to difficulty in calculating and interpreting the results. However, we were able to overcome several of the shortcomings by collecting and adapting data for many of the variables at county, state, and national levels during much of the 26-year period, thereby successfully characterizing the SLB (discussed in previous sections). We were tasked with developing a methodology that used readily accessible data to estimate four metrics. We believe we were successful in completing this task. All data used in this approach could be found on the World Wide Web and through personal communication with experts and stakeholders in the SLB. Table 2.1 summarizes data used this project. It identifies which data were used and by which metrics, the source of the data, and the number of years the data were available. More detailed tables on data and their sources are located in Chapters 3-6 for each individual metric. The majority of data were available from Federal government agencies including the Department of Commerce, Bureau of Economic Analysis; Department of Energy, Energy Information Administration; and the US Department of Agriculture including the Agricultural Research Service, the Forest Service, and the National Agricultural Statistics Survey. Data from Global Insight, Inc., used to compute Emergy, although readily accessible, were not free.

Another strength of this methodology is the use of multiple metrics to cover multiple attributes of the environmental system including ecological, economic, energetic, and system order. Sustainability is not limited to one attribute of a region and multiple metrics are necessary to cover the three pillars (economic, environmental, and social aspects) of sustainability (e.g., Graymore et al. 2008, Hanley et al. 1999). Because we used a multidisciplinary approach to estimate the metrics, we were able to take advantage of the economies of scale (i.e., specialization) to share information, knowledge, and data to support the calculation of the four metrics. For example, as data for wind erosion were being collected and analyzed, the individuals calculating GNRP were able to explain and share the process for the other metric groups that used wind erosion (rather than estimating it on their own). Once data were available for one metric, they were available for all the metrics. Assigning the collection of specific variables to individuals provided an approach that limited contacting various experts, thereby saving time (and money) of the researchers and entities that possessed data. This sharing of data and assigning responsibilities for collecting data reduced the duplication of efforts and streamlined data collection activities.

Another objective was to determine if data were available for a time-series analysis, thereby examining trends. Our initial goal was to calculate metrics and examine a regional system from 1980 to 2005. This required 26 years of data for numerous variables. EmA was limited by data suggesting results are truly only available from 1995-2005. Because data were available for a number of variables over a number of years, we successfully calculated four metrics and were able to visually test for trends. This indicates that useful data in electronic format can be easily obtained. Alone this finding is a valuable conclusion to our study and suggests that other useful metrics may be estimated with relatively little direct costs to local and regional governments.

Finally, one reason for the apparent success of this project in addressing the multidisciplinary nature of sustainability was including stakeholders in the process of identifying components of this system that were responsible for the trends of the metrics through time. We recognize that future regional analyses should include stakeholders in the process from the beginning, in order to address directly aspects of sustainability that stakeholders identify as important. It helps identify appropriate metrics that can quantify those aspects which are most useful to interested parties (i.e., the product is wanted by the stakeholders). Getting participation from individuals who were interested in the work and were potential users of the information proved quite useful in developing and improving the methodology in this study. For example, interacting with stakeholders early on assured that results from the metric calculations coincided with their observations of the SLB.

7.5 Limitations of Methodology

The majority of the limitations of this methodology relate to data needs, data availability, and data manipulation. Because many of the data needed for these metrics typically are not collected at the county level, we needed to rescale or convert state or US data to the county or regional level. Additional difficulties included measuring trends and making the methodology transferable to other regions besides the SLB. We discuss these in turn.

One of the objectives of this research was to develop a methodology that used readily accessible data. Although this objective was met, not all of the data were free. Global Insight, Inc. data were needed to estimate some components of EmA. Import and export data, down to transportation type and quantities of different goods, are desirable for EmA, but difficult to estimate without detailed data. Imports and exports to a system can be estimated by alternative means with some sacrifice in accuracy (Odum 1996). However, the cost of the Global Insight, Inc. data (≈$20K for 11 years) may preclude other regions from calculating this metric with the accuracy obtained in this study. It should be noted the import and export data were limited by the years available (1995-2005; see Table 2.1). Hence, the difficulty we had examining the results for the 26-year research period. Future research could compare the resulting trends from excluding these type data, thereby eliminating the added expense.

We took a number of steps to overcome the issue of data intensive calculations required for these sustainability metrics. In addition, we addressed the lack of region-specific data. Simplifying assumptions were needed in order to estimate the metrics, but they are common for these types of calculations. Note the assumptions become limitations if they somehow misrepresent the region of study. In this study, we assumed the SLB could be represented by state and/or US data with the appropriate rescaling (i.e., estimated on a per capita basis), and we tested some of these rescalings (e.g., Appendix 3-A). We attempted to confirm the assumptions were appropriate through discussions with stakeholders and by reviewing other data sources. For example, to estimate the Net Regional Product (NRP) for the SLB, initially we used Colorado data, but local stakeholders felt that both Colorado and New Mexico influenced the economy. Using this information, we averaged the NRP calculation for the SLB using both Colorado data and New Mexico data. In cases of missing data, interpolation was necessary to ensure a value could be computed for every year and because complete data were needed to proceed with calculations of EFA, EmA, and GNRP. Linear interpolation is a weakness if it was not appropriate. There are a number of examples described in Chapters 3-6 where we manipulated some state or US data in order to proceed with the calculations. The weakness here lies in whether these manipulations yielded adequately representative data for the SLB. It is probable that some manipulations better represented the SLB than others.

The team initially thought it could estimate confidence intervals and analyze trends for each of the metrics in order to understand uncertainty in the data. The proposed approach was to use bootstrapping, but we found it difficult to proceed given the state of the data (i.e., missing years, interpolated values, and lack of variation). From the bootstrap distribution, an estimate of bias, standard error, and confidence intervals are produced (Dixon 2001), thereby permitting hypothesis testing. Confidence intervals were difficult to estimate because there is some amount of error associated with data collection, but this error is rarely reported with the dataset. Furthermore, the metrics are a manipulated quantity rather than the individual variables. This manipulation has an unknown impact on the error. Additionally, each variable in all metrics will have some unknown variation for each year, especially when we assume that a parameter is constant across years. Using a bootstrap approach to resample the metric would miss this type of uncertainty. Therefore, we were not confident that an uncertainty analysis would yield useful results given the project methodology and our estimates could be criticized for lacking a measure of uncertainty.

Although trend analysis is quite common in environmental studies and market studies (e.g., Burn and Elnur 2002, Hirsch et al. 1982, Hirsch et al. 1991), we were only able to find a statistic of trends in one paper examining sustainability metrics (Sato and Samreth 2008), but it lacked references to address its legitimacy. Initially we considered using Mann-Kendall to test for trends. Mann-Kendall test is a non-parametric test that concentrates on the relative value (i.e., positive or negative) of the observations rather than the magnitude of the observations and is frequently used for trend detection (Burn and Elnur 2002, Hirsch et al. 1982). Although Mann-Kendall is non-parametric and, therefore, free of assumptions about the distribution of the data, it does assume data are not serially correlated. To calculate each metric on a yearly basis, we did a linear interpolation to fill variables for missing years. This interpolation resulted in a strong autocorrelation between points. Thus, we were not confident in the resulting p-value from the test (i.e., p-value overestimated the significance). The majority of published studies on sustainability metrics appear to examine trends visually through graphs of the metric calculation over time (e.g., Chen and Chen 2007, Haberl et al. 2001, Hanley et al. 1999, Lammers et al. 2008, Pezzey et al. 2006, Wackernagel et al. 2004b) which was the approach we ultimately used for this project. Nonetheless, we recognize the methodological improvement that would result if a measure of uncertainty could be included and the benefit of testing for statistical significance in apparent trends.

Multiple metrics were estimated to cover all aspects of sustainability. However, in some instances, different metrics used several of the same variables, suggesting a potential correspondence. For example, wind erosion is used in GNRP, EmA, and FI (e.g., see Table 2.1). A relationship between metrics may not be a weakness *per se*, but it limits any correlation calculations. Rather than being independent metrics, we have estimated metrics that were already linked and duplicated certain aspects of the system, but we do not think this is a problem. For example, although population drives the EFA calculation, it plays a minor role in GNRP.

The methodology presented in this report was general in structure and was useful in evaluating the sustainability of the SLB. However, certain approaches, variables, data, and calculations can only represent the SLB specifically. Accordingly, other regions will require in depth study prior to estimating the metrics. Because different regions have different issues in regards to their sustainability, the specific methodology presented here is not simply a generic recipe for sustainability metric calculations. However, it is useful in a general sense. For example, GNRP used soil erosion, groundwater level, and CO_2 emissions to document the depreciation of natural capital. A new region may have concerns related to mining, forestry, and surface water quality, requiring different data and calculations. A different region might not be able to adopt the approach used to estimate soil erosion, but it could examine how it was calculated and apply that to its own issues. The approach will have to be adapted to capture the new depreciation of natural capital and the literature and methodology presented here will provide a certain amount of direction. On the other hand, there is complete transportability in the ability to assess the dynamic order of other regional systems as FI may be computed for any system given the availability of pertinent data characterizing the state of the system.

Stakeholders expressed an interest in examining how the metrics change using different scenarios. They saw a need for scenario or futures analysis in part because of a delay between the time that an event occurs and the time when data on the event are released to the public. For example, CO_2 emissions data only become available three years after the year when the emissions occurred. In other words, the calculations are always three years behind the present year making the metric calculations somewhat limited in their ability to provide decision support for the present. Some stakeholders suggested that the lag could be managed with an alternative futures component to the methodology. However, an objective of this report was to describe an approach to examine sustainability over time, and not an approach to look into alternative futures. Kok (2009) presents a framework for considering the interrelationships between the types of variables considered in our metrics. An alternative futures approach would require significant modeling efforts that were not part of the project's objectives. The information that would be created through this modeling would be very useful for the SLB or any regional system. Regional plans could be evaluated on the basis of their sustainability. Development scenarios could be created and then modeled using the metric calculations and used to see how the metric changes under different scenarios. The results could provide local decision makers information that results in a movement toward sustainability. Our results provide a different decision support tool that requires more of an adaptive management strategy. The metrics reveal a region's existing movement toward or away from sustainability and identify components of the system that require attention. Continued monitoring of the system and quantifying the resulting trend can influence additional management decisions.

Our final concern relates to our goal of producing a straightforward, relatively inexpensive methodology that is simple to use and interpret. We cannot state with confidence that we met the goal because it would be difficult to test any one of these components. Some anecdotal evidence would suggest that the metrics are not as simple to use or interpret as we initially projected. Calculating FI was automated by developing a graphical user interface and spreadsheets were created for the remaining three metrics. However, understanding each metric and what variables should be included for different regions may prove somewhat intimidating for land managers and decision makers. Although we have scientific criteria for interpreting the metrics, it may not provide enough insight into what the results really mean. The four metrics are based on sound science, but the weakness may occur with the ability to succinctly synthesize what they tell decision makers about a region like the SLB. Therefore, we suggest this as one of the recommendations for future research activities below.

7.6 Recommendations for Future Research on Regional Sustainability Metrics

We offer the following recommendations for future research based on the results of our study:

1) Examine previous management decisions in the SLB to see if and how the metrics changed. For example, the Great Sand Dunes National Park and Preserve was created in 2000 and increased the National Monument land area by almost four times (NPS 2007). This recommendation would help to determine if any of the changes in the metrics could be linked back to the management decision to increase the public land area.
2) Continue calculating the metrics in the SLB for subsequent years to examine how sensitive the metrics are to management decisions.
3) Use stakeholder meetings to determine major sustainability issues in the region and better link the metrics on those issues and concerns. Determine if there are other established metrics that may better assess sustainability of a region by addressing known issues. This relationship with stakeholders will help ensure the metrics are capable of capturing changes pertinent to issues of public concern. The meetings can be used to gauge whether stakeholders and decision makers can understand the results of the metrics. More research can focus on simplifying the interpretation of results for various groups of people: managers, regulators, landowners, educators, policy makers, etc.
4) Develop trend analyses and/or approaches for estimating confidence intervals for individual metrics. Although a trend may appear obvious, recognizing and identifying the variation in the data and resulting metric will better identify significant trends. One example might be using econometric methods (e.g., Greene 1993, Hay et al. 2002) or sensitivity analyses.
5) Develop models of alternative future scenarios and estimate multiple metrics (Baker et al. 2004, Kok and van Delden 2009, Yeh and Chu 2004) that are sensitive to relevant changes in a system or region. For example, how would the installation of solar farms affect the metrics?
6) Test these multiple metrics in other regions and determine if the metrics are indeed capturing the trend in sustainability of regional systems.
7) Examine the correlation among alternative metrics to determine whether certain metrics could be dropped from analysis (i.e., one metric moves in a similar or opposite pattern to another over time) in order to reduce the resources needed (e.g., Bastianoni et al. 2008 used Principal Components Analysis).
8) Consider the use of other scientific approaches, rather than limiting analysis to visual examination of graphs, for deciphering the holistic results of multiple metrics, such as multicriteria methods (e.g., Shmelev and Rodríguez-Labajos 2009); data envelopment analysis (e.g., Despotis 2005, Kortelainen 2008); mathematical programming (e.g., Zhou et al. 2007); or other integrated sustainability metrics (e.g., Mayer 2008).

7.7 Conclusions

Although we met the three objectives of this research project, at this time we cannot definitely state we met the overall goal of the project. Recall from Chapter 1, the goal was to produce a straightforward, relatively inexpensive methodology that was simple to use and interpret. We believe the method is relatively inexpensive because we have identified the majority of data sources for these types of calculations leading to reduced time and resources necessary for others to compute the metrics. How straightforward the methodology is would be based on anecdotal evidence and discussions with stakeholders in the region. We do think we partially achieved the goal for some of the metrics, but are utilizing feedback from end users to fine-tune the descriptions and explanations to enable better understanding by decision makers. We recognize it may require an intermediary to compute some of the metrics, but we want decision makers to understand the methodology sufficiently so they see the benefit and importance of calculating the metrics and they understand what the results mean in order to aid in future decision-making.

We think we made progress in this regard by producing a methodology that successfully characterizes whether a region is moving toward or away from sustainability. However, the next major accomplishment will be translating the information for decision makers. Applying one or more of the eight recommendations will help us do just that.

7.8 References

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Table 7.1 – Summary of four metrics calculated for the San Luis Basin, Colorado.

Metric	**Paradigm**	**Summary**
Ecological Footprint	Strong sustainability	Movement away from sustainability, although gradually during the 26-year period
Green Net Regional Product	Weak sustainability	No definitive evidence to suggest movement away from sustainability
Emergy	Strong sustainability	Movement away from sustainability, although showing improvement recently
Fisher information	Weak sustainability	Relative stability, slight movement away from sustainability at the end of the study period

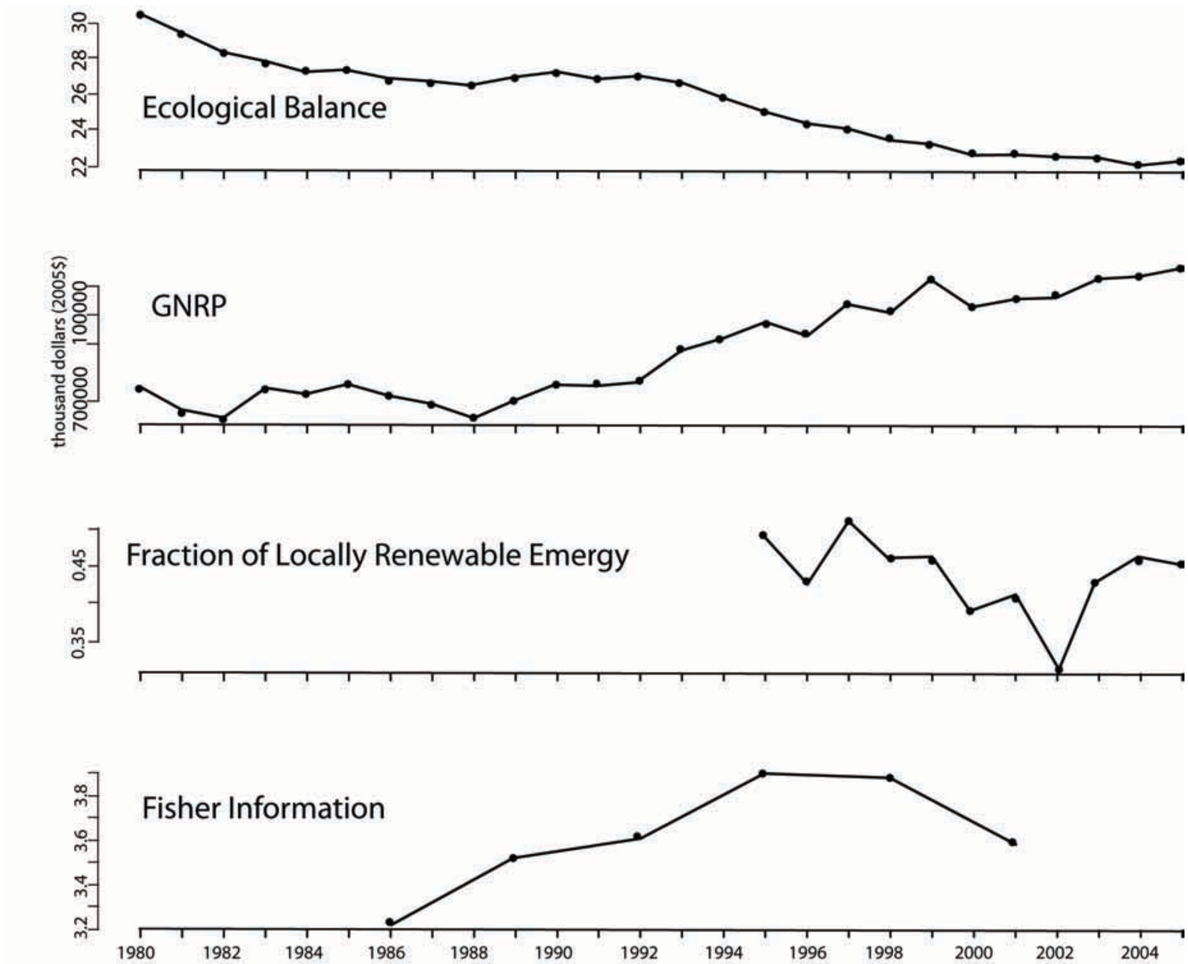

Figure 7.1 – Graphs of Ecological Balance, Green Net Regional Product (GNRP), Fraction of Locally Renewable Emergy, and mean Fisher Information for 1980-2005.

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