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An energy systems view of sustainability: Emergy evaluation of the San Luis Basin, Colorado

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ABSTRACT

Energy Systems Theory (EST) provides a framework for understanding and interpreting sustainability. EST implies that "what is sustainable" for a system at any given level of organization is determined by the cycles of change originating in the next larger system and within the system of concern. The pulsing paradigm explains the ubiquitous cycles of change that apparently govern ecosystems, rather than succession to a steady state that is then sustainable. Therefore, to make robust decisions among environmental policies and alternatives, decision-makers need to know where their system resides in the cycles of change that govern it. This theory was examined by performing an emergy evaluation of the sustainability of a regional system, the San Luis Basin (SLB), CO. By 1980, the SLB contained a climax stage agricultural system with well-developed crop and livestock production along with food and animal waste processing. The SLB is also a hinterland in that it exports raw materials and primary products (exploitation stage) to more developed areas. Emergy indices calculated for the SLB from 1995 to 2005 revealed changes in the relative sustainability of the system over this time. The sustainability of the region as indicated by the renewable emergy used as a percent of total use declined 4%, whereas, the renewable carrying capacity declined 6% over this time. The Emergy Sustainability Index (ESI) showed the largest decline (27%) in the sustainability of the region. The total emergy used by the SLB, a measure of system well-being, was fairly stable ($CV = 0.05$). In 1997, using renewable emergy alone, the SLB could support 50.7% of its population at the current standard of living, while under similar conditions the U.S. could support only 4.8% of its population. In contrast to other indices of sustainability, a new index, the Emergy Sustainable Use Index (ESUI), which considers the benefits gained by the larger system compared to the potential for local environmental damage, increased 34% over the period.

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1. Introduction

Sustainability and the related concept sustainable development are current popular ideas that have captured the attention of governments, industry, the public, and many scientists, including economists, ecologists, and environmental scientists (Adams, 2006; Cabezas et al., 2003; Kay et al., 1999; Parris and Kates, 2003; Pezzy and Toman, 2002). Sustainable development has been promulgated as a goal for environmental systems, i.e., systems composed of economic, social, and environmental components and processes (Adams, 2006; Kates et al., 2005). However, defining the goal itself or the state of the system that is to be sustained is often described in varying ways by different parties (Newton and Freyfogle, 2005; Parris and Kates, 2003). According to Adams (2006), one reason for the broad popularity of these ideas may be their vagueness, which has allowed individuals with different special interests to interpret them in ways that conform to their own particular goals, priorities, and worldviews. In addition, these ideas may be popular because they imply movement toward a solution to the present, pressing, socioeconomic and environmental problems that confront the world, such as the growing environmental impacts of civilization on the biosphere (Vitousek et al., 1997) and the increasing disparity in human-well being between rich and poor countries (Mock and Steele, 2006).

Emergy Analysis is a holistic approach for understanding systems that has been applied broadly to assess the sustainability of nations (Brown, 2003; Lefroy and Rydberg, 2003; Ulgiati et al., 1994; Lan and Odum, 1994), states (Campbell, 1998; Campbell and Ohrt, 2009; Campbell et al., 2005; Tilley, 1999), provinces

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(Tiezzi and Bastianoni, 2008), and counties (Lambert, 1999). The universal accounting quantity, emergy, is derived from the operation of the principles of thermodynamics as they govern far from equilibrium systems and as they are applied in Energy Systems Theory, EST (Odum, 1994, 1996). Determining the value of a product or service by accounting for the solar emergy, i.e., the past use of available energy converted to solar equivalent joules, that was required for its production represents a fundamental change in our understanding of the nature of value and how it can be measured (Odum, 1971a, 2007; Ju and Chen, 2011). EST and emergy accounting are used in this paper, respectively, as a framework and a method for developing a better understanding of the nature of sustainability.

The goals of this research paper are two-fold. The first goal is to develop, explore, and test a framework for understanding and interpreting the concept of sustainability that is grounded in EST (Odum, 1994). This framework for interpreting “what is sustainable” for a given system focuses on understanding the position of the system in the observed cycles of change, which characterize systems on all scales of hierarchical organization, and not on the illusion of a single condition or end state that will continue in perpetuity.

A second goal of this work is related to its position as part of a larger study. This larger study has the overall goal of using readily attainable data to develop general methods to determine if a regional system is moving toward or away from more sustainable states. The first objective under this goal was to find indices that accurately reflect the condition of a regional system and its sustainability over time. A second objective was to explore and test the EST framework (goal 1) for understanding sustainability through carrying out an emergy analysis of a regional system, i.e., the San Luis Basin region in southern Colorado, USA (Fig. 1). This region covers seven counties and contains the watershed of the Upper Rio Grande River.

2. Theory

2.1. An energy systems perspective on sustainability

Humanity and the environment form a single system that can be understood using thermodynamic methods that are applicable to all systems (Odum, 1971a,b, 1994). Before the concept of sustainability became a focus for the scientific community, the same general problem was considered in EST under the topic of carrying capacity (Odum, 1976). In fact, there is a long tradition of considering the well-being of the Earth within the context of EST (e.g., see Chapter 10 in Odum, 1971a; and Chapter 12 in Odum, 2007). In the mid-1990s several papers began to appear in the emergy literature specifically examining aspects of sustainability (Ulgiati et al., 1995; Brown and Ulgiati, 1997; Ulgiati and Brown, 1998; Campbell, 1998). Since this time there have been many studies in the literature examining the concept of sustainability as it relates to various topics, e.g., the sustainability of ecotourism (Brown and Ulgiati, 2001); the sustainability of agricultural systems from modern (Lagerberg and Brown, 1999; Cavalett et al., 2006; Castellini et al., 2006) to primitive production systems (Martin et al., 2006), and the sustainability of material cycles and recycling (Brown and Buranakarn, 2003). Lu et al. (2003) applied the Emergy Exchange Ratio (EER) to modify the Emergy Sustainability Index (ESI) of Brown and Ulgiati (1997) to consider the effects of economic exchange on sustainability defining a new index the Emergy Index of Sustainable Development, EISD. Subsequently, Lu and her colleagues have published several papers using indices to examine sustainability from an emergy and a combined emergy-economic perspective (Lu et al., 2006, 2007, 2009; Lu and Campbell, 2009).

Recent studies in EST have promoted developing appropriate technology by modeling the natural world, e.g., Tilley (2003) proposed a symbiotic collaboration of industrial ecology and ecological engineering to ensure that environmental systems will be sustainable in the future. Furthermore, Odum (1971a, 2007) proposed that the development of working partnerships between humanity and nature was the way to attain more sustainable environmental systems.

Because nothing lasts forever except arguably the universe itself (Odum, 2003), any system state or condition can only be sustained over a finite time interval. The length of this time interval depends on the external and internal available energies that can be used by the system in maintaining its current state. Therefore, in a fundamental manner, what is sustainable for a particular system depends on the relationship of that system to its external inputs of available energies and their rates of change, which in turn depend on the dynamics of the next larger system. In addition, a system’s condition depends on its internal available energy storages and their state of depletion or renewal. Thus, from the perspective of EST, sustainability of any given system state can only be understood within the context of a system’s internal resources and time series of external forcing functions that are generated in the next larger system.

2.2. Emergy measures of sustainability and system well-being

From an Energy Systems perspective, an analysis of “what is sustainable” for a system must consider the spectrum of emergy inflows (Odum, 1996) that are directly related to maintaining the current system state. Dependence on resources that are being used faster than their replacement rates is inherently unsustainable; therefore, the *sine qua non* of sustainability in the end is determined by the degree to which a system depends on renewable resources for its operation. This aspect of sustainability can be estimated by determining the fraction of the total emergy used by the system that is renewable. For purposes of comparison with other studies in the SLB project, this is the primary emergy index used to determine whether the system was moving toward or away from sustainability.

A complete definition of sustainability also requires that we specify what system state (e.g., what standard of living) is to be sustained and over what time period we expect to sustain it (Campbell, 1998). The renewable carrying capacity of a system determines the number of people that can be supported at the current standard of living by the renewable emergy inflows alone. In this study, this measure does not consider the future application of renewable energy technologies that might allow a greater fraction of the available renewable emergy sources to be used directly to support human activities.

In addition, we used the Emergy Sustainability Index (ESI) to assess the sustainability of the region. This index considers the emergy flow through the local system in relation to the potential damage that could be inflicted on the environment by the local intensity of nonrenewable emergy use (Brown and Ulgiati, 1997). It is calculated by determining system EYR, i.e., the total emergy flow (U) in the local system divided by (F) the purchased input from the larger system, and then dividing this ratio by the Environmental Loading Ratio (ELR), which measures the potential environmental damage to the system. This index has been extensively used to assess the sustainability of national systems (Brown and Ulgiati, 1997; Brown, 2003), as well as, to determine the sustainability of processes where the Emergy Yield Ratio (EYR) of the process is compared to the environmental damage caused by that process (Brown and Ulgiati, 2002). This index has also received some criticism (Raugi et al., 2005) when it has been applied to estimate the sustainability of nations, because of a logical and practical inconsistency in defining the total emergy flow in a state, national, or regional system as equivalent to the yield of that system, i.e., the ESI is defined as the ratio, (system EYR)/ELR.

In this study we searched for different ways to characterize various aspects of the sustainability of a regional system. The use of EST requires that the available energy flowing in a system be taken as the starting point for understanding its behavior. The emergy flowing through a system network is then an integrative measure of system well-being. This definition of well-being is derived from the maximum empower principle (Lotka, 1922a,b; Odum, 1996), which provides a unified criterion (i.e., maximum emergy flow in the system network) to identify system designs that are expected to prevail in competition with others for available resources. Thus, for a given set of emergy inflows movement toward higher states of empower in the system's network indicates movement toward a more sustainable state, in the sense that the system can better maintain its organizational state against competition. A complication arises because systems are hierarchically organized and all the various levels of organization that constantly interact with one another are operating under the same constraint, i.e., to maximize empower in their networks. These actions may not be synchronized, so that maximum emergy flow must be considered on different levels of organization simultaneously (Odum and Arding, 1991; Odum, 1996).

2.3. Energy Systems Theory as a theoretical context for understanding sustainability

One problem in practically defining viable methods to achieve sustainability is that often the question, "What is sustainable for this system?" is not viewed realistically within the context of the system's position in the ubiquitous cycles of change (Holling, 1986; Odum, 1994, 1999) that govern all systems (Fig. 2a). EST (Odum, 1971a,b, 1994) provides a theoretical basis for the cycles of change and a framework for understanding "what is sustainable" for a given system at a given time. Using this theoretical approach, Odum et al. (1995) promulgated the pulsing paradigm as a system design that maximizes emergy flow through a network (Odum, 1996; Campbell, 2001). The pulsing paradigm provides the causal context for understanding trajectories of ecosystem change. Odum et al. (1995) saw this idea as replacing the old concept of growth and development followed by a steady state or climax, which was first proposed by Clements (1916). The pulsing paradigm does not say the concept of growth and succession to a climax state is incorrect, it simply points out that there is a larger context for all processes and that this larger context is the pulsing (Odum, 1982) cycle of change (Holling, 1986).

This paradigm derives from the observation that pulsing patterns are ubiquitous in the universe, occurring on all scales of organization from fast biochemical reactions to the largest galaxies (Odum et al., 1995). The general mechanism of pulsing can be described by a system with coupled pairs of components (e.g., resources and consumers in Fig. 2b), which allows them to oscillate (Odum, 1994; Campbell, 2000a). Such pairs of components are found on all levels of hierarchical organization. According to Odum (1999), they consist of one component, the accumulator, that slowly builds up resources (e.g., the excess primary production of ecosystems transformed by heat and pressure within the Earth and accumulated as fossil fuel) and a second component, the frenzor, (e.g., industrial civilization) that rapidly consumes the accumulated resources once a threshold is exceeded. Such a threshold may be illustrated by James Watt's improvement of the steam engine, which was the technological breakthrough that facilitated the widespread use of fossil energy to support human activities (Campbell et al., 2009).

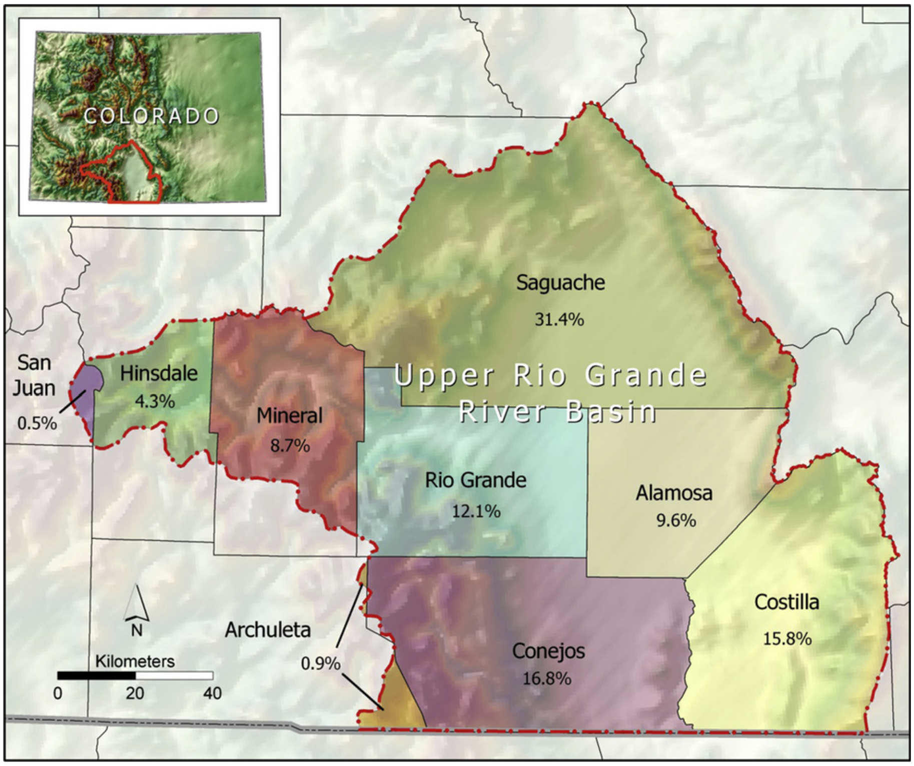

Fig. 1. A map of the San Luis Basin region showing the overlap between the boundaries of the seven counties used to define the economic region and the Upper Rio Grande watershed. The percent of the watershed area lying in each county is shown.

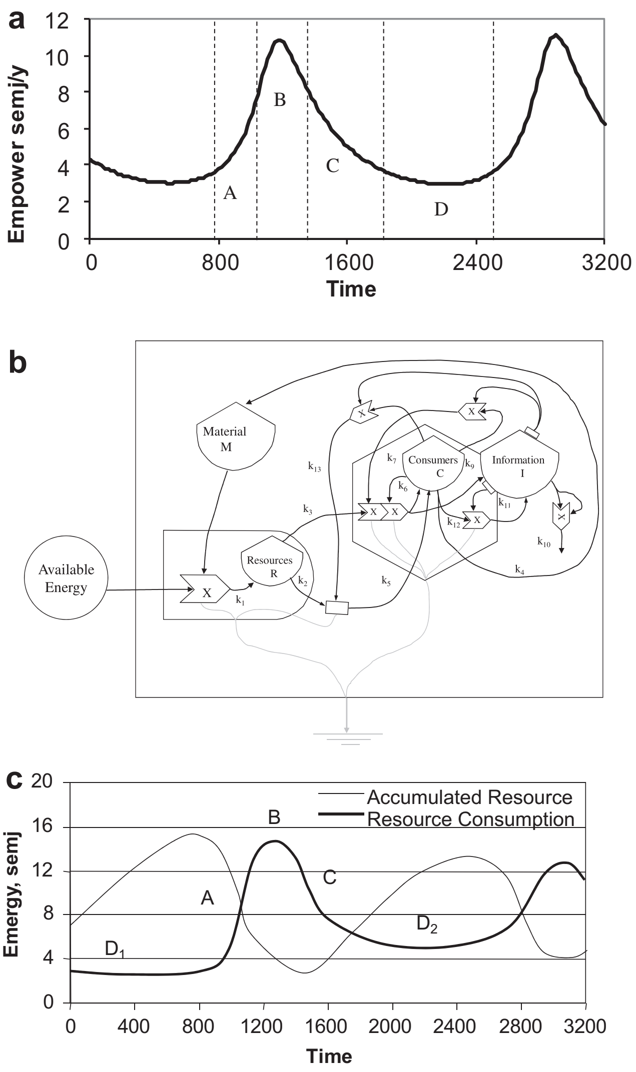

Fig. 2. a. The cycle of change showing Holling's "Fig. 8" diagram opened to illustrate the repeating cycle. The stages in the cycle are labeled as (A) exploitation, (B) climax, (C) creative destruction, and (D) renewal. References to Stages A, B, C, and D throughout the paper refer to this figure. b. An Energy Systems Model of a pulsing system showing the way that information (I) accumulated during the exploitation and climax phases of the cycle can be used to improve (k_{13}) the level of use of renewable resources (k_2) to support human activities (k_5) in the next low energy steady state. Total material, M, is a constant in this model. c. Hypothetical time series of outputs from the pulsing model, illustrating the operation of the proposed mechanism for improving system design in subsequent low energy steady states (D_2).

Pulsing results in a cycle of change in ecosystems that was described as an adaptive cycle by Holling (1986). This cycle moves through phases of (A) growth or exploitation, (B) climax or conservation, (C) decline or creative destruction, and (D) renewal (Fig. 2a), which can be explained by the time series of energy and material flows through a production–consumption–recycle model as shown by Odum (1999). Over time, any given cycle of change repeats driven by the dynamics of the system of energy accumulation, consumption and recycle. Also, any given system state, even the climax state, is controlled by the cycles of change that arise from the dynamics of its adjacent and larger systems (Garmestani et al., 2009). From this perspective, the only aspect of a dynamic system that may be sustainable is a pulsing cycle of change (Odum et al., 1995; Gunderson and Holling, 2002).

For decision-makers to understand what is sustainable in the present and to plan for what will be sustainable in the future, they need to know the position of their system within the cycles of change that govern its behavior. However, recognizing the position of a system within the cycles of change may not be straightforward, because many internal cycles and dynamic larger systems can affect the condition of the system of interest and the processes governing each pattern of change may be different. Thus, a given system may be in different phases of various cycles at the same time. Energy Systems models (Odum and Odum, 2000) constructed, analyzed, and simulated on at least three scales (the system of interest, its subsystems, and the next larger system) can be used as tools to sort out the dominant periodicities related to the various processes operating within and upon the system, and thereby determine the position of a particular system within the various cycles that are affecting it.

Once the important relationships of a system to its next larger systems are identified and considered in the analysis, ideas like "sustainable development" and "sustainability" can be more accurately interpreted and understood. For example, if the internal resources of a system along with the cycle of change from the larger system are seen as the controlling factors in determining what is sustainable for a system at a given time, methods like Fisher information can be used to examine time series data on all aspects of a system to predict when a change in the current envelope of structural and functional stability is more probable (Mayer et al., 2006).

If one views the condition of the world within the context of the cycles of change, alternative models and visions of the future arise. For example, Odum and Odum (2001) in their book "A Prosperous Way Down" present a view of the future that is based on the cycles of change in resource supply that have become apparent in the larger global system today (Campbell, 1997). The Odums go beyond the current focus on sustainability by defining prosperity in a world where there will be less petroleum resources, rather than more, available for human consumption in each succeeding year.

From the perspective of non-equilibrium thermodynamics, nature has no preferred states, it only has a preferred direction of change in evolutionary state-space, i.e., toward greater network empower (Campbell, 2000a). While people most often focus on the structural aspects of a system they want to preserve or sustain, nature cares little for structure, but will sacrifice structure to preserve functional processes (i.e., emergy flow) as evidenced by the studies of Schindler (1990), who showed that in a Canadian lake under stress from nutrient loading, primary production remained high while species diversity decreased. If the long-term success of our species is not guaranteed, it is even more important that we learn to recognize the cycles of change and prepare for these inevitable vicissitudes. This is the first step toward more robust, effective management of environmental systems.

Decision-makers also need reliable criteria to judge the relative efficacy of one system design compared to another. The maximum empower principle (Odum, 1996) implies that the success of a system or design in the long run can be predicted through quantifying the empower (solar emjoules per unit time, e.g., semj/y) passing through the system network. Predictions are based on the assumption that greater empower through a system network allows that system to be successful in the competition with other systems for available energy (Lotka, 1922a,b; Odum, 1996). If maximizing empower is the decision criterion for success in evolution as proposed by Odum (1996), development toward network designs with higher empower will be the overriding process governing the health and integrity (Campbell, 2000a) of a system and the duration of any particular system state, i.e., its sustainability.

Human beings have the capacity to make decisions that move a system toward higher states of empower in the future by focusing their knowledge and information processing abilities on modifying system design. An energy systems model with numbered pathways (Fig. 2b) illustrates the dynamics of a pulsing system, as it could be changed in the future by the use of stored information in the present to increase the system's use of renewable energy in the next steady state. This model system is similar to industrial civilization today, which is operating primarily on fossil energy. We assume that the accumulation of information (i.e., knowledge and understanding) as a component of the system makes it possible to develop directed feedback during the times of high available energy (B and C in Fig. 2a) and that the available energy in this feedback (pathway k_{13}) can be used to modify the mechanisms of energy utilization (pathways k_2 and k_5) operating in the next low energy steady state, i.e., (D_2 in Fig. 2c). Because the nonrenewable energy resources of the Earth are finite, the present goal for decision-makers, who value the well-being of future generations, should be to ensure that the highest possible state of social, economic, and environmental well-being is attained in the next low energy steady-state, primarily by more effectively using the renewable emergy available to the system (compare D_2 in Fig. 2c to D_1).

Another example of how this process of changing system design might come about was simulated by Bastianoni et al. (2009), who tested the premise that nonrenewable energy should be used to increase the utilization of renewable energy to produce greater empower supporting society in the future. We conclude that higher states of social and economic well-being in the future will be based on the application of resources today to improve system design and increase our ability to capture and use renewable emergy now and in the next renewal phase of the cycle.

3. Methods

3.1. Basis for the method

Emergy evaluation is a noneconomic method for determining relative value (Odum, 1996; Campbell, 2001; Brown, 2003) based on the quality-normalized available energy of all kinds required for the production of a product or service within any system. This method of analysis (Odum, 1996) is carried out by tracing the available energy[1] flows used in the past, both directly and indirectly, in the creation of each storage or flow in a system and then converting the available energy used in the production process into energy of one kind, e.g., solar joules. In this manner, the value of any storage or flow can be determined objectively (Odum, 1996; Campbell, 2001) in terms of its solar emergy, i.e., the available solar energy used up directly and indirectly in the production of a product or service. The unit of emergy is the solar emjoule (semj), where the prefix "em" denotes available energy used in the past (Scienceman, 1987) as contrasted with the available energy in a product or service in the present, which has units of joules. All flows and storages of energy, materials, and information are converted to the common unit (semj) by multiplying the raw units (J, g, bits) by the appropriate emergy per unit factor, e.g., the transformity (semj/J) for energy, the specific emergy (semj/g) for mass, or the emergy per bit (semj/bit) for information. Transforming all products and services in a system to emergy units provides a holistic measure of the relative advantages and disadvantages of any changes in the system by making disparate environmental, economic, and social products and services directly comparable.

The emergy evaluation of a system is predicated on quantifying the internal and external renewable and nonrenewable energy sources supporting the system, as well as, the import and export of energy, materials, and information to and from the system. Nonrenewable resources are those being used much faster than their natural replacement rates (e.g., oil, coal, etc). Potentially renewable resources like soils, groundwater, and timber, are counted as nonrenewable contributions to system operation when they are used faster than their replacement rates (e.g., the rate of erosion must exceed the rate of soil formation in a system for soil loss to be counted as an emergy input to annual system operation).

3.2. Boundaries

Unlike the analysis of a state or a nation, which have politically agreed upon boundaries; determining the boundaries for the SLB was not a straightforward problem, because two sets of boundary conditions were relevant to defining the system. The valley floor is contained within the upper drainage basin of the Rio Grande River, and thus, the topographic dividing lines between watersheds comprised one set of possible boundary conditions. This watershed includes all or part of nine Colorado counties (Fig. 1). While water is the dominant natural resource organizing the landscape in the region, the activities of people control most other activities. Since the boundaries of this system could be based with strong justification on either of two different sets of criteria, i.e., watershed boundaries or the political boundaries of seven counties, the investigation of system sustainability, which includes both environmental and socioeconomic aspects, presented us with unique challenges. In the emergy analysis, we solved this problem by using both sets of boundaries, applying each to define the region when appropriate for the process being analyzed.

Political boundaries were used to quantify all human activities, e.g., energy use, economic activity, etc. The small, sparsely populated areas of Archuleta and San Juan counties within the Upper Rio Grande watershed (Fig. 1) were assumed to constitute a negligible fraction of the total human activities carried out within the SLB. The hydrologic boundaries of the Upper Rio Grande watershed were used to determine the water flows that supported human activities in the system. All other natural inputs and storages (e.g., solar radiation and forest biomass) were determined using the area enclosed by the administrative boundaries of the seven counties.

The main source of error introduced because of the boundaries chosen is that water contributing to forest growth in the area of the seven counties to the west of the continental divide supported some of the timber harvested from the seven counties, but was not counted in the emergy base for this timber. Similarly, some economic activity of the seven counties occurred west of the continental divide, but it was counted in the economic flows within the Upper Rio Grande watershed. In both cases the emergy flows west of the divide that were counted or not counted in the analysis were small compared to similar activities in the SLB region. Therefore, we believe that the discrepancy in the spatial boundaries used for the economic and hydrologic systems introduced a relatively small error into the analysis.

Temporal boundaries for the emergy evaluation were defined based on our goal of assessing the sustainability of the SLB system from 1980 to 2005. The temporal resolution used for the evaluation was one year and the length of the study was 26 years. However, due to the lack of data on imports and exports for the years prior to 1995, the temporal boundary of the complete emergy evaluation was limited to the eleven-year period from 1995 to 2005.

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[1] Available energy is energy with the potential to do work, i.e., there is a potential difference between the available state and a ground of reference state against which useful work can be done, i.e., when the potential is dissipated. Useful work contributes to the system in which it is performed by facilitating the capture and use of external available energy by the system network.

3.3. Energy systems models

Information about the system was gathered and this knowledge was used to construct a detailed energy systems diagram of the SLB (Fig. 3) using the Energy Systems Language, ESL, (Odum, 1971b, 1994). This model captures the relevant details about the system and its configuration and it serves as a context for performing and interpreting analyses. This detailed model was simplified through aggregating components of similar function to address the research questions that we developed for this research, e.g., to evaluate emergy indices of sustainability and to assess the system's movement toward or away from more sustainable states. An aggregate model (Fig. 4) was constructed by reducing the complexity of internal components and flows of the detailed model to basic measures of economic activity, resource supply, and total emergy flow. Then, we performed a detailed evaluation of the environmental and economic inputs to and outputs from the system using the aggregate model as a guide. Finally we compiled the information on inputs and outputs into categories that matched the structure of the aggregate model (Odum, 1996; Campbell et al., 2005). The aggregate model is the basis for defining indicators and indices of system operation related to sustainability, self-sufficiency, and other system properties examined in this study (Fig. 4 and Table 1).

3.4. Emergy income statement

Because the primary purpose of the evaluation of the SLB was to assess temporal changes in system condition, we focused on evaluating the emergy income statement for the region. Emergy accounts were created for renewable local inflows, renewable production, nonrenewable local inflows, imports, and exports of the seven counties comprising the SLB. In this study, imports were not classified into renewable and nonrenewable fractions before the calculation of indices.

Emergy analysis tables provide a template for the creation of the accounts needed to construct an emergy income statement. The tables provide a simple way to demonstrate and record the calculation of the emergy values for annual flows of mass, energy, information and money. A description of the common format used to set up the emergy tables given in the Appendix can be found in Odum (1996) and Campbell et al. (2005). The data needed to fill in the emergy income statement were reported in convenient units by

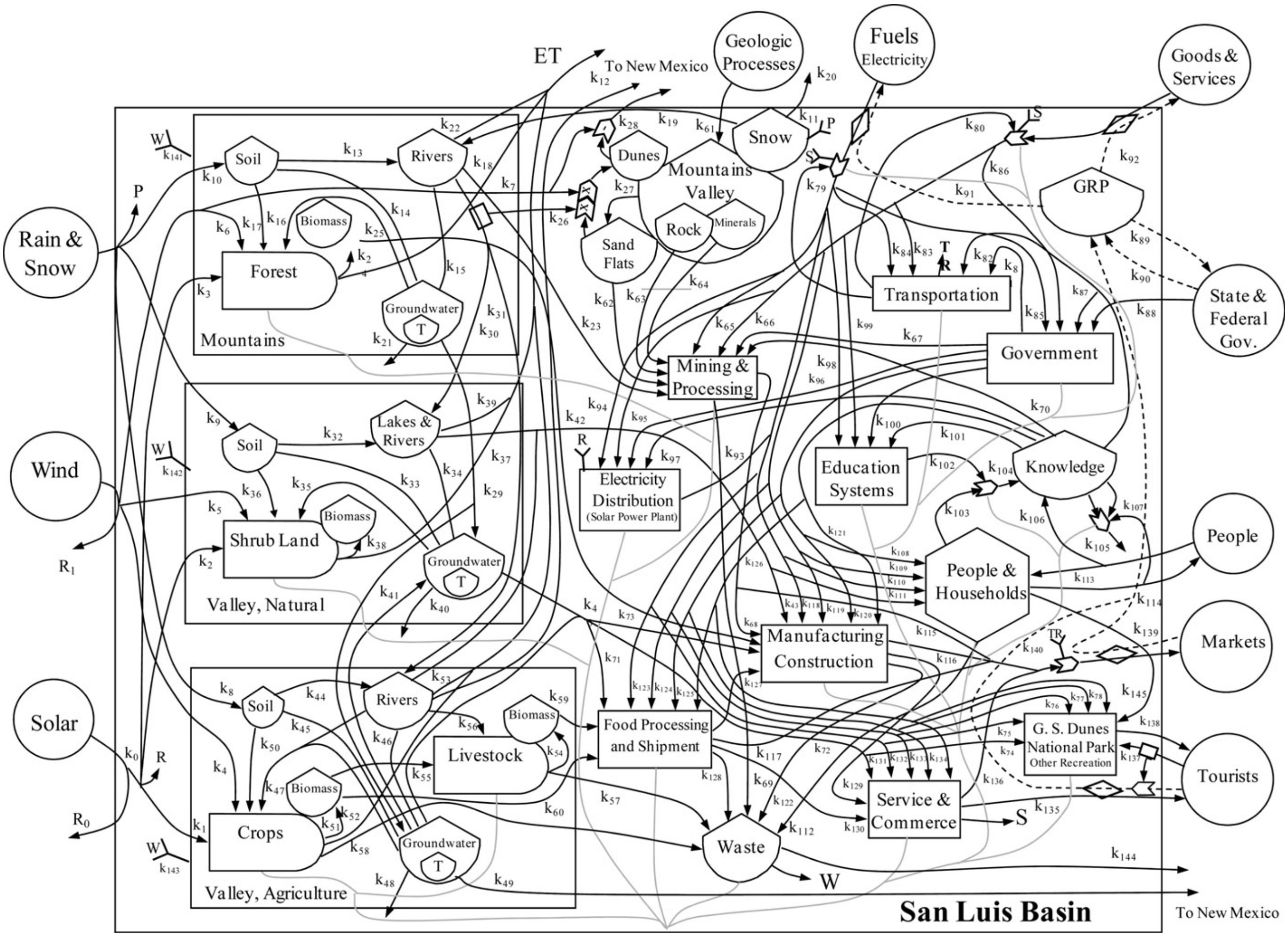

Fig. 3. An Energy Systems Language diagram of the San Luis Basin showing the major features of the regional system. External forcing functions (circles) supply energy, materials and information (*E*, *M* & *I*) to the system to support producers (bullet-shaped symbols) and consumers (hexagons). Storages of (*E*, *M* & *I*) are shown with the tank symbols. Economic and social subsystems occur within boxes and exchanges of money pass through the diamond symbols with the money flow shown as a dashed line. Energy, materials, and information flow along the solid lines and used energy (i.e., energy that no longer has the potential to do work in the system) flows on the gray lines and leaves the system through the heat sink symbol on the lower boundary. Each pathway flow is identified with a numbered "*k*" and these flows are defined in Table 2.

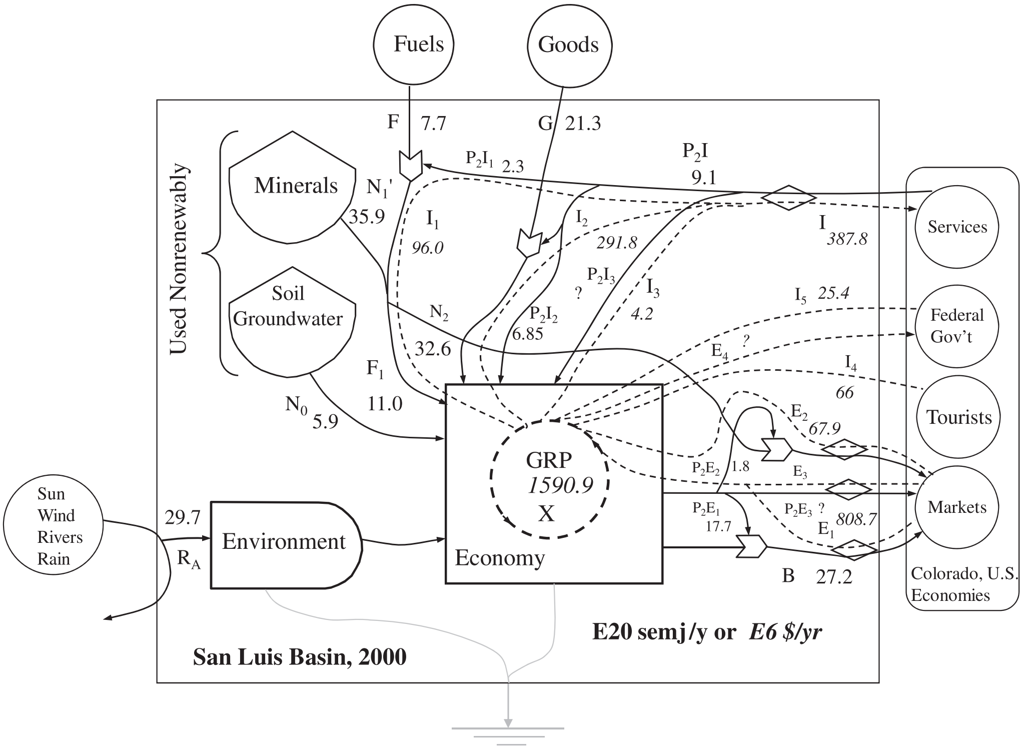

Fig. 4. An aggregated model of the San Luis Basin used to calculate summary variables and indices for the system. The aggregated diagram shows the emergy from local renewable (R_A) and nonrenewable resources (N_1) including renewable resources that are being used in a nonrenewable manner (N_0) interacting with imported fuels (F) goods (G) and services (P_2I) to support regional economic activity (X) and exports (B, N_2, and P_2E). Values on the diagram are for the year 2000.

the collection agency. These data were first converted to annual flows of energy or mass. Data on mass flows can be converted to emergy (g × semj/g) or if necessary to energy (g × J/g) and then to emergy (J × semj/J) and finally to emdollars (semj ÷ (semj/$)). In most cases, mass can be converted to energy easily, because the energy content of many items has been widely tabulated (e.g., see the USDA nutrient laboratory database http://www.nal.usda.gov/fnic/foodcomp/search/, accessed March 17, 2011). Many transformities and other emergy per unit values are available in the literature (e.g., Odum, 1996; Campbell et al., 2005; Campbell and Ohrt, 2009); however, some were specific to this study and the calculations for these new values are listed in the online supplement, (http://www.epa.gov/aed/research/desupp5.html). The online supplement also contains the data sources, the data and calculations used in this study. All emergy per unit factors are expressed relative to the 9.26 E24 semj/y planetary baseline (Campbell, 2000b).

The conversion to emdollars is performed to aid in comparisons with economic data used in public policy decision-making. Emdollars (Em$) are obtained by dividing the annual emergy flow by the emergy/dollar ratio for the larger system in the year of the analysis. Emdollars redistribute the measure of economic activity (e.g., Gross Domestic Product, GDP, Gross Regional Product, GRP, etc.) in proportion to the emergy flows of the system, so that the monetary measure better reflects the underlying sources of purchasing power, i.e., real wealth or emergy, flowing in the

Table 1
The definitions of emergy indicators and indices used to analyze the condition of the SLB regional system. Symbols and expressions in the formulae refer to Fig. 4, Table 3 and Table A-6.

Name of Index or Indicator	Symbol or expression	Definition
Total emergy used[a]	$U = (R_A + N_0 + F_1 + G + P_2I)$	Empower (emergy/time) of the regional network.
Renewable emergy absorbed	R_A	Renewable emergy inputs absorbed without double counting.
Percent renewable emergy[a]	R_A/U	The ratio of renewable to the total emergy used expressed as a percent.
Feedback or investment from the larger system often called *F*	$\text{EmImp} = (F + G + P_2I)$	Feedback is the sum of the emergy in fuels (*F*), materials (*G*) and service feedbacks (P_2I), i.e., the emergy of imports).
Local effect of investment (LEI)	U/EmImp	The effect of purchased emergy on system empower.
Renewable carrying capacity	$(R_A/U) \times$ Population	A rough measure of sustainable development.
Regional system yield (*Y*)	$\text{Exp} = (B + P_2E + N_2)$	For a regional system exports are equivalent to the yield to larger system.
Regional emergy yield ratio (REYR)	EmExp/EmImp	Emergy return to the larger system on its investments.
Nonrenewable emergy inflows	N, N_0, N_2	*N*, nonrenewables; N_0, renewable sources being used in a nonrenewable manner; N_2 minerals and fuels exported without use.
Environmental loading ratio (ELR)	$(F_1 + G + P_2I + N_0)/R$	Potential effect of nonrenewable use on the environment
Emergy sustainability index[a] (ESI)	LEI/ELR	A measure of the sustainability of the regional system formerly EYR/ELR
Emergy index of sustainable use (EISU)	REYR/ELR	A measure of the sustainability of the relationship between the regional system and its next larger system.

[a] Indices used for assessing system condition and long-term sustainability for comparison with other methods.

system. Items are given an emdollar value regardless of whether or not they had a monetary value to begin with, e.g., GRP dollars could be reassigned to give the rain an emdollar value based on its proportionate share of the total emergy flow in the region, whereas, in the economy no one pays for the rain.

3.5. Data and sources

The data needed to construct an emergy income statement for a region can be categorized as follows: (1) data on the renewable energy inputs to the system (e.g., rain, wind, sunlight) and information on renewable production carried out in the system (e.g., forest, crop and livestock production); (2) data on nonrenewable energy inputs (e.g., oil, gas, minerals, etc.), production and consumption, including any renewable energy sources used in a nonrenewable manner (e.g., soils, timber, groundwater); (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.

Data acquisition for the evaluation of the SLB regional system was impeded by several factors. First, in general, data on human systems are collected using political boundaries, whereas, hydrologic data are collected using watershed boundaries. We were fortunate with respect to the water resource data needed for this study, because the boundaries of the watershed approximately conformed to the political boundaries of the seven counties (Fig. 1). A further difficulty arose because usually data are not aggregated and reported for regional systems. For example, data on economic and social activities are collected by county and then assembled for the state. Sometimes, only the state data are published making it difficult to extract the original county estimates from the totals. We used local data collected by the county or regional authorities when it was available, and if necessary, we used data on the counties provided by the State of Colorado. Our next choice was to use average data aggregated at the state level to estimate variables for the seven counties. We followed the general guidelines for data quality given in Campbell and Ohrt (2009), where a consideration of the uncertainty in emergy analyses of this kind is given. Recently, methods for calculating uncertainty in emergy analyses have been put forward by Ingwersen (2010) and Li et al. (2011).

Information on the San Luis Basin was gathered via literature surveys and meetings with people knowledgeable about the region. Data collection was not duplicated among the four analyses that were part of the larger study. For example, the estimates of energy use for the region were made by the Ecological Footprint Analysis (EFA) study (Hopton and White, 2011) and the estimates of soil erosion and groundwater used were made by Heberling et al., 2011. When direct measurements of flows were not available, they were estimated from available data. For example, agricultural exports were not measured directly, but data on agricultural production of crops and livestock were available from 1980 to 2005. To estimate agricultural exports, we assumed that almost all the local agricultural production was exported. This assumption is not unreasonable, since the quantity of food produced in the region far exceeds the food requirements of the small population residing there. Data on emigration and immigration were available from 1985 to 2005, allowing us to estimate the net effect of the movements of people on the knowledge base of the region, assuming the average education levels of immigrants and emigrants were the same as that for Colorado as a whole.

Most plots in this paper are of annual estimates and thus only one data point exists for each year. However, to make the complex data plots easier to visually trace and to facilitate identifying patterns, we chose to use the plotting tools provided in Microsoft Excel, which produces smoothed curves by nonlinear interpolation between data points. The actual path between the annual point estimates is not known.

In addition, adjustments were made to the data to reflect the actual quantities of materials used in the SLB and to deal with missing data. For example, processed non-metallic minerals were removed from the import–export balance of the SLB to avoid falsely attributing the emergy of these materials to the emergy used in the SLB system. Also, the amount of some local nonrenewable resources (i.e., crushed stone, sand and gravel) used in the SLB was not known. The data showed that export vastly exceeded import for these materials, so we assumed that the difference was apparent production and that 10% of apparent production was used in the system.

The need for complete and accurate data on regional imports and exports was the limiting factor for determining the time series of emergy flows required to construct an income statement and calculate emergy indices. The Commodity Flow surveys performed by the U.S. Census Bureau every 5 years (1997, 2002, and 2007) provide these data, but methodologically consistent survey data were not available annually or as early as 1980, the starting point of our study. We found that a private company, Global Insight, Inc. (GI), compiles freight movements by U.S. County and we purchased these data for the seven counties for the years 1995–2005. We used the GI data in several ways, making plausible assumptions when necessary to accomplish a calculation. For example, data on nonrenewable production in the SLB (crude oil, metallic ores, broken stone or riprap, sand and gravel, and non-metallic minerals) were inferred from the GI dataset. To accomplish this we assumed the difference between imports and exports was apparent local production or consumption. Additional information on the analysis and a discussion of the uncertainty in the GI data can be found in the online supplement.

3.6. Summary tables and indices

Once the calculations and the emergy accounting tables were complete, a summary table (Odum, 1996) of the variables with their definitions and values was created. The summary variables were then combined to define emergy indices (Fig. 4 and Table 1), which were used to characterize various aspects of the regional system related to its operation, e.g., its sustainability, self-sufficiency, the balance of imports and exports, etc. Indices in Table 1 that were compared with other indices calculated in the larger study are the total emergy used (U), the percent of the emergy used that was from renewable sources (R_A/U), where R_A[2] is the renewable emergy absorbed by the system, and the Emergy Sustainability Index (ESI). The values of emergy indices calculated for the system under study were then compared to similar indices from other studies to gain an understanding of the position of the SLB system within the broader realm of environmental systems.

3.7. Emergy indices of sustainable systems

One objective of this study was to develop a robust and comprehensive set of indicators to characterize sustainable regional systems. This objective led us to reexamine the Emergy Sustainability Index (ESI) introduced above. In particular, we reconsidered the meaning of the Emergy Yield Ratio (EYR) as it

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[2] R_A, the renewable emergy absorbed as distinguished from the renewable emergy received (Campbell et al., 2005). In emergy analyses it is the renewable emergy absorbed that determines the amount of order and organization that can be created in a system. For example, incident solar radiation is received by the Earth, but the albedo must be subtracted to determine the amount absorbed.

applies to a regional system. From this reexamination, we concluded that the ratio defined by the total emergy use of a local system, *U*, divided by *F*, the emergy inputs purchased from the larger system actually represents the effect on local empower of the emergy invested from the next larger system. This index, might logically be called the Local Effect of Investment, LEI, because it shows the change in local empower that results from a system opening its borders to trade with the larger system rather than the yield of the local system to the next larger system as implied by designating this ratio as system EYR. This clarified understanding of the nature of the expression (U/F) in no way changes the mathematical expression used in calculating ESI or EISD. However, it improves the correspondence of the verbal definition of the ratio with the meaning of the mathematical expression (U/F).

This clarification led us to ask the following question, "If U/F is not the EYR of a regional system, what mathematical expression can be considered the whole system equivalent to the EYR of a process as defined by Odum (1996)?" Using an input–output model similar to that used by Odum (1996) to define the EYR of a process, we might consider the yield from a regional system to be the emergy of its exports (EmExp), which are the products delivered to the next larger system in response to the emergy invested (Campbell, 2009). Thus, the commonly used ratio of the emergy of exports to the emergy of imports (EmImp), in this case *F* is equal to the emergy of the imports, might be considered the EYR of a regional system and from this perspective we refer to it as the Regional Emergy Yield Ratio (REYR) to distinguish it from other definitions of EYR, e.g., EYR as it relates to processes. Defining the EYR of a region in this way led us to formulate a new index that captures the sustainability of the relationship between a region and its next larger system. The Emergy Index of Sustainable Use (EISU) is then the ratio of (EmExp/EmImp)/ELR and it quantifies the emergy yield gained from a regional system in comparison to the potential damage done to that regional system's environment by its relationship with the larger system. The greater the value of the REYR the more the larger system benefits from the relationship and the lower the value of the ELR the less damage is done to the region in obtaining the yield. Thus higher values of the EISU should correlate with greater empower flow through the system that includes a region and its trading partners. In this study, the ESI is used as an indicator of sustainability of the local region and the EISU is used to show the sustainability of the relationship between the local region and its next larger system.

4. Results

4.1. Detailed energy systems model of the San Luis Basin

A detailed model of the environmental system in the SLB (Fig. 3) was drawn using the ESL symbols (Odum, 1994). The definitions of the model pathways (k_is) are given in Table 2. The large rectangular box (Fig. 3) represents the boundaries of the seven counties. External forcing functions or energy sources are shown as circles that enter the system through pathway lines crossing the boundaries. They are arranged approximately in order of increasing transformity from left to right around the system boundary. Flows of energy and matter leaving the system are shown by arrows crossing the boundary. For example, both surface and groundwater flow out of the valley into New Mexico and unused solar energy (R_0 or albedo) is reflected into space. Used energy flows (gray lines) are the only flows that exit through the lower boundary of the system.

The major environmental systems within the SLB are aggregated into three classes shown on the left hand side of the diagram. These three subsystems are the mountains, which are to a large extent

Table 2
Definition of pathway flows for the Energy Systems Language model of the San Luis Basin, Colorado shown in Fig. 3.

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 region
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 valley 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
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

Table 2 (*continued*)

Pathway	Definition of flow
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 Valley joins the regional grid
k_{94}	Fuels and electricity input to the power distribution system
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

forested, and the valley floor, which is divided into an area covered by the natural shrub vegetation including phreatophytes (e.g., cottonwood) and xerophytes (e.g., sagebrush), and agricultural land, which is typically irrigated with surface and/or groundwater. Each vegetation subsystem includes surface water and groundwater with flows that are appropriate for the location and drainage. Groundwater storages have a temperature (T) specified, because hot water can be close to the surface in the region. Much of the valley floor is occupied by agriculture, growing hay, livestock, grains and potatoes. Specialized agricultural crops that require high altitude (e.g., quinoa) can be grown in the San Luis Valley, which has an average elevation of approximately 2300 m.

The valley is surrounded by still higher mountains with peaks that rise 1800 m above the valley floor. The geological complex, shown in the upper middle of the diagram, captures the main features of the mountain system. The work of geological processes deep in the earth has resulted in many of the present prominent features of the system. For example, the San Luis Basin first took form as a rift valley (Chapin and Cather, 1994). In the past, various periods of orogeny gave rise to the surrounding mountains with stores of rock and concentrated mineral deposits. Erosion of the mountains over millions of years filled the deep rift valley with sediments, which are deeply bedded with layers of groundwater present throughout the deposit (Mayo et al., 2007). In more recent times, sandy plains and the unique wind regime of the valley, along with the dogleg shape of the Sangre de Cristo range on its eastern border, have fostered the development of a dune field containing the highest sand dunes in North America. The dunes are a national treasure and are protected by the Great Sand Dunes National Park. Seasonal river flow from the Sangre de Cristo Mountains plays an important role in maintaining these dunes as indicated by the interaction symbols (Fig. 3) describing dune production as the product of the sand supply from the valley floor acted on by wind and water flows (Madole et al., 2008). Finally, the high mountains surrounding the valley ensure that a large part of the water that falls on the region comes down as snow.

The primary economic systems of the Valley are farming, food processing, mining and processing ores and building materials, and recreation, all of which are important activities tied to natural resources. Other features of the socioeconomic system (e.g., service and commerce, education, transportation and government) and their interactions are shown within the model and defined in Table 2, but they are not analyzed further in this paper. People, with their knowledge and experience, are an important component of the system and immigration and emigration change the knowledge stored within the system. Tourists enter and leave the system and may be attracted by the extraordinary, high transformity features found in the natural environment, including the Great Sand Dunes National Park, various wildlife preserves harboring rare species, hot springs, etc. Finally, human activities produce wastes (W), which are fed back into the system or transported elsewhere, where they have effects on natural and human-subsidized production processes. The effects of waste production on the emergy accounts of the SLB were not evaluated in this study.

4.2. *The emergy income statement for the San Luis Basin*

This section presents the results of constructing an emergy income statement for the SLB regional system. Tables for renewable inflows, renewable production, nonrenewable production and use, and imports and exports are found in the Appendix (Tables A-1 to A-5) and follow the form established in the emergy evaluations for the States of West Virginia (Campbell et al., 2005) and Minnesota (Campbell and Ohrt, 2009).

4.2.1. Renewable emergy inflows

The renewable emergy inflows into the SLB were documented for the period from 1980 to 2005 (Table A-1; Fig. 5a). To avoid double counting, only three of the renewable emergy inputs absorbed by the system (i.e., the geopotential emergy of runoff derived from rain and snow and evapotranspiration) were summed to determine the renewable emergy base for the system. The geopotential energy of snow was the largest renewable emergy inflow to the system. Most renewable emergy inflows varied from year to year with the greatest variation (2×) between high and low years occurring for snowfall.

4.2.2. Renewable production

Renewable production (Table A-2, Fig. 5b) included several agricultural crops, livestock, and timber. The emergy of livestock production was the largest renewable output of the system from 1980 until 1997. After 1997, hay became the primary agricultural product as measured by its annual emergy flow and it held this position to the end of the study period. Potato production increased 2-fold from 1980 to 2005. Crop production and total renewable production peaked in 2000 (Fig. 5c), and then experienced a significant decline (34%) until 2004, followed by an upswing in 2005.

4.2.3. Nonrenewable emergy production and use

The use of nonrenewable emergy in fuels and electricity increased steadily over the study period (Table A-3, Fig. 5c). In contrast, the emergy production of sand and gravel, and broken stone and riprap fluctuated along a declining trend from 1995 to 2005 (Fig. 6). Many forms of nonrenewable emergy produced in the SLB showed pulsing patterns. For example, the emergy of metallic ore production remained relatively constant from 1995 until 2001, but in 2002 it spiked upward over 3 fold and then fell precipitously the next year. The production of non-metallic minerals, nec (not elsewhere classified) increased 10 fold from 2003 to 2005. Groundwater was consumed at rates faster than its recharge in 11 of the 26 years examined (Fig. 6; Heberling et al., 2011).

4.2.4. Imported emergy

Emergy imported into the SLB (Table A-4) was dominated by the “Materials Other Than Fuels” category, which was about twice as large as the next largest import, which was the combined emergy of fuels and electricity. The emergy of items imported within the “Materials Other Than Fuels” category was further categorized by economic sector (Fig. 7) and several trends in the regional economy were observed. From 1995 to 2005, “Agricultural Goods,” principally fertilizers and agricultural chemicals, increased in three waves going from 17.8% to 37.7% of the emergy imported in the “Materials Other Than Fuels” category. Emergy in “Construction Goods” was approximately 22% of this category from 1995 to 1999, but then steadily declined to 13.0% by 2005. The emergy of “Industrial and Mining Goods” imported was high compared to other categories with a single large pulse that accounted for about 44% of category inflows in 2000 and 2001. After peaking, the emergy in this category fell precipitously in 2003, and by 2005, it accounted for only 27.2% of the inflow. From 1995 to 2005, the emergy in “Consumer Goods” was relatively constant at 23.3 ± 3.3% of the category.

4.2.5. Exported emergy

The total emergy of exports was in a declining trend from 1998 to 2003, after which there was a dramatic increase in the annual empower exported (Table A-5). This resurgence was led by total materials and further by “All Other Materials” (i.e., materials without agricultural crops, livestock, minerals and forest products; Table A-5). The emergy of the services required for the total material exports followed the trend of the materials, but was of smaller magnitude except for the emergy of services in “All Other Materials”, which exceeded the emergy of the materials themselves from 2001 to 2005.

However, from 1995 until 2003, “Sand and Gravel” contained the largest amount of emergy exported from the region and the GI shipments data showed that most of the mass of these construction materials was exported to nearby destinations in Colorado and New Mexico. After 2003 there was a steep increase in the emergy exported in “All Other Materials”, so that it was 3 times greater than the emergy exported in sand and gravel in 2004 and 2005. In the “All Other Materials” category, “Miscellaneous Food Preparations, nec” (Fig. 8) contained the largest amount of emergy exported from 1995 to 2000. The precipitous jump in the emergy of “All Other Materials” in 2004 was led by “Miscellaneous Agricultural Chemicals”. While the emergy exported in all the other categories increased from 2003 to 2005, the increase in the emergy exported in “Miscellaneous Agricultural Chemicals” was 6 times greater than that of the next largest export, “Misc. Printed Matter.”

4.3. Summary of import–export exchange

From 1995 to 2005, exported emergy exceeded imported emergy, but the difference between the two increased rapidly from 2003 to 2005 (Fig. 9a). The difference between exported and imported emergy (i.e., “Exports–Imports”) closely followed the pattern of the emergy exported, because the emergy imported was fairly constant over the 11-year period. Immigration and emigration dominated the net movement of people during different periods (Fig. 9b). There was a peak in the influx of people from 1986 to 1991 and a smaller surge of people entered the SLB in 2004 and 2005. In most other years, there was a smaller net loss of people from the valley (≅25% of peak net immigration).

4.4. Summary table and aggregate diagram

Summary variables used to perform the emergy analysis of the region and to calculate indices are reported (Table A-6) and on the aggregated ESL diagram of the SLB (Fig. 4). The values shown on Fig. 4 are for the year 2000; however, the data in Table A-6 allow evaluated aggregate diagrams to be constructed for all 11 years.

4.5. Population and per capita indicators

The population of the SLB grew steadily from 1980 to 2005 and the rate of growth increased somewhat after 1993 (Table 3). The emergy of electricity and fuels used showed a similar trend (Fig. 5c), but the rate of growth increased after 1992. The renewable emergy used per capita declined by 25% from 1980 to 2005 (Fig. 10). This number can be quite variable from year to year, e.g., there was nearly a 50% increase in this quantity from 1989 to 1990. In contrast, the total emergy used per capita rose 8% from 1995 to 2000 and then fell 15% from its peak in 2000–2005 with the largest year to year decrease (9.4%) occurring from 2002 to 2003 (Fig. 10).

4.6. Emergy indices

We computed values for emergy indices and indicators and some supporting variables from 1995 to 2005 (Table 3). The indicators and indices shown characterize several aspects of the regional system, e.g., sustainability, viability and competitiveness, import–export relationships, self-sufficiency, dependence on the larger system, investment potential, and environmental loading

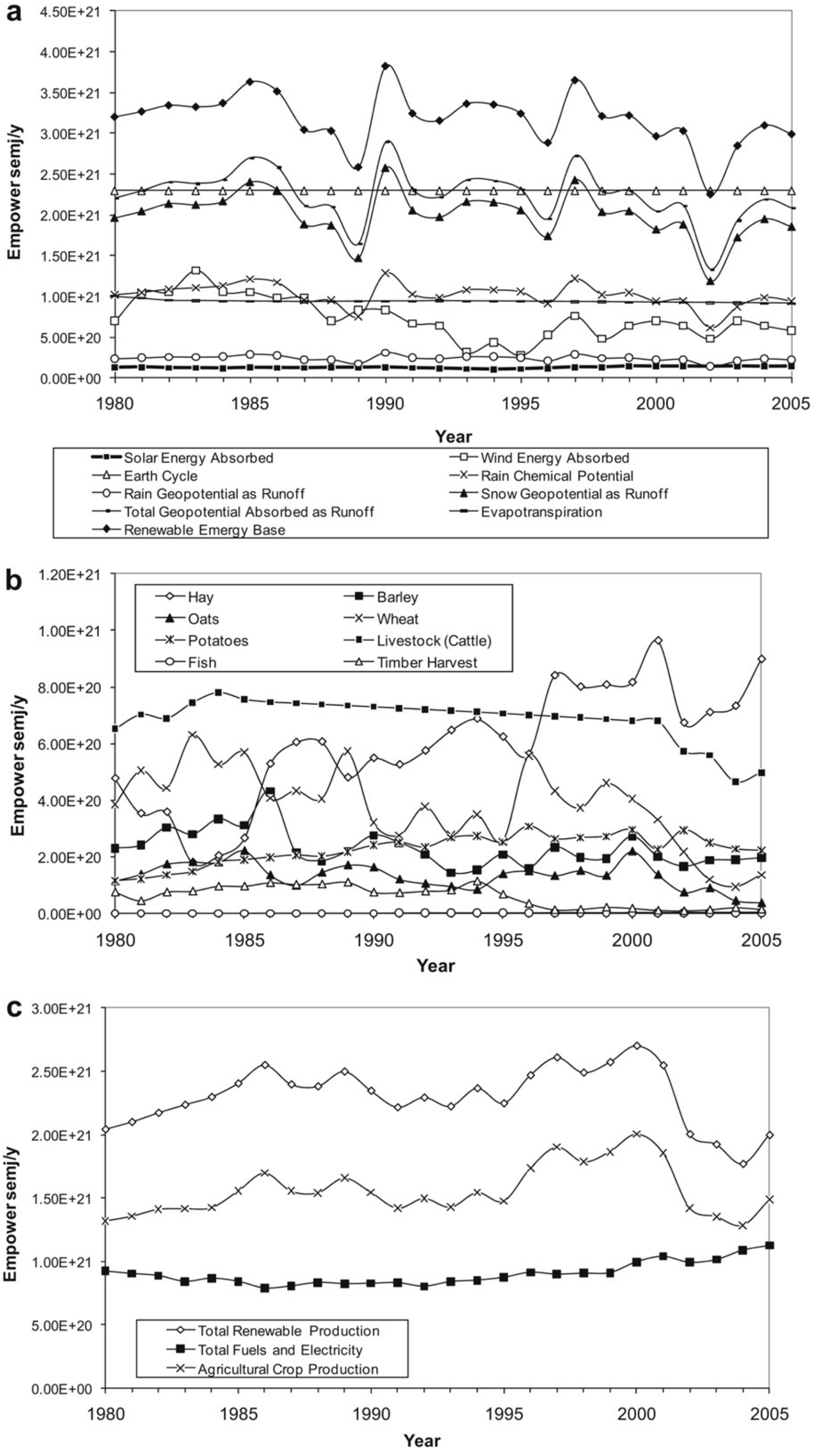

Fig. 5. a. Time series data on the renewable emergy inflows to the San Luis Basin from 1980 to 2005 are shown. b. Agricultural production in the SLB supported primarily by renewable resources. c. Total renewable production compared to agricultural crop production and the emergy of fuels and electricity used in the SLB from 1980 to 2005.

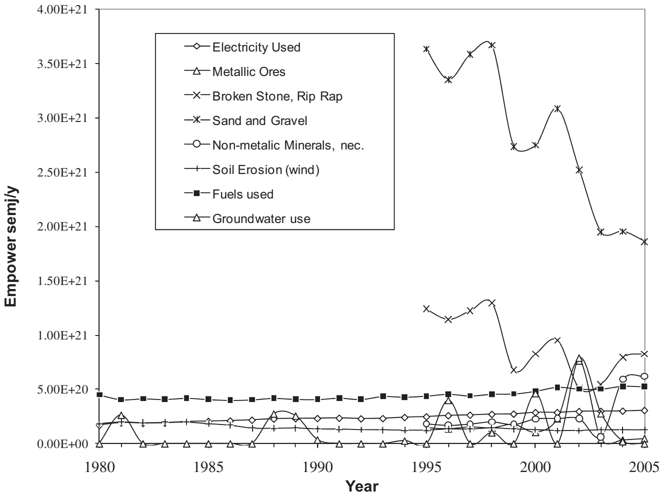

Fig. 6. Major categories of nonrenewable resources used and/or produced in the seven counties of the San Luis Basin.

(Odum, 1996; Brown and Ulgiati, 1997). In addition, mathematical expressions used in calculating the emergy indicators and indices and their units are provided.

The total emergy used (U) is the sum of the renewable and imported emergy inflows plus the nonrenewable emergy used from local sources (Fig. 11a). The pattern of total emergy used appears to be somewhat similar to the pattern of imported emergy; whereas, the general pattern of local nonrenewable emergy used is more or less the inverse of renewable emergy use. The fraction of total emergy use from locally renewable sources (R_A/U) has a somewhat similar overall pattern to the fraction of total emergy use from home sources ($R_A + N_0 + F_2)/U$)), but with distinct low points in 1996, 2000, and 2002 (Fig. 11b).

The variation of the ESI's two components, LEI (formerly system EYR) and ELR (Fig. 12) demonstrates that an increase in environmental loading from 1995 to 2002 combined with a slow decline in the LEI over this period resulted in declining sustainability from 1997 to 2002. After 2002, the ELR declined rapidly and the LEI increased slightly causing the ESI to increase. However, the ESI still declined 27% over the period from 1995 to 2005. The ESI showed that the sustainability of the regional system was lowest in 2002 and highest in 1997.

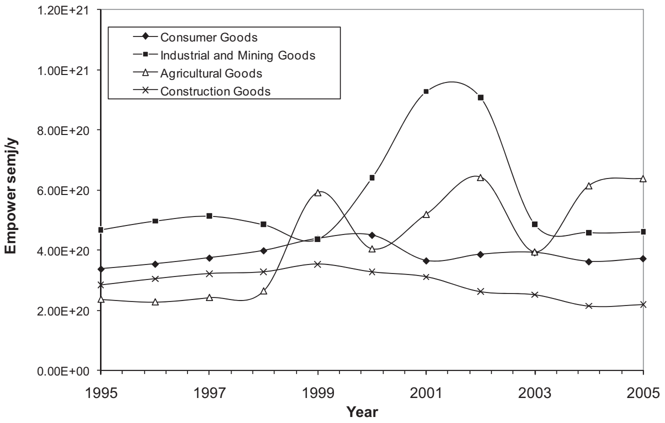

Fig. 7. The categories of "Material goods other than fuels" imported into the SLB from 1995 to 2005.

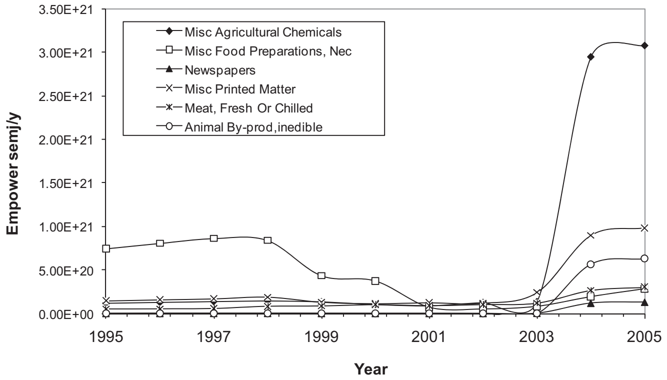

Fig. 8. The six largest categories of exports contained in "All Other Materials".

4.7. Emergy to money relationship

The nominal Gross Regional Product (GRP) of the seven counties in the SLB increased 70% from 1995 to 2005 (Table 3) and the Net Regional Product (NRP) showed a similar rate of increase over this time but had a lower absolute value (Heberling et al., 2011). During this same time the total emergy used in the region first increased 15% from 1995 to 2000 and then fell 15% to approximately its 1995 level by 2005 (Fig. 11a). The net result of these two trends was a decline in the emergy to money ratio from 5.72 E12 semj/\$ in 1995 to 3.38 E12 semj/\$ in 2005. Thus, the power of money to purchase emergy in the SLB declined 41% over the 11-year period (Fig. 13).

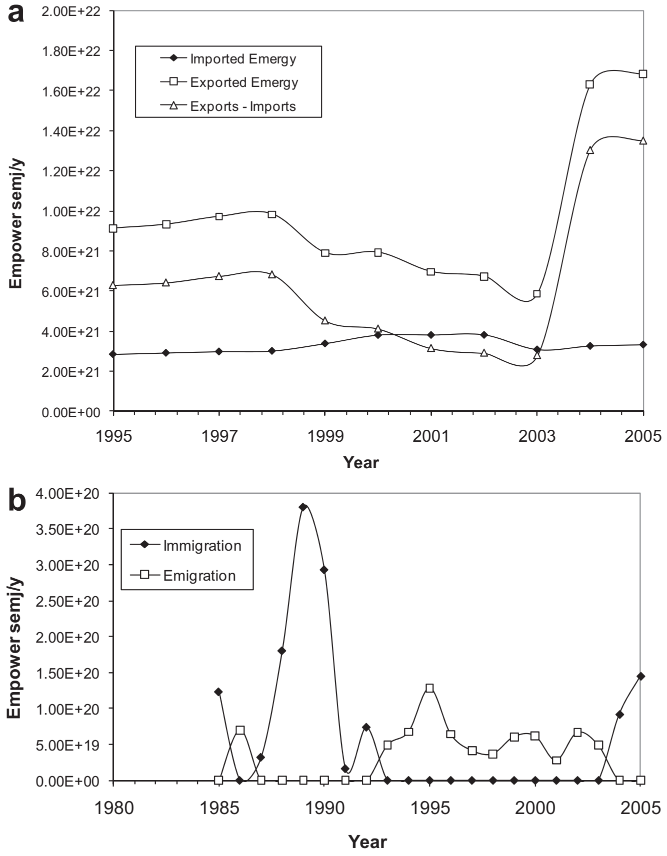

Fig. 9. a. The balance of emergy exported from and imported to the San Luis Basin from 1995 to 2005. b. The empower entering or leaving the SLB each year as a result of net immigration and emigration from 1985 to 2005.

Table 3
Emergy Indices and Indicators for the San Luis Basin.

Item	Name of Index	Expression	Units	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
				X E20[a]	X E20[a]	X E20[a]	X E20[a]	X E20[a]	X E20[a]	X E20[a]	X E20[a]	X E20[a]	X E20[a]	X E20[a]
97	Renewable Use	R_A	semj y^{-1}	32.43	28.84	36.54	32.12	32.21	29.65	30.30	22.49	28.47	30.99	29.90
98	In Region Non-renewable Use	$N_0 + N_1$	semj y^{-1}	12.59	16.68	12.79	14.27	11.78	16.88	12.96	19.87	14.33	12.31	12.02
99	Imported Emergy, EmImp	$F + G + P_2I$	semj y^{-1}	28.37	29.07	29.73	30.07	33.83	38.11	38.17	38.20	30.77	32.60	33.24
100	Total Emergy Inflows	$R + F + G + P_2I$	semj y^{-1}	60.80	57.91	66.28	62.20	66.03	67.76	68.47	60.68	59.24	63.58	63.14
101	Total Emergy Used	$U = (R_A + N_0 + F_1 + G + P_2I)$	semj y^{-1}	66.46	67.33	71.98	69.17	70.48	76.91	73.33	72.53	65.54	67.54	66.84
102	Total Exported Emergy, EmExp	$B + P_2E + N_2$	semj y^{-1}	91.25	93.21	97.12	98.25	78.98	79.24	69.59	67.27	58.60	162.97	168.30
103	Emergy used from Home Sources	$(N_0 + F_2 + R)/U$		0.57	0.57	0.59	0.57	0.52	0.50	0.48	0.47	0.53	0.52	0.50
104	Imports–Exports	$(F + G + P_2I) - (B + P_2E + N_2)$	semj y^{-1}	−62.87	−64.14	−67.38	−68.18	−45.16	−41.12	−31.42	−29.07	−27.83	−130.37	−135.06
105	Ratio of Exports to Imports	$(B + P_1E + N_2)/(F + G + P_2I)$		3.22	3.21	3.27	3.27	2.33	2.08	1.82	1.76	1.90	5.00	5.06
106	Fraction Used, Locally Renewable	R_A/U		0.49	0.43	0.51	0.46	0.46	0.39	0.41	0.31	0.43	0.46	0.45
107	Fraction of Use Purchased Outside	$(F + G + P_2I)/U$		0.43	0.43	0.41	0.43	0.48	0.50	0.52	0.53	0.47	0.48	0.50
108	Fraction Used, Imported Services	P_2I/U		0.12	0.12	0.11	0.12	0.12	0.12	0.12	0.11	0.11	0.11	0.12
109	Fraction of Use that is Free	$(R_A + N_0)/U$		0.51	0.51	0.53	0.50	0.48	0.46	0.43	0.44	0.50	0.48	0.47
110	Ratio of Purchased to Free	$(F_1 + G + P_2I)/(R_A + N_0)$		0.97	0.97	0.90	1.00	1.10	1.16	1.33	1.30	1.02	1.08	1.15
111	Environmental Loading Ratio	$(F_1 + N_0 + G + P_2I)/R_A$		1.05	1.33	0.97	1.15	1.19	1.59	1.42	2.23	1.30	1.18	1.24
112	Investment Ratio	$(F + G + P_2I)/(R + N_0 + F_2)$		0.74	0.76	0.70	0.77	0.92	0.98	1.09	1.11	0.89	0.93	0.99
113	Use per Unit Area	U/Area	semj/m^2	2.76E + 11	2.79E + 11	2.99E + 11	2.87E + 11	2.92E + 11	3.19E + 11	3.04E + 11	3.01E + 11	2.72E + 11	2.80E + 11	2.77E + 11
114	Use per Person	U/Population	semj/pers.	1.52E + 17	1.51E + 17	1.59E + 17	1.51E + 17	1.52E + 17	1.63E + 17	1.56E + 17	1.53E + 17	1.38E + 17	1.40E + 17	1.39E + 17
115	Renewable Carrying Capacity	$(R_A/U)^a$ Population	People	21366	19088	22992	21317	21193	18154	19383	14698	20681	22117	21520
116	Developed Carrying Capacity	$8^a(R_A/U)^a$ Population	People	170926	152703	183940	170536	169544	145234	155064	117581	165445	176938	172157
117	SLB Gross Regional Product	GRP	$/yr	1.16E + 09	1.23E + 09	1.35E + 09	1.39E + 09	1.49E + 09	1.59E + 09	1.60E + 09	1.63E + 09	1.71E + 09	1.85E + 09	1.98E + 09
118	Ratio of SLV Emergy Use to GRP	U/GRP	semj/$	5.72E + 12	5.48E + 12	5.32E + 12	4.99E + 12	4.74E + 12	4.83E + 12	4.58E + 12	4.45E + 12	3.83E + 12	3.65E + 12	3.38E + 12
119	Ratio of U.S. Emergy Use to GDP	U/GDP	semj/$	2.60E + 12	2.60E + 12	2.56E + 12	2.47E + 12	2.31E + 12	2.35E + 12	2.19E + 12	2.07E + 12	2.00E + 12	2.03E + 12	1.91E + 12
120	Ratio of Electricity Use/ Emergy Use	E_1/U		0.037	0.038	0.037	0.039	0.039	0.037	0.039	0.041	0.046	0.044	0.046
121	Fuel Use per Person	F_2/Population	semj/pers.	1.00E + 16	1.02E + 16	9.73E + 15	9.94E + 15	9.90E + 15	1.03E + 16	1.11E + 16	1.06E + 16	1.06E + 16	1.10E + 16	1.09E + 16
122	Population	Population	People	43793	44566	45289	45902	46377	47097	46907	47404	47598	48207	48101
123	Area	Area	m^2	43793										
124	Renewable empower density	R_A/Area	semj m^{-2}	43793	1.20E + 11	1.52E + 11	1.33E + 11	1.34E + 11	1.23E + 11	1.26E + 11	9.33E + 10	1.18E + 11	1.29E + 11	1.24E + 11
125	Regional Emergy Yield Ratio (Exp/Imp)	$(B + P_1E + N_2)/(F + G + P_2I)$		43793	3.21	3.27	3.27	2.33	2.08	1.82	1.76	1.90	5.00	5.06
126	Local Effect of Investment, LEI	$U/(F + G + P_2I)$		43793	2.32	2.42	2.30	2.08	2.02	1.92	1.90	2.13	2.07	2.01
127	Emergy Sustainability Index	(LEI or system EYR)/ELR		43793	1.74	2.50	1.99	1.75	1.27	1.35	0.85	1.64	1.76	1.63
128	Emergy Index of Sustainable Use	(EmExp/EmImp)/ELR		43793	2.40	3.37	2.83	1.96	1.30	1.28	0.79	1.46	4.24	4.10

[a] Except as noted. Where the units column is blank the indicators are dimensionless.

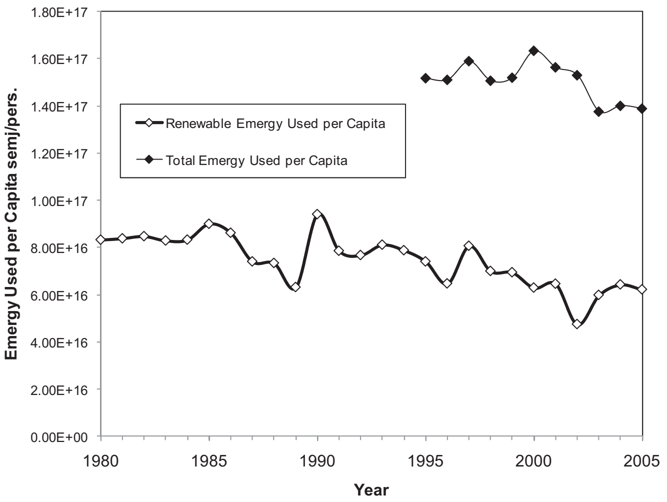

Fig. 10. The renewable emergy used per person from 1980 to 2005 and the total emergy used per person from 1995 to 2005.

4.8. Emergy index of sustainable use

The variation of the EISU's two components, REYR (EmExp/EmImp) and the ELR (Fig. 14), showed that an increase in environmental loading from 1997 to 2002 combined with a decline in the REYR after 1998 resulted in declining sustainability of the relationship between the SLB and its larger system during this period. After 2002, there was a rapid increase in the REYR, which was caused by a resurgence of exports. From 2002 to 2005, REYR increased 2.87 times and EISU increased 5.18 times.

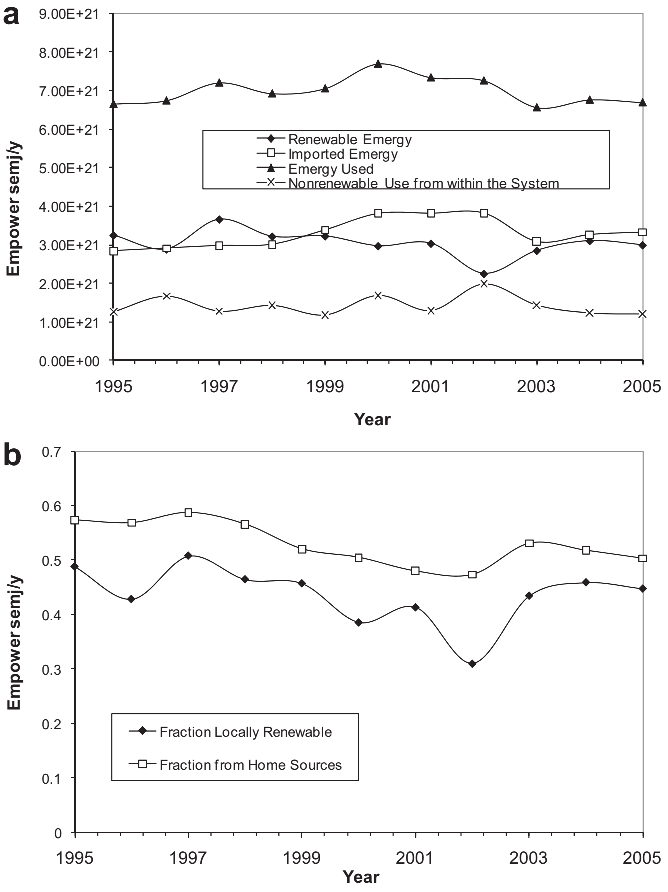

Fig. 11. a. The total emergy used by the system compared to the nonrenewable use from within the system, renewable emergy and imported emergy that are its components. b. The fraction of the total emergy used that comes from local renewable emergy and the fraction of use from home sources.

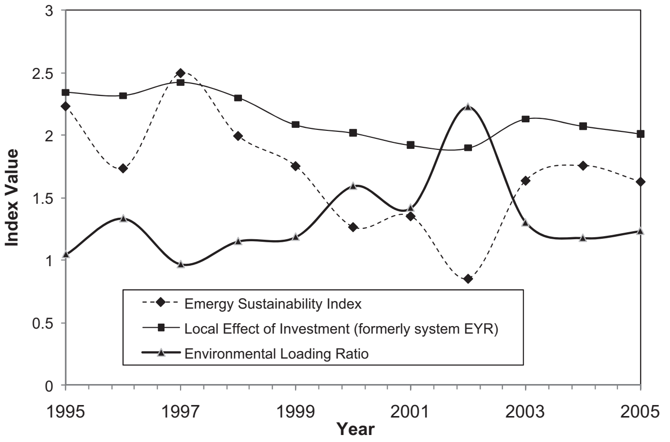

Fig. 12. The Emergy Sustainability Index (ESI) and its components the Local Effect of Investment, LEI, (formerly system EYR) and the Environmental Loading Ratio (ELR) shown for the San Luis Basin from 1995 to 2005.

5. Discussion

Emergy analyses that consider how a system changes over many years are becoming more common. Historical studies of nations have been performed (Abel, 2007; Rydberg and Jansen, 2002; Sundberg et al., 1994; Tilley, 2006) and nations have been evaluated over decades (Cialani et al., 2005; Ferreyra and Brown, 2007; Hagström and Nilsson, 2005; Huang et al., 2006). 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, we were unable to find another study that examined the sustainability of a region with nonstandard boundaries (i.e., boundaries that were not based on standard political or administrative reporting units) over many years. Such nonstandard systems, like the SLB, may have biophysical and/or economic factors that give them integrity, but often the institutional basis for management of these systems does not exist or is fragmented (Costanza et al., 2001).

The SLB is unique because it is the first system where snow has been shown to account for the largest renewable emergy input to

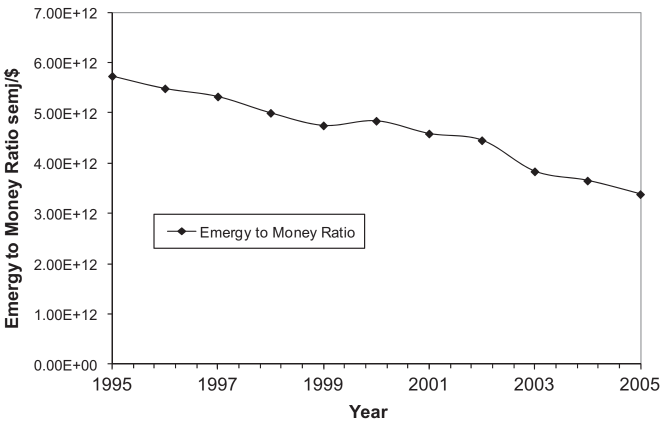

Fig. 13. Emergy to Money Ratio (U/GRP) in the San Luis Basin from 1995 to 2005.

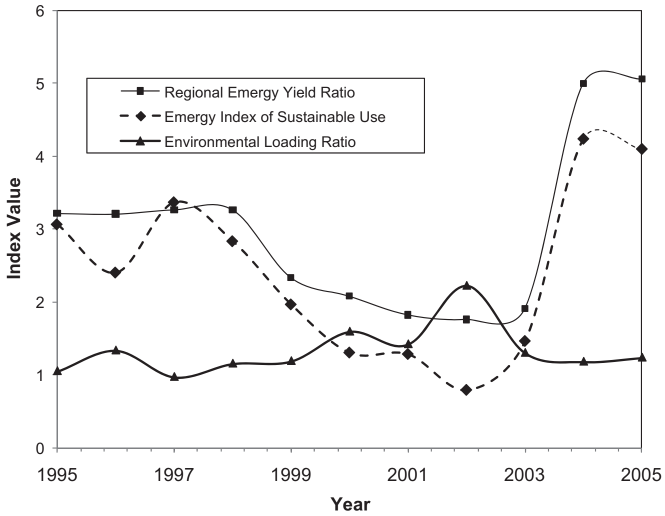

Fig. 14. The Regional Emergy Yield Ratio (REYR = Exp/Imp), the Environmental Loading Ratio (ELR), and the Emergy Index of Sustainable Use (EISU = REYR/ELR) for the SLB from 1995 to 2005.

a system. The variation in the geopotential energy of snow is the primary driver behind the fluctuations in total geopotential energy inflow and in the renewable emergy base for the region. The present socioeconomic system in the SLB is largely organized around agriculture, which is itself dependent on the surface water and groundwater flows that originate in or are replenished from the high mountain snowpack.

5.1. *Cycle of change of the agricultural system*

To understand the current position of the SLB within the dominant cycle of change governing it, we must examine the development of agriculture in the region. Beginning around 1850, the San Luis Valley was first developed for commercial agriculture through the exploitation of its surface water flows, but agricultural production was limited relative to its potential during this time (Emery, 1996). Artesian water was discovered in 1887 and by the early 1890s, there were 2000 groundwater wells supplying water for agriculture. The development of groundwater resources contributed to a rapid expansion of agriculture in the region, and by 1980, there were 7700 wells withdrawing groundwater from the confined aquifer and 2300 wells pumping the unconfined aquifer (Emery, 1996). Thus, the dominant process governing economic and social development in the region since the middle of the 19th Century has been the growth and expansion of agriculture based on the increasing use of water resources. Agriculture continues to the present day as a major economic activity in the region (SLVDRG, 2007). This historical analysis of the development of water resources shows that the SLB was apparently a fully developed (climax stage) agricultural system by 1980; and thus, the period from 1980 to 2005 is a reasonable time period over which to examine the sustainability of this agricultural system.

5.2. *Renewable emergy inputs to the region*

Usually, the renewable emergy base of a system is determined by averaging the independent emergy inputs to the system over many years. This method of estimating the renewable energy inflows to a system is based on the assumption that social and economic structures adjust over time to best utilize the average emergy signature of a place. This study departs from this custom by looking at the year-to-year variability in the availability of renewable resources. One caveat to our approach is that including the annual variability of the renewable emergy base may give undue significance to the noise in the signal, in the sense that the variability of the indices may not be linked to the level of organization that those inputs can support in the long run. However, when a system is dependent on renewable resources to the extent that the year-to-year variations in an input's magnitude result in marked changes in system productivity, it is perhaps worthwhile to consider the inter-annual variability of renewable sources. In the SLB, both the productivity of agriculture and the unique natural systems of the region are highly dependent on the year-to-year availability of water; therefore, we think the inclusion of the variability of renewable resources in our analysis is justified.

5.3. *Changes in the water cycle of the region*

Until 2002, renewable production (e.g., crops, livestock, and timber) was more than twice the emergy of total fuel and electrical consumption (including services). After 2002, this ratio fell below 2:1, as a result of a marked decline in agricultural production and the steady increase in the quantity of fuels and electricity used. The rapid fall in the emergy of agricultural production (Fig. 5c) coincided with a steep decline in precipitation and snowfall (Fig. 5a), which was manifested in a large net consumption of groundwater in 2000 and 2002 (Fig. 6). Even though precipitation recovered in subsequent years, there was a smaller net consumption of groundwater the next year and crop and livestock production did not begin to recover until the third year after the drought. These patterns indicate the sensitivity of this system to changes in precipitation and the adverse consequences that might be expected from multiple consecutive years of decreased precipitation. In fact, the frequency of occurrence of years with low precipitation has increased from 1980 to 2005, and if this trend continues, it will certainly threaten the vitality of agricultural production in the region.

5.4. *Vulnerability of the region to cycles of climate change*

Snowmelt has special properties in that it delivers high quality energy in a pulse that carries twice the emergy of the next largest renewable input, evapotranspiration. This pulse is essential to recharge groundwater and to maintain rare geological features like the Great Sand Dunes. If climate change in this region results in drier winters or in warmer winter temperatures, the formation and duration of the snowpack will be affected. Changes in long-term snowfall or winter temperatures would be expected to result in significant changes in the hydrological and geological features of this unique system, and as a result, tourism and agriculture might be affected. Climate trends and changes predicted for this general region (State of New Mexico, 2005) are broadly consistent with warmer and/or dryer winters. Predictions of a dryer warmer climate combined with the observed increasing frequency of drought years may indicate that the climax agricultural system of the region has already begun to move toward the declining stage in the cycle of change (Fig. 2a, stage C).

5.5. *Cycles of change in nonrenewable resource use*

Nonrenewable energy use (i.e., fossil fuels and electricity) shows steady growth from 1980 to 2005 that follows the increase in population (stage A). However, the construction industry in the SLB and its vicinity apparently declined from 1995 to 2005 as evidenced by the 40% decline in construction materials (i.e., sand and gravel and crushed stone) produced and exported (stage C). Nonmetallic minerals (e.g., gypsum sulfur, salt, etc.) in unprocessed form are mined in the SLB, but only a small amount is expected to be used there. Exports in this category increased rapidly from 2003 to 2005 as part of a general economic resurgence during this time.

Renewable emergy used in a nonrenewable manner showed different patterns related to the climax stage of agricultural development in the region. For example, soil erosion from wind steadily declined over the time period possibly indicating gradual improvement in cultivation methods (i.e., improved efficiencies) that are expected to occur in a fully developed system. Annual groundwater withdrawals exceeding the recharge rate were the mirror image of precipitation shortages with the greatest withdrawal occurring in 2002, the year with the lowest precipitation. During times of large withdrawals, the emergy supplied by groundwater made a significant contribution to the annual emergy used in the region (e.g., in 2002 the emergy supplied from groundwater approached that supplied by fuels and electricity). Groundwater withdrawals in excess of recharge rates ultimately threaten the water resource base of the SLB and the sustainability of agriculture in the region.

5.6. *Cycles of change in imports and the emergy budget of the SLB*

The Global Insight data showed that processed non-metallic minerals accounted for most of the emergy in imported material goods excluding fuels and electricity and that this input fell 57% from 2000 to 2003. Further investigation revealed the non-metallic mineral, 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 and shipped out of the region. At this time, the mines in Northern New Mexico supplied 80–85% of the perlite used in the U.S. from U.S. sources (Barker et al., 2002). Therefore, the large emergy flow of processed non-metallic minerals moving through the region pertained to the larger U.S. system, and it was not counted in the emergy use of the region. In the emergy analysis of West Virginia, a similar adjustment was made for the large flow of natural gas passing through the State in a national pipeline (Campbell et al., 2005).

Agricultural goods imported increased in three waves from 1995 to 2005 indicating cycles in the use of fertilizer and agricultural chemicals and by extension cycles of change in crop cultivation. Thus, within the larger cycle of change governing the development of agriculture in the region, there are many smaller cycles related to the expansion and contraction of production cycles, e.g., in the cultivation of wheat, barley, and oats.

The timing of the decline in the emergy of construction goods imported corresponds to a fall in the production of sand and gravel and broken stone in the region. This correspondence indicates that from 2000 to 2005 the construction industry in the region was in the declining stage of a cycle of change. The peak (1999–2002) in the emergy of industrial and mining goods imported corresponds to the peak production of metallic ores (2002). This pattern indicates a cycle of change in some as yet unidentified mining activity in the region during this time. However, from the GI data, we know the rapid increase in imports in this category was primarily due to industrial gases from 2000 to 2002 and electrometallurgical products in 2002.

The growth (9.8%) in the emergy of consumer goods imported to the SLB from 1995 to 2005 was consistent with population growth (10%) over this period. This cycle of change is linked to the growth of population, as well as, fuel and electricity use in the region, which in turn maybe linked to the growth of economic development in the hinterlands of the United States.

Immigration increased the emergy inflow of knowledge to the region in two pulses: 1986–1991 and 2003–2005. We have no data that will allow us to set the former pulse in context, but the later corresponds to a period when the emergy of a labor-intensive export related to agriculture was increasing rapidly. During the peak inflow of immigrants in 1989, the emergy contributed to the region in their education and skill level exceeded the emergy of the petroleum used in that year by 41%, indicating that the movement of people can represent a significant gain or loss of emergy for the region.

5.7. *The cycle of change in exports*

The exact nature of the agricultural chemicals (e.g., soil conditioners, humus, pesticides, fungicides, etc.) that led the 2003–2005 economic resurgence is not known, but we do know that the goods exported were labor-intensive as indicated by the fact the services required for their production contained as much emergy as the materials in the products exported. From 1995 to 1998, the emergy exported followed an increasing trend due to an increase in the manufacture of “Misc Food Preparations”, which was the largest category of “All Other Materials”, exported before 2003. During this time the major exports from the SLB were the value-added products from agricultural production as might be expected from the climax agricultural system that existed in the region after 1980. The declining trend in the sand and gravel and crushed stone exported from 1995 to 2005 implies that demand generated from construction projects in the larger region was in the declining phase of a construction cycle.

5.8. *Cycles of export–import exchange*

The emergy of exports exceeded the emergy of imports by a considerable margin over the entire study period. Therefore, we may conclude that the SLB is a hinterland supplying raw materials and primary products to Colorado, New Mexico, and other areas within the United States, Canada and Mexico, as shown by the shipment destinations recorded in the Global Insight data. From 1999 to 2003, the emergy of exports declined and from 2001 to 2003 the emergy of imports also declined, indicating that the import–export sector of the regional economy was contracting during this time. The data shows a distinct cycle of change in the emergy of exports with a steady plateau from 1995 to 1998, a declining phase from 1998 to 2003 and a subsequent rapid growth phase from 2003 to 2005.

5.9. *Summary table and the aggregate model*

There are several gaps in the data and uncertainties in the current values of the model flows. In particular, we were not able to apply the method of Campbell et al. (2005) to determine the import and export of pure services to and from the region. Thus, there is a question mark in the places designated by P_2I_3 and P_2E_3 on the diagram (Fig. 4) and in Table A-6. In addition, data sources for the taxes paid to state and federal government over the entire time period have not been found. However, the error introduced by the missing data on the import and export of pure services from this rural area is expected to be small.

5.10. *The cycle of population growth and consumption*

The fuel used in the region 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 entire increase in energy use over this time. From 1980 to 2005, the consumption of electricity per capita increased by 44%, which accounts for the additional growth in electricity consumption above that expected from population increase alone. The use of more high quality energy in the form of electricity is indicative of an increase in quality of life over this time. Per capita fuel consumption declined 7% over the period but population grew 25%, which can explain why there was only a 16% rise in fuel consumption. From this analysis, we conclude that population growth along with changes in the per capita energy consumption can explain the observed increase in fuel and electricity consumption.

The overall quality of life for people in the region is high as indicated by the total emergy used per person (1.59 E+17 semj/person in 1997); a value comparable to that found in Minnesota (1.53 E+17 semj/person in 1997), a state with high levels of well-being (Campbell and Ohrt, 2009).

5.11. Cycles of change in the emergy indices

The sustainability of the region was characterized and investigated through an examination of changes in several emergy indices over time. The fraction of emergy use that comes from renewable sources is an indicator of the potential for long-term sustainability of the present state of the system. This fraction declined from 1997 to 2002 and then increased abruptly indicating movement toward a more sustainable state. This increase was due both to an increase in precipitation after 2002 and to a continuing relatively constant level of emergy purchased from outside the system. On average, renewable emergy accounted for 44% of total use over the 11-year period, which is five times that of an average location in the United States (Campbell and Ohrt, 2009). This index declined 4% over the 11-year period indicating that the system moved toward a slightly less sustainable state over this time.

The principal difference between the patterns of the fraction of emergy used from renewable sources and that used from home sources (an indicator of self-sufficiency) is determined by drought years. In a drought, emergy contributions from renewable resources decline due to a decrease in precipitation, and the fraction of use from home sources increases due to increased use of groundwater, as seen most clearly for the years 1996, 2000 and 2002. The pumping of groundwater during drought decreases the variability of the total emergy used in the system by compensating for declines in the renewable emergy inflows derived from precipitation. The fraction of use from home sources exceeds 40% in some years making the SLB a moderately self-sufficient system with a value similar to the State of Maine (Campbell, 1998).

The ESI gives a measure of the sustainability of a regional system from the perspective of that system. The ESI of the SLB was above two in two (1995 and 1997) of the eleven years analyzed and below one in 2002. The average ESI (2.04 ± 0.33) from 1995 to 1999 was significantly different ($p < 0.01$ of a type 1 error) from the average ESI (1.42 ± 0.34) from 2000 to 2005. This analysis implies that there is better than a 99% probability that there was a change in the relative sustainability of the region (as measured by the ESI) associated with the occurrence of two drought years (2000 and 2002) in rapid succession.

The SLB can be set within a context of the sustainability of nations by comparing its ESI to the ESIs of 42 countries calculated by Brown (2003). The ESI of the SLB at worst (2002) was similar to that of China (0.85 compared to 0.81) and at best (1997) it was comparable to that of Colombia (2.50 compared to 2.40). Over the 11 years examined, this index showed that the sustainability of the regional system decreased almost 27% due to the combined effects of an increase in the ELR and a gradual decline in the LEI, which represents the ability of purchased emergy to generate greater emergy flows in the region.

The renewable carrying capacity of the system (Table 3) showed that the region's potential to support its population (48,101 in 2005) at the current standard of living using renewable emergy alone was 21,520 people or 45% of the 2005 population. From 1995 to 2005, this index showed that the sustainability of the region decreased 6%; however, the index varied over a range of 20% from a low of 31% in 2002 to a high of 51% in 1997. Because population increased from 1995 to 2005, the renewable carrying capacity showed a slightly greater decline in sustainability (6%) compared to that calculated from the percent renewable emergy used (4%).

The well-being of the regional system is of particular concern to the people who live there. One index of regional well-being is the total emergy used annually, which remained fairly stable (coefficient of variation (CV) = 0.05) over the period examined despite variability in the emergy of individual inflows and outflows. The adjustment of a system's resource use to maintain empower in the face of variable inputs is a process predicted by the maximum empower principle (Odum, 1996; Campbell, 2000a). These adjustments occur, in part, from human activities that compensate for year-to-year variations in the renewable emergy inflows. For example, the decline in precipitation in 2002 was compensated by the increase in the emergy of groundwater withdrawal keeping overall emergy use by the system fairly stable, despite the perturbation caused by lower precipitation.

The pattern of increasing economic activity and that of relatively constant emergy use within the region produced a declining emergy to money ratio (semj/$). When more money and the same or less real wealth flow through a system in a year, inflation results (Odum, 1996). Thus, the buying power of a dollar or the real wealth (emergy) that could be purchased by a nominal dollar spent in the SLB decreased 41% from 1995 to 2005. This is the trend that one expects in the growth stage of the cycle of economic development in a region.

The EISU (REYR/ELR) is a new measure that quantifies the sustainability of the relationship between a local system and its next larger system. This index applies to open hierarchical systems, where there is the possibility of mutual benefit through establishing exchange between the various systems at different levels of organization. The REYR, which was defined as the ratio of the emergy of exports to imports of the region, ranged from a low of 1.76 in 2002 to a high 5.06 in 2005. Therefore, it was advantageous for the larger system to trade with the SLB over the entire time. The EISU showed that the sustainability of the relationship between the SLB and its larger system declined by 76% from 1997 to 2002 due to a rising ELR and a declining ratio of exported to imported emergy. After 2002 the emergy return on investment increased due to a sudden increase in the emergy of exports so that by 2005 the EISU was 5.2 times its value in 2002. The EISU indicated that the sustainability of the relationship between the SLB and its larger system increased 34% from 1995 to 2005, in contrast to measures of the sustainability of the SLB region *per se*, which declined over this time. This difference in sustainability observed at different levels of hierarchical organization emphasizes the need to assess sustainability on several scales of organization simultaneously (Odum and Arding, 1991; Odum, 1996) to ensure that all the costs and benefits of any particular policy or management alternative are clearly understood.

5.12. Implications of the new and revised indices for emergy analyses

Raugi et al. (2005) first pointed out problems with the way that EYR was being used in emergy analyses. These problems are especially noticeable when EYR is applied to describe the ratio of the emergy used by a whole system to the purchased emergy inflows. While U/F is a useful ratio, it does not have the same meaning as that originally assigned to the EYR by Odum (1996), because it takes the definition of EYR originally applied at one scale, i.e., that of a production process, and applies it at the larger scale of a whole system. Thus, while it is mathematically correct that $R + F + N = Y$ on the process scale and that $R + N + F = U$ on the scale of the whole system, the meaning of the index is altered when the scale of the analysis is changed, such that Y/F for a process is not equivalent, conceptually, to U/F for a whole system.

Note that the ratio (U/F) redefined as the Local Effect of Investment (LEI) is not the same as and it should not be confused with the existing emergy investment ratios listed in Odum (1996), which show the matching between the economic and environmental contributions to the system in various ways (e.g., the ratios purchased to free ($(M + S)/(R + N)$ or nonrenewable to renewable $(N + M)/R$)), where purchased inputs (F) from the larger system are composed of materials (M) and services (S). Conceptually, total emergy flow U is a quantity related to whole system function and is not a yield from the system. When U changes overall system condition is affected, and thus the LEI shows the effect of purchased emergy inflows on local system empower. Furthermore, changing the verbal definition of U/F does not affect the mathematical definition of ESI or any past results of its use in emergy analyses.

The definition of REYR as the ratio of exported to imported emergy describes the yield of a regional system to its next larger system, and in our view, this definition of system yield is more consistent with the original conception of EYR (Odum, 1996) as an index used to characterize the yield to the larger system gained from its investments in a production process.

Redefining the yield of a whole system in this manner allowed us to develop a new index, EISU = (EmExp/EmImp)/ELR, which captures the sustainability of the relationship between a local system and its next larger system. We believe that the reinterpretation of (U/F) as LEI and the definition of whole system yield as the ratio of exported to imported emergy more accurately characterizes the different functions of F in whole systems such as nations, states, and regions. For example, REYR and EISU show a large benefit, respectively, to the larger system and to the relationship between the region and its larger system from the export resurgence that occurred after 2002. In contrast, the LEI shows that relatively little benefit accrued to the region *per se* from this increase in exports.

5.13. Future cycles of change in the SLB

One national trend that will affect the SLB in the near future is the movement toward broader development of renewable energy sources. Many states including Colorado have set goals to obtain a certain amount (30% by 2020 for CO) of their electric power from renewable energy. (http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=CO24R&state=CO&CurrentPageID=1, accessed March 17, 2011). The SLB has a high potential for the development of solar energy (http://www.nrel.gov/gis/solar.html, accessed March 17, 2011) and if some of this energy is used in the region, the SLB can expect future development to be more sustainable to the extent that it will rely more on renewable sources of power. One caveat is that the amount of renewable emergy supplied by a power source must be corrected for the nonrenewable emergy used to obtain the renewable power flow. This trend was in its inchoate stages of growth beginning a new cycle of change during our study of the SLB as evidenced by the construction of an 8 MW solar power plant in the valley during this time. At present there are on-going plans, discussions and debate related to the development of solar power in the San Luis Basin.

6. Conclusions

We developed an Energy Systems framework for interpreting "what is sustainable" for a given system at any particular time by combining the insights of Holling (1986) on the cycle of change with those of Odum (1999) on understanding the cycle of change within the context of a model of internal storages and external forcing functions as represented by a pulsing Energy Systems model. We explored the efficacy of this framework by applying it to better understand the complex cycles of change manifested in a real system, the San Luis Basin, CO. We identified the position of the SLB within cycles of change governing various aspects of its development. We concluded that when the current state or condition of a system is viewed within the context of the cycle of change that is imposed upon it by its internal dynamics and the dynamics of the next larger system, decision-makers can make more robust choices about policies to promote system well-being in the present, while planning for conditions that their systems may face in the future.

The emergy evaluation provided an answer to the question "Is the SLB regional system moving toward or away from more sustainable states?" The long-term sustainability of the SLB based on the fraction of renewable emergy used and the renewable carrying capacity declined 4 and 6 percent, respectively, from 1995 to 2005. This trend is consistent with the observed moderate rate of growth of the regional economy and use of fossil energy resources. However, the ESI declined 27% over the study period and showed a somewhat less benign picture of regional sustainability in that there was a statistically significant difference between the average value of the ESI from 1995 to 1999 and its value from 2000 to 2005. A new index, EISU, was developed to quantify the sustainability of the relationship between a region and its next larger system. In contrast to the declining indices of regional sustainability, this index rose 34% over the study period. Thus, the accurate assessment of sustainability for the whole system depends on evaluating multiple levels in the hierarchical organization of the network of energy flows.

The total emergy used by the SLB region varied little over the study period indicating that system well-being and competitiveness were remarkably stable over this time. This stability in overall system emergy flow was evident in spite of large variations in the renewable emergy base of the system and the types of resources used. System empower was maintained by using groundwater to support agriculture in low precipitation years and this compensatory mechanism is consistent with the operation and predictions of the maximum empower principle.

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Appendix

Emergy Accounts for the San Luis Basin, CO and a Summary Table of Emergy and Economic Indicators with their Definitions.

Table A-1
Renewable emergy inflows to the San Luis Basin.

	Renewable energy sources										
Year	Solar energy absorbed	Wind energy absorbed	Earth cycle	Rain chemical potential	Rain geopotential on the land	Snow geopotential on land	Rain geopotential as runoff	Snow geopotential as runoff	Total Geopotential as runoff	Evapotranspiration	Renewable[a] emergy base
	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/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

[a] The Renewable emergy base for the systems consists of the sum of the geopotential of runoff from rain and snow and the evapotransiration.

Table A-2
Production in the San Luis basin that is based primarily on renewable resources.

	Renewable production								
Year	Crops	Hay	Barley	Oats	Wheat	Potatoes	(Cattle)	Fish	Harvest
	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/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 A-3
Nonrenewable emergy inflows in the San Luis Basin.

Nonrenewable emergy sources											
Year	Coal used	Used	Fuels used	Used	Produced[a]	Ores[a]	Stone, rip	Gravel[a,b]	Metallic	Soil erosion	Groundwater
	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/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

[a] Assumed from the Global Insight Inc. data to be produced in the Valley.
[b] Ten percent was added for local consumption.

Table A-4
Imports into the San Luis Basin.

Imports												
Year	Coal	Petroleum	Natural gas	Electricity	Total fuels and electricity	Materials other than fuels	Services in materials other than fuels	Services in fuels	Services in electricity	Total goods and services	Immigration	Tourism	Federal and state outlays
	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y		semj/y	semj/y	semj/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 A-5
Exports from the San Luis Basin.

Exports																
Year	Total materials exported	Services in material exports	Total e xports	*Agricultural crops*	Potatoes	Grain, wheat, barley, oats	Vegetables, fruit, nuts, seeds	Horriticulture specialities	Livestock	*Minerals total*	Metallic ores	Crude petroleum	Broken stone or riprap	Gravel Or sand	Misc nonmetalic minerals, nec	
	semj/y	semj/y	semj/y			semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/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	7.19E + 15	1.13E + 21	3.30E + 21	1.82E + 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	1.33E + 18	1.04E + 21	3.05E + 21	1.68E + 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	2.41E + 18	1.11E + 21	3.26E + 21	1.80E + 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	5.55E + 18	1.18E + 21	3.34E + 21	1.99E + 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	2.30E + 18	6.16E + 20	2.49E + 21	1.75E + 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	6.54E + 17	7.51E + 20	2.50E + 21	2.27E + 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	7.78E + 17	8.64E + 20	2.81E + 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	5.26E + 17	4.60E + 20	2.29E + 21	2.29E + 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	8.59E + 17	4.94E + 20	1.77E + 21	6.31E + 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	1.08E + 18	7.21E + 20	1.78E + 21	5.94E + 20	
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	2.25E + 18	7.51E + 20	1.69E + 21	6.21E + 20	

Exports										
Year	*Forest products total*	Primary forest products, logs	Lumber and dimension stock	Wood products	All other materials	Services in agricultural products	Services in minerals	Services in forest products	Services in all other materials	Emmigration by age
	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y	semj/y
1988										0.00E + 00
1989										0.00E + 00
1990										0.00E + 00
1991										0.00E + 00
1992										0.00E + 00
1993										4.93E + 19
1994										6.78E + 19
1995	1.22E + 20	1.11E + 19	5.43E + 19	5.67E + 19	1.12E + 21	2.30E + 20	2.34E + 20	6.73E + 20	9.36E + 20	1.28E + 20
1996	1.32E + 20	1.21E + 19	5.89E + 19	6.14E + 19	1.21E + 21	2.25E + 20	2.17E + 20	7.28E + 20	1.01E + 21	6.44E + 19
1997	1.42E + 20	1.29E + 19	6.30E + 19	6.57E + 19	1.29E + 21	2.51E + 20	2.32E + 20	7.67E + 20	1.07E + 21	4.18E + 19
1998	1.38E + 20	1.31E + 19	5.83E + 19	6.63E + 19	1.33E + 21	2.76E + 20	2.34E + 20	6.96E + 20	1.13E + 21	3.73E + 19
1999	1.82E + 20	2.31E + 19	6.75E + 19	9.12E + 19	8.57E + 20	3.03E + 20	1.57E + 20	7.95E + 20	7.68E + 20	6.08E + 19
2000	1.74E + 20	2.12E + 19	7.06E + 19	8.19E + 19	7.65E + 20	2.66E + 20	1.83E + 20	8.19E + 20	6.81E + 20	6.21E + 19
2001	4.67E + 19	8.48E + 18	3.48E + 18	3.48E + 19	4.25E + 20	2.85E + 20	1.92E + 20	9.52E + 19	6.33E + 20	2.82E + 19
2002	2.70E + 19	4.99E + 18	3.40E + 18	1.86E + 19	4.46E + 20	6.72E + 20	1.46E + 20	6.17E + 19	6.07E + 20	6.66E + 19
2003	2.75E + 19	5.28E + 18	2.06E + 18	2.01E + 19	6.51E + 20	6.60E + 20	9.50E + 19	5.18E + 19	1.06E + 21	4.93E + 19
2004	5.40E + 19	1.21E + 19	9.84E + 18	3.20E + 19	5.18E + 21	5.80E + 20	2.36E + 20	1.45E + 20	6.22E + 21	0.00E + 00
2005	5.68E + 19	1.30E + 19	1.05E + 19	3.34E + 19	5.60E + 21	5.68E + 20	2.32E + 20	1.44E + 20	6.29E + 21	0.00E + 00

Table A-6
Summary of Annual Emergy Flows The San Luis Valley Co, 1995–2005.

Note	Symbol	Item	1995			1996			1997			1998			1999		
			Emergy E20 semJ	Dollars E6 $	2000 Em$ E6 Em$	Emergy E20 semJ	Dollars E6 $	2000 Em$ E6 Em$	Emergy E20 semJ	Dollars E6 $	2000 Em$ E6 Em$	Emergy E6 Em$	Dollars E6 $	2000 Em$ E6 Em$	Emergy E20 semJ	Dollars E6 $	2000 Em$ E6 Em$
63	R_A	Renewable sources used	32.4		1379.8	28.8		1227.1	36.5		1555.0	32.1		1367.0	32.2		1370.5
	R_1	Renewable elec. produced	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0
64	N	Nonrenewable source flows	12.6		535.6	16.7		710.0	12.8		544.2	14.3		607.4	11.8		501.3
	N'	Internal fuels and minerals extracted	47.6		2025.2	43.9		1869.6	47.0		2001.6	48.6		2069.6	34.6		1472.0
65	N_0	Dispersed Rural Source	1.2		52.6	5.3		227.1	1.3		56.9	2.5		104.7	1.3		57.0
66	N_1	Concentrated use, minerals, hydroelec.)	11.4		483.1	11.3		482.9	11.5		487.3	11.8		502.6	10.4		444.3
67	N_2	Exported without Use	43.2		1836.7	39.8		1695.7	42.7		1815.7	44.1		1877.5	31.5		1339.9
68	F	Imported Fuels, Min. + U, Elec.	6.9		294.6	7.3		309.0	7.1		301.5	7.3		310.6	7.3		312.2
69	F_1	Fuels and minerals used ($F + N_1 -$ Ren. &Elec.)	11.4		483.1	11.3		482.9	11.5		487.3	11.8		502.6	10.4		444.3
70	F_2	In valley minerals used ($F_1 - F$)	4.4		188.5	4.1		173.9	4.4		185.8	4.5		192.0	3.1		132.1
71	G	Imported Goods (materials)	13.3		566.7	13.9		591.1	14.6		620.1	14.8		630.1	18.2		776.3
72	I	Dollars Paid for all Imports		312.5			304.9			315.8			323.0			357.5	
73	I_1	Dollars Paid for Service in Fuels, Min, Elec		71.8			76.8			76.4			72.9			77.6	
74	I_2	Dollars Paid for Service in Goods		240.7			228.1			239.5			250.2			279.9	
75	I_3	Dollars Paid for Services		0.0			0.0			0.0			0.0			0.0	
76	I_4	Dollars Spent by Tourists		55.3			57.4			59.3			61.8			63.8	
77	I_5	Federal Transfer Payments		23.5			25.1			24.5			24.0			24.2	
78	P_2I	Imported Services Total	8.1		346.0	7.9		336.9	8.1		343.8	8.0		339.1	8.2		351.0
79	P_2I_1	Imported Services in Fuels, Min. Elec.	1.9		79.5	2.0		84.8	2.0		83.1	1.8		76.5	1.8		76.2
80	P_2I_2	Imported Services in Goods w/o fuels	6.3		266.5	5.9		252.1	6.1		260.6	6.2		262.6	6.5		274.8
81	P_2I_3	Imported Services	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0
82	P_1I_4	Emergy Purchased by Tourists	1.4		61.2	1.5		63.4	1.5		64.5	1.5		64.9	1.5		62.6
83	P_1I_5	Net Emergy Purchased by Federal $	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0
84	B	Exported Products w/o minerals	27.4		1164.0	31.5		1342.3	31.3		1331.0	30.8		1309.4	27.3		1160.3
86	E	Dollars Paid for All Exports		826.8			861.3			937.9			3536.1			962.1	
87	E_1	Dollars Paid for Goods w/o minerals		736.8			777.7			847.0			3420.2			867.1	
88	E_2	Dollars Paid for Minerals Exported		90.1			83.6			90.9			116.0			94.9	
89	E_3	Dollars Paid for Exported Services		0.0			0.0			0.0			0.0			0.0	
90	E_4	Federal Taxes Paid		0.0			0.0			0.0			0.0			0.0	
91	P_2E	Exported Services Total	20.7			21.8			23.2			23.4			20.2		
92	P_2E_1	Exported Services in Goods other than minerals	18.4		0.8	19.6		0.8	20.8		0.9	21.0		0.9	18.7		0.8
93	P_2E_2	Exported Services in Minerals	2.3		0.1	2.2		0.1	2.3		0.1	2.3		0.1	1.6		0.1
94	P_2E_3	Exported services	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0
95	X	Gross Regional Product (2000)		1161.8			1229.6			1354.1			1385.7			1486.0	
96	P_2	Emergy $ ratio for the US in 2000 semj/$	2.4E + 12			2.4E + 12			2.4E + 12			2.4E + 12			2.4E + 12		

Note	Symbol	Item	2000			2001			2002			2003			2004			2005		
			Emergy E20 semJ	Dollars E6 $	2000 Em$ E6 Em$	Emergy E20 semJ	Dollars E6 $	2000 Em$ E6 Em$	Emergy E20 semJ	Dollars E6 $	2000 Em$ E6 Em$	Emergy E20 semJ	Dollars E6 $	2000 Em$ E6 Em$	Emergy E20 semJ	Dollars E6 $	2000 Em$ E6 Em$	Emergy E20 semJ	Dollars E6 $	2000 Em$ E6 Em$
63	R_A	Renewable sources used	29.6		1261.6	30.3		1289.4	22.5		956.9	28.5		1211.7	31.0		1318.7	29.9		1272.5
	R_1	Renewable Elec. Produced	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0
64	N	Nonrenewable source flows	16.9		718.5	13.0		551.3	19.9		845.5	14.3		610.0	12.3		523.7	12.0		511.6
	N'	Internal fuels and minerals extracted	35.8		1524.9	41.3		1758.6	37.4		1593.6	23.7		1007.6	31.3		1331.3	31.1		1325.0
65	N_0	Dispersed Rural Source	5.9		251.2	1.2		50.5	9.1		387.0	4.0		171.4	1.5		62.2	1.3		53.3
66	N_1	Concentrated use, minerals, hydroelec.)	11.0		467.2	11.8		500.7	10.8		458.6	10.3		438.6	10.8		461.4	10.8		458.2
67	N_2	Exported without Use	32.6		1386.7	37.7		1602.4	34.7		1476.5	21.4		911.3	28.8		1225.0	28.7		1221.0
68	F	Imported Fuels, Min. + U, Elec.	7.7		328.9	8.1		344.6	8.0		341.5	8.0		342.2	8.3		355.2	8.3		354.3
69	F_1	Fuels and minerals used ($F + N_1 -$ Ren. &Elec.)	11.0		467.2	11.8		500.7	10.8		458.6	10.3		438.6	10.8		461.4	10.8		458.2
70	F_2	In valley minerals used ($F_1 - F$)	3.2		138.3	3.7		156.2	2.8		117.1	2.3		96.4	2.5		106.3	2.4		103.9
71	G	Imported Goods (materials)	21.3		905.3	21.3		905.3	22.0		937.0	15.3		650.3	16.5		704.2	17.0		721.8
72	I	Dollars Paid for all Imports		387.8			402.2			394.3			371.5			379.0			416.3	
73	I_1	Dollars Paid for Service in Fuels, Min, Elec		96.0			106.3			93.4			105.9			127.4			155.2	
74	I_2	Dollars Paid for Service in Goods		291.8			295.9			300.9			265.6			251.6			261.1	
75	I_3	Dollars Paid for Services		0.0			0.0			0.0			0.0			0.0			0.0	
76	I_4	Dollars Spent by Tourists		66.0			69.7			67.0			71.3			73.6			73.1	
77	I_5	Federal Transfer Payments		25.4			26.6			27.1			29.8			0.0			0.0	
78	P_2I	Imported Services Total	9.1		387.5	8.8		374.4	8.2		346.9	7.4		316.9	7.7		327.7	8.0		338.4
79	P_2I_1	Imported Services in Fuels, Min, Elec.	2.3		95.9	2.3		99.0	1.9		82.2	2.1		90.3	2.6		110.2	3.0		126.1
80	P_2I_2	Imported Services in Goods w/o fuels	6.9		291.6	6.5		275.4	6.2		264.7	5.3		226.5	5.1		217.5	5.0		212.2
81	P_2I_3	Imported Services	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0
82	P_1I_4	Emergy Purchased by Tourists	1.5		66.0	1.5		64.9	1.4		58.9	1.4		60.8	1.5		63.6	1.4		59.4
83	P_1I_5	Net Emergy Purchased by Federal $	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0
84	B	Exported Products w/o minerals	27.2		1155.6	19.9		845.8	17.7		753.6	18.5		786.2	62.3		2652.8	67.2		2861.6
86	E	Dollars Paid for All Exports		876.5			654.0			718.9			933.3			3536.1			3788.4	
87	E_1	Dollars Paid for Goods w/o minerals		808.7			566.1			648.5			885.9			3420.2			3667.0	
88	E_2	Dollars Paid for Minerals Exported		67.9			88.0			70.4			47.4			116.0			121.4	
89	E_3	Dollars Paid for Exported Services		0.0			0.0			0.0			0.0			0.0			0.0	
90	E_4	Federal Taxes Paid		0.0			0.0			0.0			0.0			0.0			0.0	
91	P_2E	Exported Services Total	19.5			12.1			14.9			18.7			71.8			72.4		
92	P_2E_1	Exported Services in Goods other than minerals	17.7		0.8	10.1		0.4	13.4		0.6	17.8		0.8	69.5		3.0	70.0		3.0
93	P_2E_2	Exported Services in Minerals	1.8		0.1	1.9		0.1	1.5		0.1	1.0		0.0	2.4		0.1	2.3		0.1
94	P_2E_3	Exported services	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0	0.0		0.0
95	X	Gross Regional Product (2000)		1590.9			1600.3			1630.2			1709.5			1849.8			1975.7	
96	P_2	Emergy $ ratio for the US in 2000 semJ/$	2.35E + 12			2.4E + 12			2.4E + 12			2.4E + 12			2.4E + 12			2.4E + 12		

Appendix. Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jenvman.2011.07.028.

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