MAXIMIZING SUSTAINABLE REGIONAL PRODUCTION: BALANCING WATER, ENERGY, AND CARBON

By

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2013

To my wife, Alicia, and my two girls, Anna and Ellie

ACKNOWLEDGMENTS

I wish to thank my advisor, Dr. Mark Brown, for his constant encouragement and guidance in this effort, as well as his great patience throughout the process. I also wish to thank my committee members, Dr. Matt Cohen, Dr. Joseph Delfino, and Dr. Alan Hodges for their contributions and insights to the development of this dissertation.

This work would not have been possible without the funding received through the NSF's AMW3 IGERT program. I would like to thank Dr. Brown for giving me the opportunity to be a part of this program. I would also like to thank my colleagues and friends in the IGERT cohorts for their friendship and encouragement along the way.

Finally, I would like to thank my wife, who has been so supportive and patient in this endeavor. Without her constant sacrifices, this dissertation could never have been written.

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BEA	United States Bureau of Economic Analysis
CO_2	Carbon dioxide
CH_4	Methane
DOE	Department of Energy
EFA	Ecological Footprint Analysis
EIA	Energy Information Agency
EIO-LCA	Economic Input Output Life Cycle Analysis
EPA	Environmental Protection Agency
ET	Evapotranspiration
FDEP	Florida Department of Environmental Protection
FLUCS	Florida Land Use Characterization System
FOKS	Fuel Oil and Kerosene Sales
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IMPLAN	IMpact analysis for PLANing
IO	Input-Output
IPCC	International Panel on Climate Change
ISO	International Standards Organization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MCDA	Multi-Criteria Decision Analysis
MEA	Millennial Ecosystem Assessment
$MTCO_2E$	Metric Tons of Carbon Dioxide Equivalents
NAICS	North American Industry Classification System

NASS	National Agricultural Statistics Survey
NPP	Net Primary Production
N_2O	Dinitrogen oxide
PRCIS	Peace River Cumulative Impact Study
SEDS	State Energy Data System
SES	Social-Ecological System
SFWMD	South Florida Water Management District
SIT	State Inventory Tool
SJRWMD	Saint John's River Water Management District
SWFWMD	Southwest Florida Water Management District
SWUCA	Southwest Water Use Caution Area
TEDB	Transportation Energy Data Book
UEV	Unit Emergy Value
UN	United Nations
USGS	United States Geological Service
VIUS	Vehicle Inventory and Use Survey

Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Doctor of Philosophy

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May 2013

Chair: Mark Brown
Major: Environmental Engineering Sciences

Regional sustainability is a question of increasing importance for regional planners with water and energy use and the production of greenhouse gases (GHG) emerging as chief constraints on achieving sustainability in the long term. Modeling the sustainability of regions is difficult as one must predict the impacts of cascading interactions within complex social-ecological systems. In this dissertation a combination of Economic Input Output Life Cycle Assessment and linear optimization methods was explored as a way to model regional sustainability. The Peace River region of central Florida was used as a case study for the model. The goal function of the optimization was to maximize regional economic output measure in both monetary and emergy terms. The model optimized regional production under water, energy, and GHG emission constraints by changing the area devoted to individual land uses. Each of the constraints was tested separately and in combination.

The results of the model showed that changing the mix of land uses could potentially provide a 1.8% increase in economic output, and a 6.2% increase in the supported population while maintaining groundwater and flood storage constraints. In addition, it was also shown that by including renewable energy land uses in the regional

analysis, a 20% reduction in greenhouse gas emission and a 20% reduction in fossil fuel could be achieved, and still provide a 1.3% increase in economic output and a 2.5% increase in regional population. This result suggests that increased sustainability for the region is attainable, and highlights solar photovoltaics and bioethanol from water efficient sorghum as key technologies for the region to pursue to achieve these goals.

This study makes several steps toward a better integration of regional sustainability modeling. The accounting of direct and indirect changes in resource consumption within regional land uses, the linearization of land uses in the optimization model, and the calculation of shadow prices for ecosystem services for the region are novel capabilities that can be used to give decision makers increased insight into how development decisions impact the regional system as a whole.

CHAPTER 1
MODELING REGIONAL SUSTAINABILITY

Introduction

Regional Sustainability

In 1987 the UN Brundtland Commission published its report *Our Common Future*[1] in which it stated that global societies should strive toward sustainable development, which they defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” Translating global initiatives to local levels remains a key issue for achieving sustainable patterns of humanity and environment since without sustainable action at all scales, the overarching global goal is not possible. Of particular importance is sustainable action at intermediate (regional) scales, since personal and national sustainable action seems more easily accomplished. At the regional level, managers and policy makers are assigned the task of trying to sustain prosperity and at the same time limit environmental degradation…a task not without its complexities because of the myriad interacting parts, limited data availability, and high uncertainty of regional systems.

The question of how to develop sustainable human societies may be one of the most pressing issues facing humanity today. The human population has grown exponentially over the last century[2] as has human consumption of natural resources,[3] resulting in the fact that today, humans have become one of the greatest forces driving change in the biosphere.[4] Several research groups have developed sustainability indicators which reveal that many nations of the world have exceeded sustainable levels of consumption of the earth’s resources.[5] At the same time, environmental indicators reveal that many of the earth’s support functions for humanity are being rapidly degraded.[6] As the earth nears limits to human carrying capacity, answering questions of efficient resource distribution, sustainable scale, and just distribution take on new urgency.[7]

While sustainability questions are being actively addressed with research and indicator development at the global scale,[8] few tools exist at the local and regional scale. At these smaller scales, different pictures of sustainability can emerge since regions vary dramatically in their available ecological resources, population levels, and consumption patterns. Some regions may already be over their local carrying capacity, while other regions may still have capacity for growth. If regions are to negotiate a sustainable pattern in the coming years they will need appropriate tools to identify environmental constraints, and reveal which development options increase long term productivity, and which will decrease long term productivity.

Regional Scale

Methods for measuring sustainability developed at the global and national scale have been applied at regional level as well.[9] But while these methods can provide a measure of the sustainability of the region, they do not answer some of the critical questions managers and policy makers need to understand about the path a region should follow to become more sustainable. Methods are needed at the regional level that can compare various development options, and that can suggest a development path that leads to a productive yet sustainable system. Regional managers need to be able to understand the tradeoffs the region faces in making sustainable development decisions. Most current sustainability analysis methods are far more descriptive than they are prescriptive.

Measuring Sustainability

To determine if a region is sustainable, data is needed on the flows of different kinds of resources, and the environmental impacts of those flows. Environmental accounting methods have been developed to try to account for all the flows within complex socio-ecological systems. Life Cycle Assessment methods have been used to track both resource flows and their associated impacts within systems.[10] Often they are used to provide sustainability comparisons between competing development options. A combination of Life Cycle Analysis with Economic Input Output modeling (EIO-LCA) has resulted in models of national resource use and their associated environmental impacts.[11] EIO-LCA models have been developed at the national and state,[12] and the multi-state level,[13] but they have not been developed below the state level due to difficulties in collecting all the required data. While these models are very successful at tabulating resource flows and pollution impacts generated within an economy, they do not integrate all the environmental, economic, and social criteria into a sustainability model or metric. While they are able to account for interactions between economic industries, they don't account for the capacity of a region to absorb the environmental impacts that are produced.

There are two broad approaches used to try to integrate all the environmental, economic, and social aspects to determine the sustainability of socio-economic systems. The first approach is to try to put all resources on a commensurate scale. Emergy Synthesis and Ecological Footprint Analysis (EFA) integrate the various aspects of sustainability by expressing the system's production and absorption capacity in common terms. A second approach to integration is to develop a non-commensurate set of sustainability criteria, and then assign a weight to each criterion in a combined index. Sustainability analysis using Multi-Criteria Decision Analysis (MCDA) models relies on this second approach.

Emergy Synthesis

Emergy accounting evaluates all resource flows on the basis of the equivalent energy of solar energy which was required to generate the resource flow.[14] This embodied energy basis allows emergy to account for both ecological and economic aspects of systems in commensurate terms. Emergy synthesis is a valuable tool in that it can be applied at any scale. It has been applied to measuring and comparing the sustainability of systems at national,[15,16] state,[17,18] and regional watershed[19,20] levels. An Emergy Sustainability Index (ESI) has been defined as an integrated metric to evaluate the sustainability of systems.[21] The index accounts for the level of system production that is attained by importing emergy sources as well as the associated load placed on the environment. The ESI accounts for both the level of production of the system and the environmental impacts in a single aggregated metric. The ESI can give valuable insight into how far away from long term sustainability a system is currently. However, the synthesis process does not provide tradeoffs between different organizations of the region. In addition, emergy synthesis relies on highly aggregated regional flows, and has a unique algebra that requires careful analysis to avoid double counting.[22] The more regional flows that are included in the regional model, the more difficult it can be to track emergy flows without double counting.

Ecological Footprint Analysis

Ecological Footprint Analysis was initially introduced in the 1990s as a way to calculate the carrying capacity of social-ecological systems[23]. EFA selects land area as the integrating factor in its sustainability analysis. It calculates the land area required to provide the resource flows required for the population of a region, as well as provide all the land area required to dissipate wastes. EFA compares the total land area required per capita to support a region to the global average of productive land per capita. Systems that are above the global carrying capacity are considered beyond sustainable limits. This methodology puts sustainability into terms of the amount of land area that is being used to support the system which is easily understandable for most people. The method has been applied widely to socio-ecological systems at various scales, including global[24], national[25,26], and regional[9,27] scales.

The EFA approach integrates ecological limitations into its evaluation, but it faces the same shortcomings as emergy synthesis in that it does not give regional managers insight into potential development paths. It helps the manager know where the system is relative to a sustainable level, but does not help regional managers know how to more efficiently allocate resources.

Multi-Criteria Decision Analysis

The second approach to addressing the problem of disparate sustainability metrics is to combine multiple metrics using a weighting scale. This approach can be used with MCDA to perform sustainability analysis.[28] MCDA is able to combine disparate measures of economic, environmental, and social sustainability goals as criteria in an optimization model. The inclusion of an optimization model in MCDA allows for analysis of different resource allocations and development scenarios, making it a much more forward-looking approach than other sustainability analysis methods. Several MCDA models have been built to address sustainability issues at the regional scale.[29–31]

However, in order to integrate the various sustainability criteria, MCDA relies on a priori weighting of the criteria to generate a value function that is then maximized in the optimization.[32] Either regional stakeholders or modeling experts must make the determination of which sustainability metrics are most important before the model is run, or what minimum levels they must achieve within each criteria. What is then actually maximized in the model is the value function that was defined by the researchers by weighting the various sustainability measures. This ranking of which goals are most important defines what the end goal of the system should be, and the optimization finds a solution that is closest to that goal. The drawback of this approach is that not all of the sustainability measures are necessarily simultaneously satisfied. The weighting of the value function determines which sustainability measures will be met, and which will not.

Maximum Sustainable Production

Regional modeling methods are needed that are simple enough for regional managers to use and adapt to their particular regional level. The models should address gaps in data, account for the interdependencies of social, economic, and environmental factors, and be able to model the trade-offs between these factors. A novel combination of modeling techniques is introduced in this dissertation in order to address shortcomings of previous sustainability modeling.

One of the first questions to be answered in order to construct such a modeling tool is the goal for the system. While sustainability is a desired outcome for the system, sustainability on its own is not a metric for human welfare. Minimizing the human population might achieve system sustainability, but if high value is placed on human society, this is a less desirable solution than other options. The overall goal for this modeling effort is defined as maximizing the long term production of the system.

Maximum sustainable production, then, requires that the level of production can be maintained for future generations and should be considered as an average production level over several decades to allow for long term variation in environmental variables and natural disturbance cycles.

Defining and Valuing Production

All social-ecological systems provide multiple products as output. Not all products are equally important or desirable, and so some method of valuing system products is needed. In this dissertation, two methods are used to evaluate regional production. The first uses monetary value as measured in the price paid for all goods and services produced. A common measure of a social-ecological system's production is the Gross Domestic Product (GDP), and it is the primary valuing tool used today in social systems.

A second valuation measure is the emergy evaluation method.[14] Emergy is a donor based value system proposed by H.T. Odum to capture both economic and environmental values. It is a quality-corrected measure of the available energy that was required to make something, expressed in common units of solar emJoules. System empower is a measure of the total emergy flowing through a system per unit time, and it can be used as a measure of total system production.

Defining System Boundaries

As in any system analysis, the boundaries of the regional system must be defined. There exist many criteria that could be used to choose a regional system boundary. In this dissertation research a close match between physical and social system boundaries was needed. The surface watershed was chosen as the boundary for the physical system. The boundary for the social system was chosen to match the watershed boundary as closely as possible using political county boundaries that approximated the watershed area. This was a convenient boundary because both the physical and economic data required for a regional system model are often reported at the county level.

Limiting Factors

No model can completely capture all the interactions of a complex system. A good model economizes by selecting the most important factors, and may ignore secondary factors. For a model of system production, factors that are likely to be limiting are considered most important. Three critical resource categories that require trade-offs between economic and ecological production are chosen for this model: water, energy, and land area. In addition, the regulation of carbon as a greenhouse gas is modeled as a globally important ecosystem service that may be regulated in the future and comprise a part of system constraints.

Energy is a fundamental input into all production processes. For change to happen in a system, energy must be supplied. Energy flows within the environmental system are derived from the energy that drives the biosphere. Energy can also be obtained from outside the system in exchange for goods and services produced within the system. Current global energy supplies and economics allow this to happen at a net energy gain for many regional systems, and this strategy is heavily employed to raise a region's carrying capacity beyond that of the native environmental energies. The energy mix of a region, and the future availability of energy sources are important considerations in determining a maximum sustainable production of a region.

Water is a critical material component of almost all production processes. In many regions of the world, water is already a limiting factor in social-ecological systems.[33] Water, however, is rarely imported from outside a watershed because of high transport cost and high political barriers. Regions often instead draw on available water stored in underground aquifers. This water is recharged slowly, and pumping it faster than recharge results in dropping water levels. Water has the potential to become even more constraining for regions in the future as these storages of groundwater are extracted faster than they are replenished. Water in the system is considered to be consumed once it leaves the boundaries of the system, either by evapotranspiration, river flow, groundwater flow, or embodied in physical products that are exported.

Land area can also be a limiting resource in a region. Regions need to understand and manage the tradeoffs between regional growth and consequent land use changes. Land use change alters the level and mix of ecosystem services that are provided by a landscape. Ultimately long-term sustainability will require that regions provide production-limiting ecological resources and services from within instead of relying mainly on outside sources or energy intensive replacements driven by non-renewable resources. Therefore, achieving a maximum sustainable level of regional domestic production will require finding a balance between the production of the economic and ecological sectors that maintains the region’s natural capital and the flow of ecosystem services that come from that capital.

Greenhouse gas emission and carbon sequestration are also considered within the model. The greenhouse gases considered are carbon dioxide (CO_2), methane (CH_4), and dinitrogen oxide (N_2O). Carbon is not considered a limiting materiel in regional production, but rather its storage represents an environmental service that is provided by the region to the global system. The storage of carbon helps to control greenhouse gas concentrations at a global scale. The impacts of this sequestration are not confined to the region in question, but impact the wider biosphere and have far reaching consequences for climate regulation. Allocation of globally important ecosystem services to regions is a matter of current debate, and includes questions of just distribution of resource consumption. The model deals with allocation by allowing for external policy directives to set allowable emission levels.

The research in this dissertation sought find and maintain the maximum sustainable regional product by developing an input/output model of a regional social-ecological system that allows the production of that region to be explored in terms of its limiting factors. The model identified the maximum sustainable regional product based on an extrapolation of the current system's organization and then was used to predict changes to that maximum level due to changes in the region's land use. Energy and water provision were selected as the most important limiting factors of production within the model. Greenhouse gas (GHG) emissions were also considered as a system waste product that has impacts beyond the scale of the region itself. These three factors were used to develop sustainability constraints for the region.

Study Area

This study was focused on the Peace River watershed in southwestern Florida. This watershed has several characteristics that make it an interesting case study. The Peace River watershed lies within the Southwest Water Use Caution Area (SWUCA). SWUCA is a 5,100-square-mile, eight-county area in southwest Florida where depressed aquifer levels have caused saltwater to intrude into the aquifer along the coast, contributed to reduced flows in the upper Peace River, and lowered lake levels in portions of Polk and Highlands counties.[34] Development within the region has tapped available water resources to the point where restrictions have been issued on water supply and water quality has been adversely affected. The question of the sustainability of current water use is actively being addressed in the region.[35] The Peace River also has significant areas of phosphate mining within its boundaries. By state law, phosphate lands mined since 1975 must be reclaimed after the mining and dewatering process is complete. This represents over 10% of the land area that could shift its land use in the future. Developing this reclaimed land with appropriate land uses could potentially improve the long-term sustainability of the system.

Conclusion

This chapter has laid out the purpose of the regional modeling effort, given an overview of the applicable modeling methods, and discussed some of the assumptions that must be made in the creation of a regional sustainability model. Chapter 2 develops a regional Economic Input-Output Life Cycle Analysis (EIO-LCA) model that predicts changes to energy and water consumption and GHG emission due to changes in economic activity within the region. Chapter 3 develops a regional land use optimization model that incorporates the EIO-LCA data developed in Chapter 2. The optimization model is used to maximize the region's total production, subject to a set of sustainability constraints. Chapter 4 applies the resulting optimization model while considering future development options. The impact of renewable energy land uses on the region's maximum sustainable production is evaluated. The goal of this effort is to make steps toward a better integration of ecological and economic modeling, with the hope that it will give decision makers increased insight into how development decisions impact the regional system as a whole.

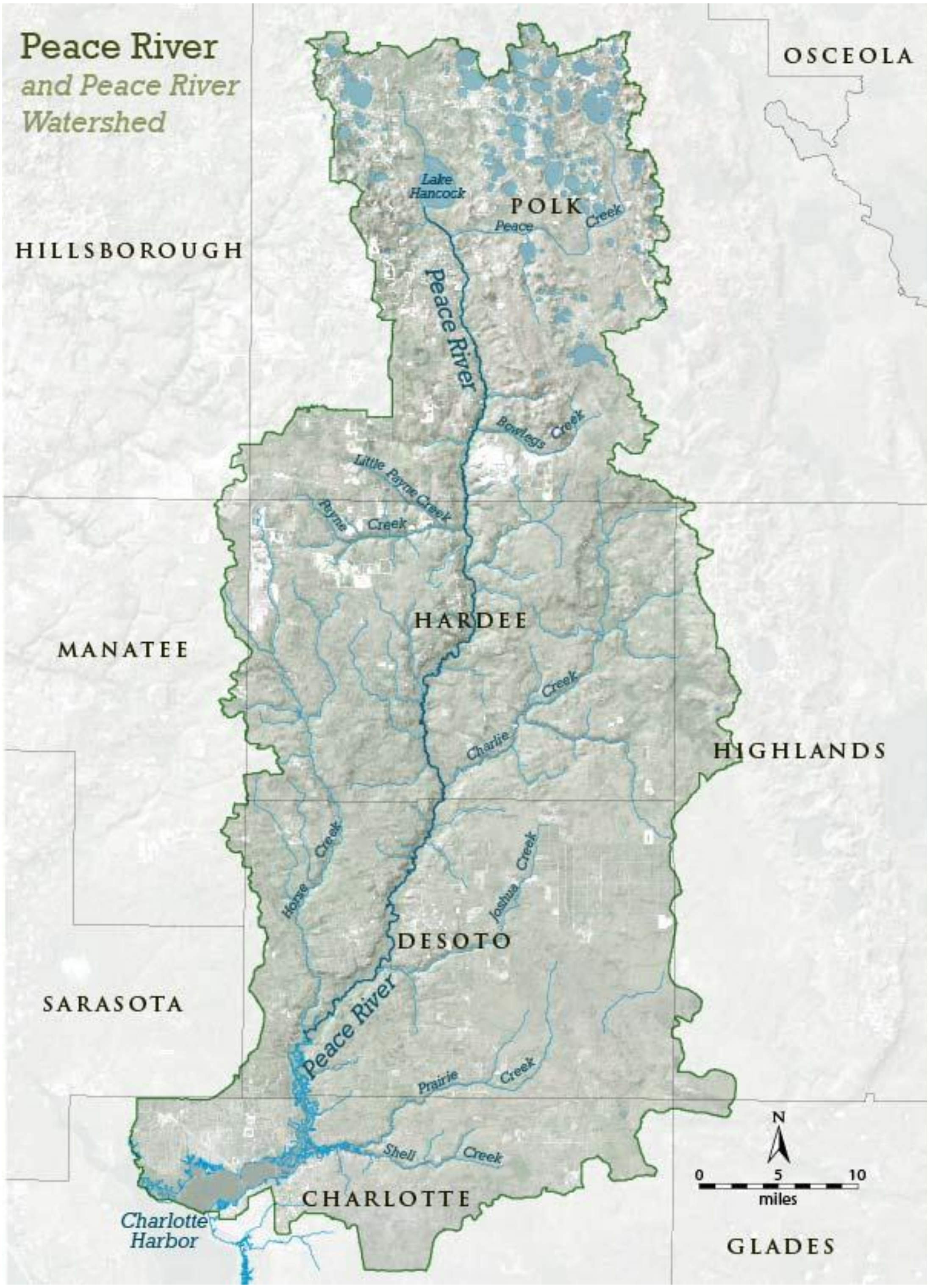

Figure 1-1. Peace River watershed and region. Available from http://www.swfwmd.state.fl.us/waterman/lakehancock/img/peace-river.jpg

CHAPTER 2
DEVELOPMENT OF A REGIONAL EIO-LCA MODEL

Introduction

This chapter outlines the construction of a regional EIO-LCA model for both the state of Florida and for the Peace River region within Florida. The model is built using a combination of a commercially available regional economic input-output model and publicly-available data on regional water, energy, and greenhouse gas emissions. The result of the Florida and Peace River regional models is a list of resource intensities for all the model industries in the regions. The regional EIO-LCA model is used to calculate direct and indirect input requirements for all the industries in the model. This input information is then used to calculate an emergy signature for each industry within the model, accounting for both direct and indirect resource consumption.

Methods

Economic Input Output Life Cycle Assessment

Environmental accounting techniques have been developed to track flows of resources through economic network interactions. Life Cycle Assessment (LCA) is concerned with quantifying both resource inputs and environmental impacts of waste products for the entire life cycle of a product, from cradle to grave.[10] A Life Cycle Inventory (LCI) traces material and energy flows used as inputs in a production chain. Two LCA methods have been developed and widely applied. Process-based LCA is a bottom up method of accounting. It relies on an in-depth knowledge of the inputs used in a production process, and then links these inputs back to their own production processes to form an entire production chain. It relies on large databases, and requires a boundary to be set on how far back the supply chain will be followed. Economic Input

Output Life Cycle Assessment (EIO-LCA) is a top down assessment method.[36] It uses an economic input-output (IO) model to capture information about all the purchases required from other industries to make that industry's product. Since it encompasses the entire economy, it accounts more completely for resource flows. However, it suffers from accuracy in that it must aggregate industry production functions and use averaged resource flows. EIO-LCA models have previously been developed at the national and also at the state level.[12] However, this type of model has yet to be applied at the watershed scale.

EIO-LCA models are based on economic input output models which were originally developed by Wassily Leontief in the 1930s. An IO model separates the economy into a set of industry sectors by aggregating businesses with similar end products. A transaction matrix is developed that uses these sectors as row and column headings. Financial transactions are represented as row industries selling products to column industries. Reading across a row gives the sales of goods and services from one industry to all other industries in the economy, while reading down a column gives all the purchases made by that industry in order to produce its product. Several columns are added beyond the transaction matrix to represent final demand, the goods and services that are sold to end consumers who are not producing additional goods and services. Final demand categories include the end consumption of the population, government organizations, and exports. Several rows are added below the transaction matrix to represent value added transactions which include the purchasing of labor, payment of rents and taxes, and profits. The transaction matrix, **Z**, captures the flows of money paid for goods and services throughout the economy for the year of the data.

Leontief recognized that if the production relationships in the matrix were assumed to remain linear, a predictive model could be developed that would calculate the change in total economic activity that would occur for any given change in the final demand for a product. The first step in creating the model is to define the technical coefficient matrix, or the **A** matrix. The **A** matrix is defined by starting with the transaction matrix **Z** and dividing each column in the transaction matrix by its respective column total as shown in equation 2-1.

$$a_{ij} = z_{ij}/x_j \tag{2-1}$$

In this equation, a_{ij} is the technical coefficient, z_{ij} is the transaction, and x_j is the column total. Reading down a column of the **A** matrix gives the production function for a particular column industry, showing how much it must purchase from each industry in the matrix in order to make a dollar's worth of its own product. Reading across a row of the **A** matrix reveals the sales output that row industry must provide to each industry in the matrix. If there is an increase in final demand for a product in the economy, the industries that make that product must produce that additional final demand and their suppliers must produce more of the goods and services required to supply the industry producing final demand. Changes to the final demand of the whole economy can be represented as a vector, **f**. The additional production required to meet the new final demand is then (**I** x **f**)**,** where **I** is the identity matrix. The additional production of the direct suppliers needed to supply the final demand producing industries can be represented as (**A** x **f**), and the total change in economic activity, **x**, is then **x** = (**I** + **A**)**f**. This equation captures the change in output due to the additional final demand and the additional production of its first level suppliers, also called its direct inputs. However, there are also indirect inputs to consider. The suppliers of the suppliers must also provide more output, and so the effect of the new final demand ripples through the network of the economy causing additional production in each successive level of suppliers. The total direct and indirect requirements are given by equation 2-2.

$$\boldsymbol{x} = (\boldsymbol{I} + \boldsymbol{A} + \boldsymbol{AA} + \boldsymbol{AAA} + \boldsymbol{AAA} + \cdots)\boldsymbol{f} \tag{2-2}$$

In matrix algebra, this expansion series is equal to the quantity $(\mathbf{I}\text{-}\mathbf{A})^{-1}$ which is termed the Leontief matrix. The change in output is expressed by equation 2-3.

$$\boldsymbol{x} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{f} \tag{2-3}$$

Input-output modeling is based on several simplifying assumptions that are important to understand, because they reveal the approximate nature of the model:

- Constant returns to scale: The model must assume that an industry's production functions are linear; this is to say if any additional output is required, all inputs will increase in linear proportion. This is a good approximation over a limited range of change, but large changes in production may introduce different efficiencies of scale.
- No supply constraints: The model must assume that an industry has unlimited access to raw materials, and that these materials are available at close to the same price. This ensures that an industry's output is limited only by the demand for its products.
- Homogeneous sector output: The model assumes that the proportions of commodities that the model industries produce remain the same, regardless of total output. An industry won't increase the output of one product without proportionately increasing the output of all its other products.
- Industry technology assumption: This assumption comes into play when data is collected on an industry-by-commodity basis and then converted to industry-by-industry matrices. The model assumes that an industry uses the same technology to produce all its products. In other words, an industry has a primary or main product and all other products are byproducts of the primary product.

The economic IO model is based on monetary data, and these monetary flows are related through price to the flow of physical goods in the economy. Several research groups have developed methods of including physical flows in IO models. The EIO-LCA model developed by Hendrickson et al.[37] includes physical flows by supplementing the IO matrix with an external set of resource intensity vectors. Resource intensities are defined by dividing the independently reported resource use of an industry by the monetary output of that industry, and so they have units of resource/$ output. This operation is performed for each industry in the model resulting in the resource intensity vector, **r**, shown in equation 2-4.

$$r_i = resource\ use\ /\ x_i \tag{2-4}$$

The symbol r_i is used to denote the resource use in sector *i*, and x_i is the total dollar output for sector *i*. A vector of the total resource use, **b**, can be obtained by multiplying the total economic output by the resource intensities as shown in equation 2-5.

$$\Delta\mathbf{b} = \mathbf{R}\Delta\mathbf{x} = \mathbf{R}(\mathbf{I} - \mathbf{A})^{-1}\Delta\mathbf{f} \tag{2-5}$$

R is a matrix with the elements of the vector **r** along the diagonal and zeros elsewhere, and **x** is the vector of relative change in total output based on an incremental change in final demand. This methodology can be used for both input resources such as water and energy use, or for waste products such as GHG emissions.

The EIO-LCA framework can be used to track resource use in the economy, and can be used to predict the change in resource requirements as the demand changes. In addition to the assumptions of the economic input output model, the EIO-LCA model assumes that the resource/dollar output ratio remains constant as production scales up and down, and that no resource substitution is carried out. These simplifying assumptions allow an estimate of the total resource requirements associated with changes in a region's production.

Economic Model

The regional economic model was created using a commercial economic impact analysis software developed by MIG, Inc. known as the “IMpact analysis for PLANing” (IMPLAN) software. IMPLAN uses as its base the national benchmark input-output (IO) models created every five years by the U.S. Bureau of Economic Analysis (BEA). In order to create regional economic models, IMPLAN uses the national technical coefficients matrix and combines that matrix with regional industry output totals and regional value added data, which include labor costs and taxes. This modeling method requires the assumption that each industry’s mix of material and service purchases is proportional to the purchases of the corresponding national level industry. Since production functions are rarely available for regional industries, this approximation is necessary to complete the model, and is generally considered to be acceptable because the technology to produce a given set of goods or services is likely to be fairly similar throughout the U.S. The output of IMPLAN’s regional model is a regional transaction matrix that gives monetary values for all of the region’s intra-industry purchases. The IMPLAN transaction matrix and its associated databases are used as the economic model for the regional EIO-LCA. IMPLAN’s 2002 dataset was used, which divides the economy into 509 input-output industries. Two models were created within the software, an economic model of Florida, and a model of the four-county area that encompasses the Peace River watershed, and includes Polk, Hardee, De Soto, and Charlotte counties.

Resource Consumption Data

Resource consumption data for the regional economy was obtained from reports by state and federal agencies. This data was reported at various levels of aggregation, so a mapping of categories was created between the 509 industries of the IMPLAN model and the reported resource consumption categories so that resource use could be allocated across all industries.

Development of water intensity vectors

Water intensities were previously developed for 428 industries at the national level for the EIO-LCA database.[38] The authors of this study pointed out that these values are national averages, and should not be used for regional analysis because of the potential for large differences in water requirements between different regions. Using regional water use data, water intensity vectors were developed for both Florida and for the Peace River region. The 2000 USGS report on state-wide water use[39] was used as the data source for the Florida regional model. Total water use by state has been estimated by the USGS every five years from available data sources, which include the state's water management districts, water use permits, and water utility reports. The USGS data was reported in more highly aggregated categories than the regional economic data, and a methodology was developed to allocate it to the individual industry level. The allocation method proceeded in several steps. First, water use was assigned directly to any industry that was reported at the same level of aggregation as the economic industry. For the state of Florida, direct assignment of water use was made for electric power generation, 14 agricultural industries, 4 mining industries, 1 recreational industry, and also for residential use. The remaining water use was assigned to the aggregated sectors reported by the regional data sources, and then allocated within those sectors to individual industries using the same allocation proportions observed in the national EIO-LCA model. The calculations employed in the allocation method are explained in greater detail in Appendix A.

A water use intensity vector was also developed for the Peace River region. Water use data for 2002 was obtained from the Southwest Florida Water Management District's Estimated Water Use Report.[40] The water management district reports on water use only within its boundaries, while portions of Polk and Charlotte county lie outside the SWFWMD. Correction factors were developed in order to scale water use to represent the full county area. These factors were created by comparing year 2005 county level data obtained from the USGS Florida report[41] with year 2005 data from the SWFWMD.[42] Data for Polk and Charlotte counties for 2002 was then scaled by these correction factors to estimate total water use in the counties. Within the Peace River region, self-supplied agricultural, mining, citrus processing, phosphate mining, power generation, and residential water use were matched directly with their corresponding industries. Publicly-supplied water and the remaining self-supplied water were allocated among the remaining industries using the same methodology developed for the Florida water use intensity vector. Water use for each industry was then divided by the economic output of each industry to create the water use intensity vector.

In addition to total water use intensity, intensity vectors were developed for both groundwater and surface water use. Since not all the water that is withdrawn from the environment is considered to be consumed within the economic activity to which it is allocated, a "consumed" water intensity vector was also developed. Water that evaporates during use or is embodied in products in the course of economic use is considered to be consumed as it is diverted from any further surface and groundwater interactions. The "unconsumed" water is returned to the regional system as wastewater flows. Florida state averages of water consumption for various economic activities were used to calculate consumed water intensities for the region.[39]

Development of energy intensity vectors

National level energy intensity vectors were previously developed by the Carnegie Mellon University Green Institute.[12] These energy intensity estimates were made by allocating data on U.S. fuel use to 428 industry categories. Directly reported data was used wherever possible, and economic allocation was used when further allocation was required in accordance with ISO 6000 standards.

For this effort, an energy intensity vector was developed for the state of Florida. Data from the EIA's State Energy Data System (SEDS) report was used to set the state's total energy use in the power, industrial, commercial, transportation, and residential categories.[43] Available public data sets were then used to allocate this energy use among the 509 industry categories of the regional economic model. Energy use was directly allocated for all industries in which data was available for the allocation. These industries included the electric power generation, transportation, agriculture, mining, and residential sectors. Whenever data was reported at a more aggregated level than the individual industries within the economic model, it was first allocated to the lowest aggregated sector possible. Energy use within these aggregated sectors was then allocated to individual industries in the same relative proportion as the allocation of the national energy intensities within that same sector. Finally, the energy input for each industry was divided by the economic output of the electric power industry to give the energy intensity.

Energy consumed for electric power generation was the largest energy use category, comprising 43% of Florida's total energy use.[43] Data from EIA's Electric

Power Annual State Data Tables[44] was used for the state's consumption of coal, natural gas, petroleum fuels, biomass and waste, nuclear, and other alternate energy sources. Private and government power generation and distribution industries were combined to form a single electric power industry for the model.

Transportation was the second largest category of energy use, accounting for 31% of Florida's total energy use. Florida's total consumption of all transportation fuels was obtained from the EIA SEDS database.[43] In the SEDS database, all fuels used throughout the state for transport and mobility applications were included within the transportation category, including fuel used by non-transport industries to provide their own transportation, as well as fuel used for residential transport. The national economic model, on the other hand, had ten transportation industries that included only the industries that provide transport as a paid service to other industries. In order to allocate transportation fuels to the economic transport industries, a methodology was developed using three different fuel use data sets. First, fuel use was allocated based on fuel type using EIA's Fuel Oil and Kerosene Sales (FOKS)[45] data set. Allocations were made from this data set to the air, rail, and water transport industries. Next, highway fuels were allocated using a combination of DOE's Transportation Energy Data Book (TEDB)[46] and the BEA's Vehicle Inventory and Use Survey (VIUS).[47] The TEDB was used to allocate fuel use by vehicle type, and the VIUS was then used to allocate truck vehicle types to specific industries. Energy intensities were developed for the truck transport, and ground passenger transport industries from this data. In addition, residential transportation fuels were allocated to the residential sector. All remaining transport fuel use was allocated to the commercial and industrial sectors. The details of these allocations are included in Appendix B.

Energy intensity vectors for Florida agricultural industries were developed using the 2002 Agricultural Census.[48] The census reported energy expenditures for each state, using the North American Industry Classification System (NAICS), which was then mapped to the IMPLAN industry categories. In the 2002 census, all fuel expenditures were reported in one aggregated category. However, in the 1997 Agricultural Census,[49] fuel costs were reported in separate categories for natural gas, gasoline, diesel, and liquefied petroleum gas. The 1997 data was used to estimate 2002 fuel consumption for each fuel type by assuming that the percentage of expenditures on each fuel remained constant across both years. Fuel consumption for 2002 was then calculated by multiplying the resulting 2002 fuel expenditures by 2002 fuel prices[50] for industrial uses in Florida for 2002.

Residential energy consumption was reported directly in the EIA SEDS database for fuels delivered directly to households.[43] The transportation fuels that remained after industry fuel use allocation were also allocated to the residential sector. In contrast with other sectors, the energy intensity for the residential sector was calculated in units of energy per capita as the residential sector's energy use was assumed to scale linearly with population.

Energy intensities for Florida mining operations were developed using USGS data on the physical amount of minerals mined in Florida[51] and data on the national average mining fuel use per unit of mined materiel as reported by NAICS category for several mining industries in the year 1997.[52] These energy intensities per ton of mined material were assumed to remain constant over time, and were used to estimate the energy use for three major Florida mining industries: phosphate, limestone and sand, and mineral mining.

All remaining fuel use was allocated either to the industrial or the commercial sector. The industrial sector included agriculture and mining services, forestry, utilities other than electricity generation, construction, and manufacturing. The commercial sector included wholesale, retail, professional services, and government industries. No data was available at the state level to develop energy intensity measures for these individual industries. The state's remaining energy use was then allocated in proportion to the allocation of the national energy intensities within these sectors.

Florida's regional energy intensities were adopted for the Peace River region, as there were no data sets available for energy allocation at the county level within Florida. The only exception was within the electric power generation industry. Data on power plants within the region and their fuel use was obtained from the U.S. EPA's e-grid database.[53] Data from the year 2000 was used as no data was available for 2002. The commercial generation facilities that lie within the Peace River region were selected from the database. Industries that self-supply electricity were excluded from the power sector calculations, as they were considered to consume all the electricity they generate internally, and not contribute to the region's marketed electric power supply. The Florida energy intensity vector was updated with the Peace Region's electric power energy intensity to create the region's energy intensity vector.

Development of a GHG emission intensity vector

GHG emission intensities were developed for Florida using the EPA's State Inventory Tool (SIT).[54] The SIT was developed to assist states in performing a standardized reporting of greenhouse gas emissions based on the International Panel on Climate Change's methodology.[55] The tool consists of a series of Excel spreadsheets that accept data inputs on state fuel use and industrial production activities. The tool calculates the emissions of different greenhouse gases, including carbon dioxide (CO_2), methane (CH_4), and nitrogen dioxide (N_20) emissions which were the greenhouse gases considered for the regional model. The SIT provides default data by state for energy consumption, emission activities, and GHG emission rates. Florida's estimated emissions were tabulated using the default GHG emission rates specified for the state of Florida for the year 2002. Each industry's fuel consumption from the regional EIO-LCA model was multiplied by the default emission rate to arrive at the overall emissions for the industry. The emissions were then divided by the economic output of each industry to calculate the emission intensity vector. Four emission intensity vectors were developed, one for carbon dioxide (CO_2), methane (CH_4), and nitrogen dioxide (N_20) emissions, and one for total GHG emissions. All emissions intensities were reported in units of metric tons of CO_2 equivalents ($MTCO_2e$). Only the emissions associated with fuel use were included in the regional EIO-LCA model, land use emissions were accounted for separately within the optimization model developed in Chapter 3.

Development of a value-added intensity vector

A value-added intensity vector was developed for Florida and the Peace River regions. Value-added measures the value of industry output paid directly to human inputs in the production process. Value-added categories included in the model were labor payments, profit for owners, and rent income from the IMPLAN database.[56] This total value-added for each industry was divided by the total economic output of the industry to give a value-added intensity in units of dollars of value added per dollar of economic output. This vector is later used in the calculation of indirect labor inputs in each industry.

Model Construction

The economic data for each region was combined with the corresponding set of regional resource intensity vectors to create the input tables for the regional EIO-LCA model. The model was constructed as a macro running in an Excel spreadsheet. The inversion of the region's transaction matrix was performed within Matlab and then imported into Excel. The regional EIO-LCA model was used to calculate the direct and indirect resource use for a one million dollar change in production for each of the industries in the model.

Emergy Evaluation of Regional Industries

Emergy intensities were calculated for each individual industry in the region using the output of the regional EIO-LCA model. The output of the EIO-LCA model included both the direct and indirect resource consumption for water, energy, and labor inputs. In the emergy calculation, each resource component was multiplied by its respective unit emergy value (UEV). UEV's for ground and surface water were obtained from a recent evaluation of Florida's water resources,[57] while UEV's for fuels were obtained from recent calculations of the global average UEV's for fossil fuels.[58] Electricity was not included as a direct energy input, but was included as an indirect energy input based on the purchases each industry made from the electric power generation industry.

In order to complete the emergy valuation, the emergy of labor within the region had to be calculated. This was done by summing the emergy of the direct water and fuel inputs used to support the residential population. In this case, electricity was included as a direct energy input, as no indirect inputs were considered for the residential sector. The residential emergy was then divided by the total value-added provided by the regional labor force. The result was an average labor UEV in units of sej/$M. The emergy of labor for each individual industry was then calculated by multiplying this average labor UEV by the total value-added for that industry. The emergy of indirect value-added calculated in the EIO-LCA model was used to represent the emergy of service contributions to each industry, as it captured the payments made to labor in the purchases from other industries.

Results

Water Intensities

The water intensities for Florida that were calculated by direct allocation to an industry are reported in Table 2-1. This table includes a comparison of Florida's intensities with the national water use intensities. Florida's agriculture is shown to have significantly higher water intensities than the national average in vegetable, fruit, greenhouse, sugarcane, and other crop production. Florida's cattle industry is a notable exception in that it has a lower water intensity than the national average. Florida's mining sector is more water intensive, likely due to the need to extract groundwater to facilitate surface mining. Florida's power generation water use is higher than the national average as well. Finally, the recreation industry is also much more intensive than the national average due to golf course irrigation.

Table 2-2 shows the directly allocated water intensities for the Peace River region. In contrast to Florida, the water intensity of the Peace River region's vegetable and fruit production is lower than the national average. Mining water intensities remain higher than the national average, as does the region's recreation water intensity. Water intensity for the power generation sector is shown to be lower than the national average.

Energy Intensities

Electric power generation is the largest energy use in Florida and the Peace River region, and this category makes the largest impact in differentiating national and regional energy intensities. The energy intensities for electric power generation were directly allocated for both Florida and the Peace River region, and are reported in Table 2-3. Fuel intensities were calculated for coal, natural gas, petroleum, waste and biomass, and alternate fuel sources, which included nuclear, hydro, wind, and solar electricity. These intensities are compared to the national average intensity, showing significant differences in fuel sources between regions. Florida's alternate power source is almost entirely nuclear power, with a very small percentage from hydroelectricity. Florida has a much higher use of petroleum and nuclear power than the national average, while its coal and natural gas use are lower than average. A biomass fuel intensity was not reported in the national energy intensity vector, and so no comparison could be made in this category. The Peace River region has much higher than average use of natural gas and petroleum, with coal use being much lower than average. The Peace River did not have any alternative energy sources generated within the region for the year of the model.

GHG Emission and Value Added Intensities

The calculated GHG intensity vector for Florida was also used for the Peace River region. Since the Peace River region's fuel use was calculated using Florida energy intensities, the emission intensities are the same for the two regions. The only exception is in the power generation industry, where data was available to differentiate the Peace region's energy use from the Florida's. The value added vectors for Florida and the Peace River region have differences due to the difference in labor costs within these two regions.

Regional EIO-LCA Models

The regional EIO-LCA models were used to calculate the direct and indirect resource use of each industry in the respective regions. How much of a product's footprint is masked by indirect effects occuring outside the producing industry can be shown by comparing the magnitude of direct and indirect inputs for each industry. Figure 2-1 and Figure 2-2 show the normalized cumulative distribution of water use and energy use in the region, respectively. These distributions are plotted against the log of the ratio of direct to indirect resource requirement. For log values above zero, the direct resource consumption represents more than half of the total resource requirement for that product; while for log values below zero, the indirect resource values constitute a greater portion of the resource requirement. Both Florida and the Peace River show similar patterns within their resource requirements, in that the highest resource consuming industries also have the highest direct to indirect resource ratios. For both water and energy consumption, the industries that have higher indirect consumption than direct consumption make up less than 10% of the total direct consumption in the region. However, the vast majority of industries fall into the negative log quadrant where indirect fuel use is greater than direct fuel use.

Emergy Evaluation

The emergy signature of Florida and the Peace River was calculated using the results of the regional EIO-LCA model. Figure 2-3 shows the emergy values for the Peace River regional industries compared on a log scale. There are 5 orders of magnitude between the lowest and highest industry emergy values. The industries with the highest emergy inputs include the electric power generation and the transportation industries. Figure 2.4 shows the breakdown of inputs into each emergy value on a normalized scale. The blank spaces in the graph are industries that are not present within the Peace River region. The emergy contributions of direct water inputs are visible primarily in the agricultural industries, while they make small contributions elsewhere. Indirect water use is a very small factor in the total emergy value. Direct energy inputs dominate the electric power generation and the transportation industries. However, most industries are dominated by indirect energy inputs due to purchased electricity. Commercial industries can be seen to have higher labor and service components than most other industries.

Discussion

Regional Resource Intensity Vectors

The goal of the regional EIO-LCA model is to relate regional economic production to environmental resource use. The resource intensity vectors that were developed for the regional model were critical to defining these relationships. The more accurately the regional resource use can be specified, the more the model will represent the regional resource use as being different from the national model. Large differences between average intensity values for the nation, the state, and the region are demonstrated in Table 2-1, Table 2-2, and Table 2-3.The methodology developed in this dissertation of allocating regional data first and then filling in missing values with national and state level averages is a valuable tool for regional modelers with data access limitations. The down-casting of the national and state models allows for regional modelers to make reasonable estimates for resource intensities in the industries where no regional data is available.

The national input output model is updated every five years, and efforts are continuing to develop national resource intensities. The potential also exists for a regional modeler working in a particular region to develop time series of resource intensities for the region as new data comes available. This could provide additional information in two ways, both capturing technological change in resource efficiency over time, as well as providing estimates of the uncertainties associated with the different resource intensities of the region.

Direct and Indirect Resource Use and Emergy Evaluation

A major benefit of the regional EIO-LCA model is its capability to estimate both the direct and indirect resource consumption for each industry in the model. Because it takes the entire regional economy into account, it can make comprehensive estimates of resource requirements without suffering from cutoff errors. The regional modeler can use this data on direct and indirect resource use to construct regional emergy models with unprecedented detail. Normally emergy evaluations of regional systems must rely on just a few internal compartments with highly aggregated resource flows. Figure 2-3 shows the emergy value of each industry included in the Peace River model, totaling several hundred industries. An emergy analysis with this level of detail has never been conducted for a region. The potential exists to use this method to compare emergy valuations across multiple regions to develop robust ranges for the emergy values of a wide range products and services.

The emergy evaluations constructed with data from the model have several important properties that should be pointed out that make them different than other emergy evaluations. The first property that is important to recognize is that the construction of the model treats all industry outputs as splits that follow monetary flows. This avoids the issue of trying to track co-products within the economic matrix in order to avoid double counting. A potential drawback to this approach is its reliance on prices to determine splits. Prices can shift relative to each other over time, which will change the percentage of splits in the model. In addition, waste flows that have no economic value, but may serve as inputs to other processes will not be accounted for in the model. A second property of the regional EIO-LCA data is that it does not include resource use in products that are imported from outside the defined region. This is because the economic matrix only includes regional transactions. Inputs that are purchased from outside the region could be estimated using IMPLAN's regional purchase coefficients. The resource requirement of the imported products could then be estimated by assuming that imports have the national average resource requirements, using the national EIO-LCA model for the calculation.

The emergy values that are calculated in the regional model represent an average value for the industry's production, and not a value for a specific final product. Any given industry includes all the output products that industry produces, in the proportions dictated by the economic input output model. Only in the case where byproducts are a small component of total production could direct comparisons be made between industry emergy values and product emergy values. However, since the reported emergy unit values are in sej/$M, deriving an average product emergy from the industry emergy would just require price information for the product in the year of the model. The regional EIO-LCA model is built using producer prices, so to convert to a retail price the transportation, wholesale, and retail margins must be added to the producer price. Estimates of these margins are available as part of the IMPLAN database. This model then has the potential to provide regionalized emergy values for a vast array of products that currently have no emergy valuations published.

The method employed in this chapter for estimating the emergy of industry outputs accounts only for water, energy, and labor inputs. These are likely to be the largest contributors to the emergy signature, but they are not necessarily the only contributors. Other material inputs such as fibers and minerals have been excluded. The difficulty with including other materials is that independent data sources are incomplete or non-existent at the regional level, and often at the national level as well. Zhang[59] made estimates of material inputs in the national economy, but due to data limitations, the model had to assume that material flow through the economy was directly proportional to dollar flow. This simplifying assumption could be used to give rough estimates of material inputs for the industries in the model, but represents a different methodology than using resource intensities based on reported resource use.

While material inputs may be significant factors in the emergy signature of primary manufacturing and mining industries, it is not clear that they will be limiting factors in future production. Many materials either have substitutes, or can be recycled if appropriate processes are implemented. Energy and water have no substitutes in production processes. It is interesting to note that even though water as a material is required in large amounts by many of the region’s industries, its contribution to total emergy is shown to be fairly small in this model. It makes a significant contribution only in the agricultural industries. Other materials are likely to account for even less of the total emergy of industries.

Environmental Impacts

The regional EIO-LCA model provides insight into the effects of an inter-connected economy on direct and indirect resource consumption, and how that resource consumption will change with changes in economic activity. To fully capture the impacts of economic changes on the sustainability of a region, a consideration of the environmental impacts due to these changes is also needed, including the impacts on ecosystem services. In Chapter 3 the regional EIO-LCA model is combined with a land use model in order to capture environmental impacts from regional production.

Table 2-1. Directly allocated water intensities for Florida

	Industry	Total Water withdrawn[39] (gals)	Economic Output[56] ($M)	Florida Water Intensity (gal/$M)	National Water Intensity[60] (gal/$M)	Percent Difference
1	Oilseed farming	3.91E+08	55.55	7.03E+06	8.78E+06	-19.9%
2	Grain farming	2.57E+10	79.00	4.62E+08	1.19E+09	-61.2%
3	Vegetable and melon farming	1.58E+11	1455.22	2.85E+09	2.36E+08	1106.2%
4	Tree nut farming	3.39E+08	57.47	6.11E+06	4.63E+08	-98.7%
5	Fruit farming	6.80E+11	1858.92	1.22E+10	4.50E+08	2621.8%
6	Greenhouse and nursery production	1.49E+11	1684.65	2.69E+09	5.21E+07	5057.0%
7	Tobacco farming	1.97E+09	24.80	3.56E+07	1.92E+07	85.2%
8	Cotton farming	3.30E+09	27.94	5.95E+07	1.24E+09	-95.2%
9	Sugarcane and sugar beet farming	3.13E+11	439.88	5.63E+09	7.55E+08	645.8%
10	All other crop farming	8.50E+10	40.24	1.53E+09	3.85E+07	3874.8%
11	Cattle ranching and farming	5.63E+09	743.43	7.57E+06	2.13E+07	-64.4%
23	Gold, silver, & other metal ore mining	2.56E+09	71.41	3.58E+07	4.95E+07	-27.7%
24	Stone mining and quarrying	2.44E+10	281.91	8.65E+07	4.91E+07	76.1%
25	Sand, gravel, clay, and refractory mining	1.32E+10	128.60	1.03E+08	5.84E+07	76.1%
26	Other nonmetallic mineral mining	2.74E+10	848.58	3.23E+07	1.20E+06	2588.3%
30	Electric Power	4.60E+12	9603.28	4.79E+08	2.54E+08	88.7%
478	Other amusement and recreation industries	1.08E+11	7200.73	1.50E+07	2.29E+05	6474.5%

Table 2-2. Directly allocated water intensities for the Peace River region

	Industry	Total Water Withdrawn[40] (gals)	Economic Output[56] ($M)	Peace Water Intensity (gal/$M)	National Water Intensity[60] (gal/$M)	Percent Difference
3	Vegetable and melon farming	6.74E+09	41.50	1.62E+08	2.36E+08	-31.1%
5	Fruit farming	1.10E+11	485.16	2.27E+08	4.50E+08	-49.5%
6	Greenhouse and nursery production	4.97E+09	59.11	8.41E+07	5.21E+07	61.5%
10	All other crop farming	6.30E+08	3.74	1.68E+08	3.85E+07	337.3%
11	Cattle ranching and farming	4.74E+09	55.87	8.49E+07	2.13E+07	298.9%
12	Poultry and egg production	2.99E+08	11.34	2.64E+07	3.87E+07	-31.7%
13	Animal production, except cattle and poultry	6.26E+08	20.29	3.08E+07	1.59E+07	94.1%
24	Stone mining and quarrying	2.15E+07	17.79	1.21E+06	4.91E+07	-97.5%
25	Sand, gravel, clay, and refractory mining	1.30E+09	36.50	3.57E+07	5.84E+07	-38.8%
26	Other nonmetallic mineral mining	8.64E+09	377.42	2.29E+07	1.20E+06	1807.5%
30	Power generation and supply	3.77E+09	460.86	8.18E+06	2.54E+08	-96.8%
32	Water, sewage and other systems	4.69E+09	10.23	4.59E+08	0.00E+00	N/A
60	Frozen food manufacturing	9.01E+07	552.23	1.63E+05	2.37E+05	-31.2%
61	Fruit and vegetable canning and drying	9.10E+08	153.94	5.91E+06	8.59E+06	-31.2%
157	Phosphatic fertilizer manufacturing	7.26E+09	1102.63	6.59E+06	8.44E+06	-22.0%
478	Other amusement and recreation industries	2.67E+09	254.77	1.05E+07	2.29E+05	4481.7%

Table 2-3. Comparison of electric power generation energy intensities

	National	Florida				Peace River region			
Fuel Type	Energy Intensity[46]	Fuel Use[47]	Output[41]	Energy Intensity	% Diff	Fuel Use[48]	Output[41]	Energy Intensity	% Diff
	(TJ/$M)	(TJ)	($M)	(TJ/$M)		(TJ)	($M)	(TJ/$M)	
Coal	78.3	726684	14541	59.32	-24%	41840	461	90.79	16%
NG	22.9	564636	14541	46.09	101%	97389	461	211.32	823%
Petro	3.8	3583700	14541	29.29	671%	4077	461	8.85	133%
Biomass	0	47475	14541	3.88	N/A	1766	461	3.83	N/A
Alternate	2.5	410579	14541	30.47	1114%	0	461	0	N/A

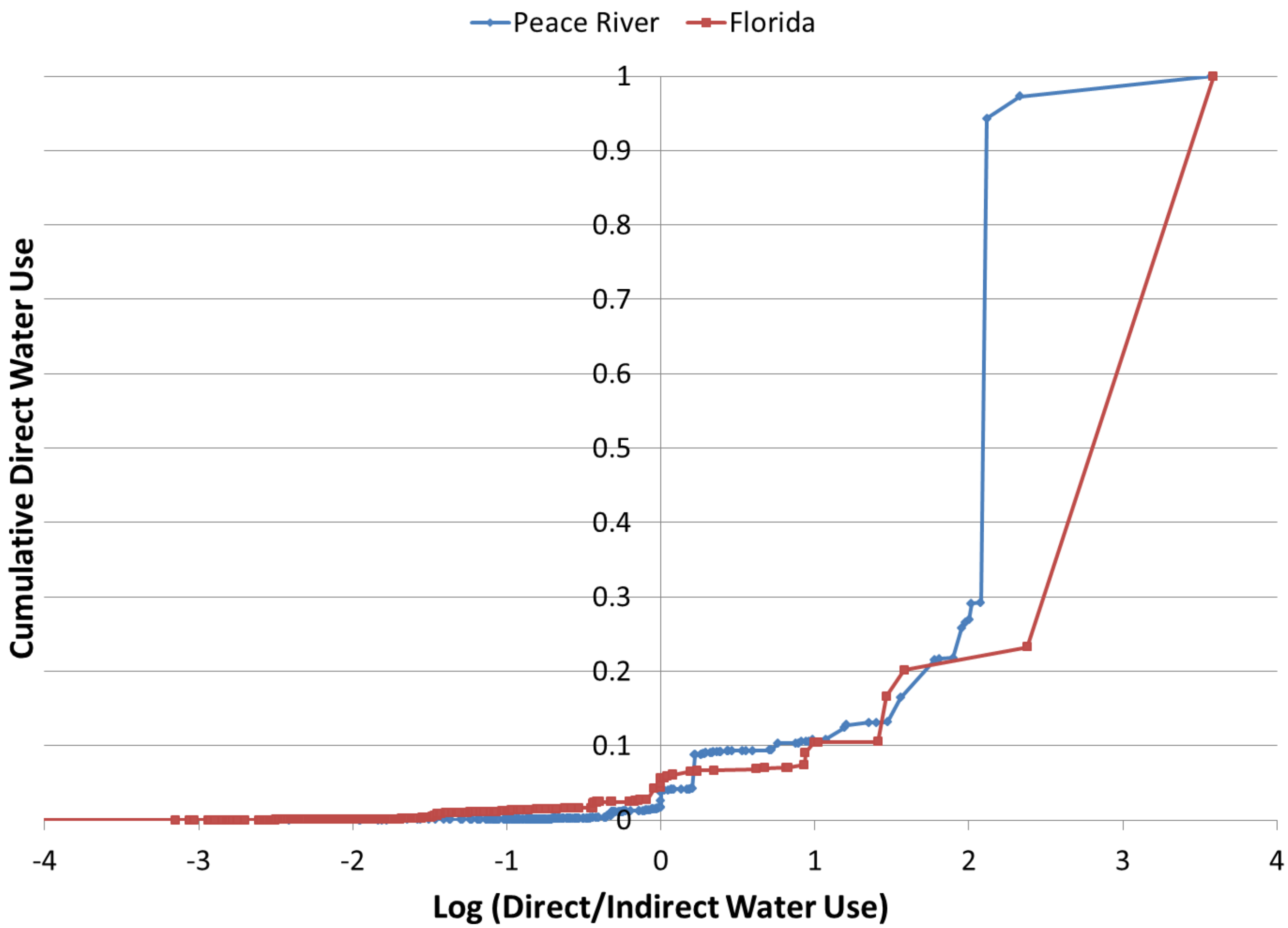

Figure 2-1. Comparison of regional direct and indirect water use for each industry in the regions. The largest water users in both regions have high direct to indirect water use ratios.

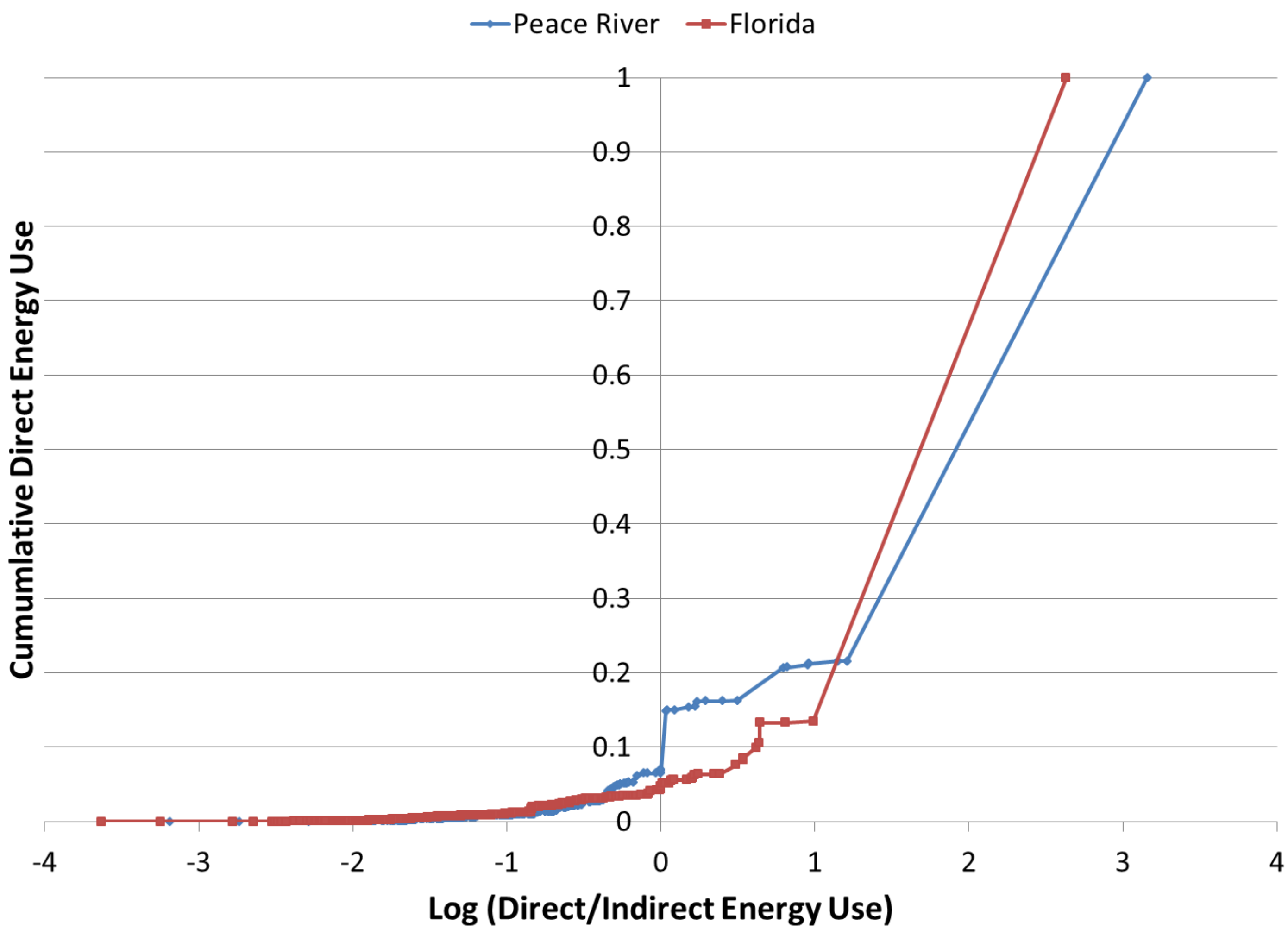

Figure 2-2. Comparison of regional direct and indirect energy use for two different regions. The highest energy consumers in both regions have the highest direct to indirect energy use ratios.

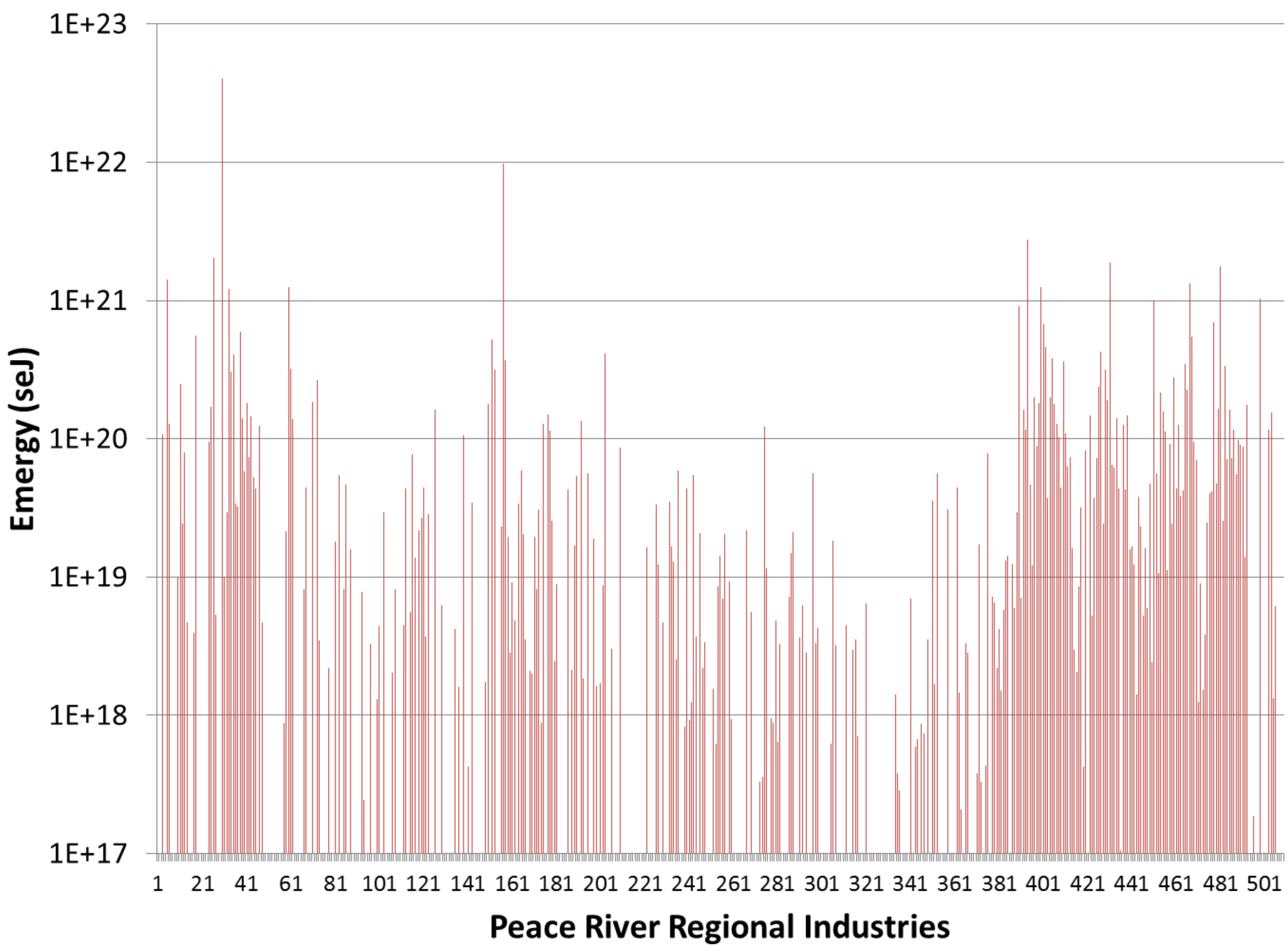

Figure 2-3. Emergy values for Peace River regional industry output showing a range of five orders of magnitude in emergy values.

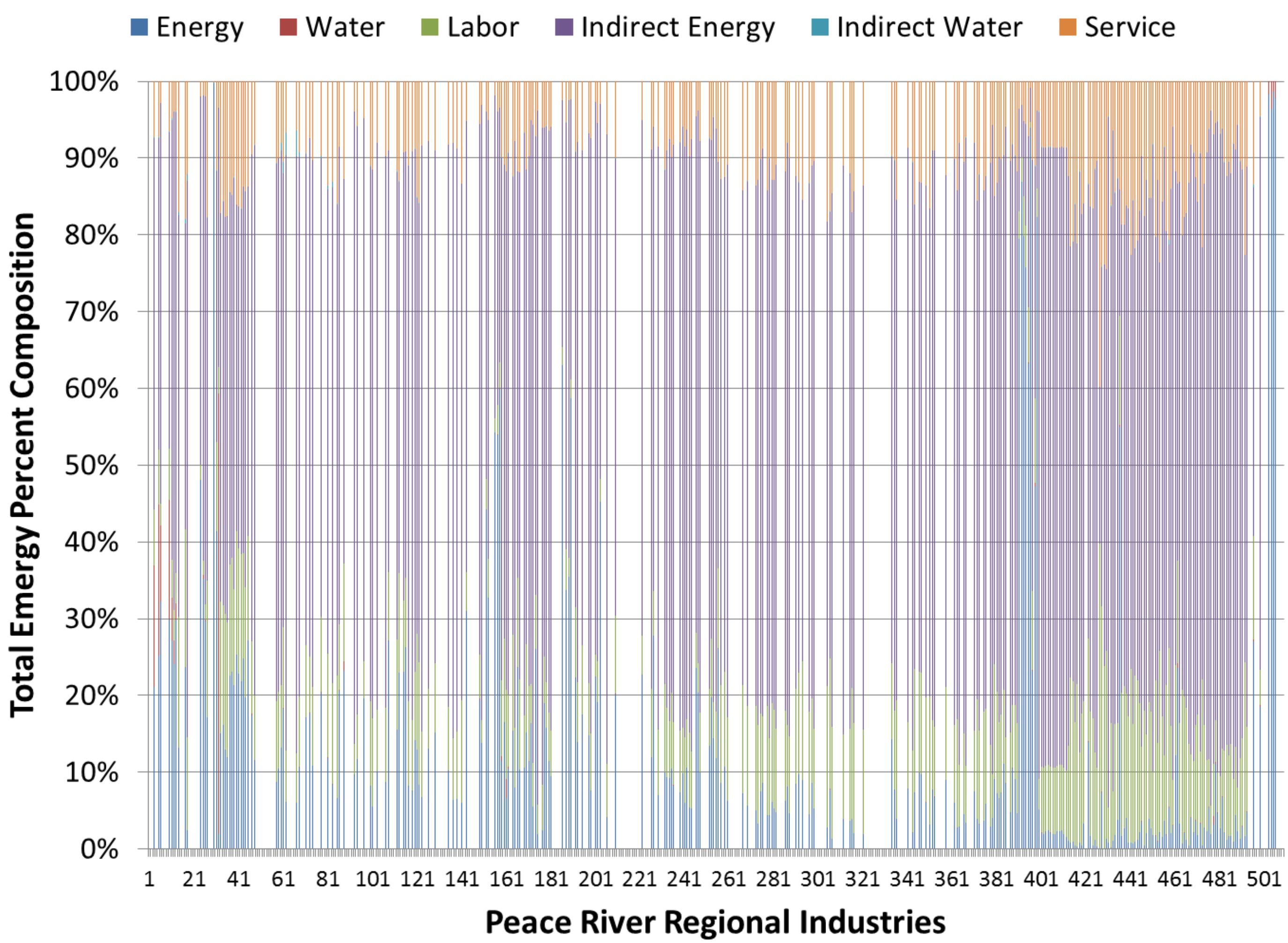

Figure 2-4. Composition of emergy values for Peace River regional industries showing distinct signatures for agricultural, power, manufacturing, transportation, and commercial industries

CHAPTER 3
DEVELOPMENT OF A LAND USE OPTIMIZATION MODEL

Introduction

This chapter outlines the development of a linear programming optimization model for the Peace River region. The goal of the optimization is to maximize the sustainable production of the region. Land use was chosen as the variable that would be manipulated within the optimization model in order to achieve maximum sustainable production. This required defining 19 different land uses within the Peace River region for which the environmental and economic resource flows were modeled. A set of constraints were then defined for the optimization in order to bound the possible mix of land uses within geographic, economic, and sustainable limits. Within this chapter, the sustainability constraints employed were based on regional water use and included groundwater recharge and flood water storage. The sustainability constraints incorporated information on economic water consumption obtained from the regional EIO-LCA model developed in the previous chapter. The results of the optimization for the Peace River region are reported and the impacts of the selection of sustainability constraints are explored.

Methods

Water and Carbon Balance Models

The regional EIO-LCA model predicts resource flows within the economic system, but it does not capture all the resource flows in the environment. To predict changes to these flows, an environmental model is constructed of the Peace River region using simple water and carbon mass balance models for each land use within the Peace River model. Since water flows are sourced from the environment, and waste water flows are returned to the environment, this type of model helps account for environmental water flows due to economic activity.

Linear Programming Optimization Models

Optimization models are used widely to determine how to allocate limited resources to maximum effect. Optimization using linear programming was developed for use in military logistics planning during WWII, and revealed publically in 1947. The main feature of the optimization model is a goal or objective function that is to be either maximized or minimized. Along with the objective function, a set of constraints are developed that set the limits of the available resources that are required by the objective. In linear programming, these constraints are expressed as linear equations and are written in terms of a limiting variable. Combining all the constraint equations defines the solution space. Search algorithms are used to efficiently explore the solution space and find the maximum or minimum value for the objective that still meets all the constraints.

Linear programming models have been used in a wide range of applications, including land use planning[61] ,watershed management[62] ,and ecosystem service analysis.[63] In this modeling effort, the objective function is set to maximize system production, as defined earlier. The constraints are designed to maintain the long term sustainability of the region. The constraints may be defined as being physically based, or they can be defined by the social side of the system as laws or policies that apply to the specific region.

This optimization model assumes both linear objective functions and linear constraints. The resulting model scales all land use impacts linearly with area. While this is an approximation, it is a defensible assumption for most natural, agricultural, logging, mining, and even residential land uses as long as the interactions of the land uses are appropriately accounted for. This assumption likely does not hold for commercial and industrial land areas, where production can be increased independent of land area. The nonlinearity of these land uses was addressed in the optimization model by forcing their area to remain constant.

The construction of the regional optimization model required defining major land uses within the region, and assigning average economic and environmental flows of water, energy, and GHG emissions to these land uses. Publically available data sources were used to define both the regional land uses and resource flows within those land uses. Data sources were selected to correspond as closely as possible to the year 2002 so that they matched the year of the regional EIO-LCA. An exact match was not always possible, and in these cases data as close as possible to the year 2002 was selected.

Land Use

Land use data for the Peace River region was compiled from the three water management districts that contain portions of the four counties within their boundaries: the Southwest, South, and St. Johns River Water Management Districts. A single data set was not available for any one year, and so data from 2004- 2006 were combined to yield a complete land use data set for the four-county region. This land use data[64],[65],[66] was reported according to the Florida Land Use Characterization System (FLUCS). FLUCS land uses were aggregated to form 19 economic and environmental land uses within the regional model.

Water Balance Model

A water balance model was developed for the Peace River region in order to allocate water flows to specific land uses. The water balance model incorporated both economic and environmental water flows. Data for environmental flows was obtained from the Peace River Cumulative Impact Study (PRCIS)[35] conducted jointly by the Southwest Florida Water Management District and the Florida Department of Environmental Protection. The PRCIS report created a water balance model for the sub-basins of the Peace River watershed for several different time periods in order to understand anthropomorphic impacts to the region's water cycle. Data for the years 1997-1999 from the PRCIS report was used to define average environmental flow conditions.

The first step in the water balance modeling process was to align economic and environmental boundaries. The surface watershed boundary of the Peace River is almost completely contained within the political boundaries of four counties: Polk, Hardee, DeSoto, and Charlotte County. However, the political boundary of these four counties encompasses more area than the watershed itself. In the optimization model, the watershed boundary was redefined to coincide with the political boundary. Surface runoff and stream base flow contribution values for the land uses within the watershed area were applied across the entire four county area. This modification resulted in a significantly greater volume of stream flow in the water balance model than in the actual physical system, but it preserved the relative magnitudes of environmental flows within each of the land uses and still allowed the calculation of a groundwater recharge balance across the region. The alternate approach of limiting the economic data to the area within the natural watershed boundary was deemed not to be feasible because the economic data was reported only at the county level.

Environmental water flows

Rainfall was the major environmental input flow. The annual rainfall variation for the region is large, varying from 30 up to 70 inches a year. The PRCIS[35] reported an average rainfall value of 50 inches per year from 1997-1999. This rainfall value was used as the input value for rainfall in all land uses.

Evapotranspiration (ET) was the largest water outflow in the system. ET was not measured directly in the PRCIS study, but was estimated based on a regional land use analysis. In the study, a reference evaporation for the region was calculated using a modified Penman-Montief equation and regional data on solar irradiance and temperatures. Regionally specific crop coefficients were then used to estimate an actual ET for each land use. Crop coefficients used in the study for Peace River land uses were obtained from literature values that were appropriate for central and southern Florida. The crop coefficients from the PRCIS report were adopted for the water balance model.

The PRCIS study also reported runoff coefficients for land uses in the region for two hydrologic soil types and for dry and wet rainfall seasons. In the regional water balance model, the mid-points of these two reported ranges for two different soil types were combined in a weighted average to develop a single runoff coefficient for each land use. The weighted average adopted the PRCIS study assumption that 38% percent of the rain falls in the dry season, and 62% falls during the wet season. The runoff coefficients for the region’s wetland areas were modeled as storing water during the dry season and having runoff only during the wet season.

The estimated ET and runoff for each land use were subtracted from rainfall to give a value for groundwater recharge. The surficial, intermediate, and Floridan aquifers were all considered a single groundwater unit for the water balance model. Data was not available to differentiate between these different underground reservoirs.

Within the PRCIS study, a percentage of the groundwater recharge was allocated to base flow, based on hydrograph separations for the Peace River. The regional water balance model maintained this percentage of base flow contribution to stream flow as a constant for all land uses.

Economic water flows

Modification of the environmental water flows by economic use was accounted for in characterizing the region's land uses. Ground water and surface water withdraws for economic use were obtained from USGS reports.[39] Florida state averages were used to determine the amount of this water that is consumed as additional ET or is embodied in a final product, and the amount returned to the watershed in wastewater flows. These water extractions and return flows were included in the water balance model of each land use. In the water balance model, wastewater applied at the surface of the ground was considered to enter the vadose zone and recharge the surficial aquifer. Wastewater that was injected underground into the aquifer without interacting with the vadose zone was also considered to be a contribution to groundwater recharge. Wastewater that was discharged directly to surface water bodies was considered to contribute directly to stream flow.

For each land use, wastewater return flows were assigned to the land use that initially extracted the water regardless of where the return flows are re-applied. Following this convention is necessary to allow net groundwater flows for each land use to be calculated in the model. The total groundwater extracted (represented as negative recharge values) for each land use type was added together with the groundwater recharge values (represented as positive recharge values) to give a net groundwater recharge for each land use. The sum of groundwater recharge over all the land area in the model represents the net groundwater recharge for the entire watershed.

Economic Model

The economic model of the Peace River region relies on year 2002 economic data from IMPLAN[56] for the four county region. The 509 industries in the regional EIO-LCA model developed in chapter 2 were allocated to 12 different economic land uses defined for the region. Individual land uses were defined for industries that were land use intensive, and for industries where production was proportional to land area. Commercial and industrial land uses that were not land intensive were grouped together. Resource consumption due to economic activity in the industry was allocated to each land use.

Economic Linkages

The area of each land use is the variable that is being manipulated in the optimization model. However, the initial definition of a land use only accounts for its direct resource consumption. Increasing or decreasing any economic land use also causes resource consumption to occur outside that land use, within the economic sectors that provide the required production inputs. This resource consumption occurs outside the physical area of the land use, but is being driven by the land use's own production processes. To account for these interactions in the model, three kinds of economic linkages are considered: backward, forward, and induced linkages. Backward linkages are the purchases that each industry makes from other regional industries in order to make their product. The indirect resource consumption from backward linkages was calculated in the regional EIO-LCA model developed in Chapter 2 using a Leontief predictive model. However, increasing an economically productive land area not only creates additional resource demand within the region, it also creates an additional supply of economic goods that can feed additional production processes in the region. Forward linkages consider the additional output products that could be produced within the region based on an increase in the supply of inputs. These outputs can be either directly exported, or they could be further processed within the local economy to produce higher value-added goods. The processing of these goods within the region will generate further economic activity and require additional resource consumption.

The Ghosh model makes the assumption that the percentage of regional products processed within the region into higher value-added goods remains constant for any increase in regional supply. The model then uses the current economic structure to calculate how much more resource use the processing of this additional supply will consume in the local economy. As a linear model, it assumes that there will be a market for these additional goods, and that their creation will not change the prices received for these goods. The Ghosh model is created from the economic transaction matrix by dividing each row by the total output of the row as shown in equation 3-1.

$$g_{ij} = z_{ij} / x_i \qquad (3\text{-}1)$$

The predictive model is then created as shown in equation 3-2 where x is the total output vector, the quantity (I-GT)-1 is the Ghosh matrix, and v is the vector of value added.

$$\boldsymbol{x} = (\mathbf{I} - \boldsymbol{G}^T)^{-1}\boldsymbol{v} \qquad (3\text{-}2)$$

As with the Leontief predictive model, the resource intensity matrix can be multiplied by the change in total output from the Ghosh model to give the direct and indirect resource consumption due to changes on the supply side as shown in equation 3-3.

$$\Delta \mathbf{b} = \mathbf{R}\Delta \mathbf{x} = \mathbf{R}(\mathbf{I} - G^T)^{-1}\Delta \mathbf{v} \quad (3\text{-}3)$$

The final economic linkage to be considered was the induced linkage. This linkage considers the resource consumption impact caused by an increase in labor payments to the population living in the region. When a land use increases, thereby increasing economic activity, it also increases income to the workers that are providing labor to that economic activity. A portion of this income is usually spent within the region, creating an additional demand for regional products and services. IMPLAN software provides a set of induced impact multipliers that are multiplied by the change in final demand from the Leontief model to determine changes due to increased spending by the population. The induced impacts calculated in IMPLAN are combined with the backward and forward linkages to give a more complete estimate of regional impacts based on changing economic output.

Combined Economic/Ecological Land Use Model

To complete the modeling of the individual land uses, the indirect resource consumption that occurred in other land uses due to backward, forward, and induced linkages was subtracted from those land uses and re-allocated to the driving land use. This re-allocation was done for each land use in the model that had an economic component, resulting in both additions and subtractions for each land use. Each resource category was redefined in this way, according to equation 3-4

$$R_{i,r} = D_{i,r} + \sum_{1}^{n} L_{i,r,Out} + \sum_{1}^{n} G_{i,r,Out} + \sum_{1}^{n} I_{i,r,Out} - \sum_{1}^{n} L_{i,r,In} - \sum_{1}^{n} G_{i,r,In} - \sum_{1}^{n} I_{i,r,In} \quad (3\text{-}4)$$

In this equation, R_i stands for the resource use of land use *i* and category *r*. $D_{i,r}$ stands for the direct resource use of that land use, $L_{i,r,Out}$, $G_{i,r,Out}$, and $I_{i,r,Out}$ stand for the indirect resource use from the Leontief, Ghosh, and induced linkages respectively that occur outside land use *i* but are driven by its production. These indirect resources are added together for land uses 1 through *n*. $L_{i,r,In}$, $G_{i,r,In}$, and $I_{i,r,In}$ stand for the indirect resource use from land uses 1 through *n* that were inside land use *i* and are subtracted out of it.This total resource flow $R_{i,r}$ was then divided by the total area of the land use, A_i to yield area-based resource intensities for each resource category for each land use.

$$R_{i,r}/A_i \quad \text{(3-5)}$$

These area-based resource intensities were the inputs for the optimization model used to characterize the change in resource consumption as land areas were changed in the model.

Linear Optimization Model

The optimization model for the Peace River Region was constructed in Microsoft Excel using the solver add-in feature, which is a commercial optimization package employing the Simplex linear programming algorithm. Building the model required the definition of a regional goal function and development of constraints for the model. A 50-year time horizon was selected for the model in order to include activities such as phosphate mining, which is a major part of the current economic structure. Based on current mining rates, this activity was projected to remain in the region over the time horizon of the model.

Goal function

As stated in Chapter 1, the objective function of the optimization model was to maximize regional production. Two measures of production were defined: total monetary throughput and regional emergy throughput. Total monetary throughput was defined as the sum of the production of each land use as measured in dollars. It should be noted that this is not the same measure as gross domestic product, which does not include intra-industry flows in its calculation, but instead includes only final consumption. The total throughput includes intra-industry flows.

Total emergy throughput was defined by adding the largest environmental emergy flow plus the direct and indirect emergy flows in the economy for each land use. In the case of emergy as well, intra-industry flows are included in the total throughput calculation. For all land uses, the evapotranspiration of water was the largest environmental emergy flow. Economic emergy flow for each land use was calculated using the following categories of resources use: direct and indirect water input, direct and indirect energy input, and direct and indirect labor input. Indirect labor input represents the category usually referred to as goods and services in an emergy valuation. It represents the labor input embodied in inputs of goods and services purchased from outside the land use. The land use emergy valuation did not include material use other than water. Since the emergy flow was calculated using the regional model, it included only indirect flows from purchases within the region, and did not include an emergy evaluation of purchases from outside the region, other than the primary energy sources. This convention limited the objective function to a maximization of the throughput of the region’s internal emergy flows plus the primary fuel inputs.

Variables

The manipulated variables in the linear programming model were the land areas allocated to different land uses within the region. To construct the model, resource flows were defined in terms of flow per unit of land area. The assumption of the model is that these flows will vary in direct proportion with land use. As each land use area was changed, the economic and environmental flows associated with that land use changed linearly.

Constraints

Several types of constraints were defined for the optimization model. Physical constraints dealt with the physical characteristics of the region. The primary physical constraint was the total area available in the system. After optimization, the sum of all land uses had to be equal to the total land area. In addition to the total area, several other land areas were held constant in the model. The area of water was set as constant in the model, including river, lake, and estuary area, as these land types are not readily converted to other land uses. In addition, wetland area was constrained by the maximum extent of wetland area in the system before wide-spread development, defined as the total wetland area from the 1940 land use analysis. [35] No minimum wetland area was defined in the model.

Water resource constraint: Sustainability constraints limit resource use to levels that can be sustained indefinitely within the system. Groundwater sustainability limits were defined by limiting groundwater consumption so that the currently modeled amount of groundwater recharge in the system was maintained into the future. Groundwater consumption was defined as groundwater that was withdrawn and subsequently either evaporated, or was transported out of the region though means other than groundwater flow. The intent of the constraint was to maintain average aquifer levels in the system.

A flood control constraint was also developed for the region. This constraint considered the storage of runoff from a large storm event in the system. The 25-year, 6-hour return storm for the region was used to define the rainfall event,[67] with the assumption that upland land areas would have 2 inches of initial abstraction, and the remaining 4 inches of water would become runoff. All developed upland areas and forested upland areas were assumed to have this average runoff. Water bodies including lakes and streams were assumed to have enough freeboard to hold the 6 inches of rainfall, plus an additional foot of rain. Wetlands were assumed to hold the 6 inches of rain, plus an additional 6 inches of rainfall for an average of a foot of rain. Unimproved pasture land was assumed to hold its own runoff in low lying areas essentially causing no net runoff of water. The flood control constraint was defined so that storm water storage in the region must be equal to the projected runoff. Spatial characteristics of the landscape were not considered in the runoff model, so the location of the flood storage was not evaluated.

Several economic constraints were included to govern the economic interactions within the system. The first economic constraint dealt with the population supported in the region. According to IMPLAN data,[56] 40% of the 2002 population was employed within the region. A constraint was defined so that the working population of the region must be large enough to provide all but 1% of total employment requirements. A separate constraint was defined so that unemployment could not exceed 5% of the working population. This constraint was implemented by bounding the total number of workers available from the residential land use with the total jobs available from the economic land uses. The effect was that the residential area of the region was constrained to grow only large enough to provide the labor workforce required to meet the region's labor needs. The percentage of the population that was not considered part of the workforce, 60%, remained constant in the model.

Electricity generation constraint: The Peace River region produced electricity from multiple power generation plants in 2002. Based on calculations from the regional EIO-LCA model of average commercial, industrial, and residential electricity demands, approximately 25%, or 10,000 TJ of the electricity produced in the region in 2002 was not consumed within the region, but exported to surrounding areas. The model's electricity production was constrained so as not to exceed the amount of electricity exported in 2002, any additional electricity production must be consumed within the region. Since there are large urban markets bordering the Peace River region, the potential may exist to export more electricity, but additional export was not evaluated in the model.

Commercial and industrial area constraint: The commercial and industrial land areas were held constant in the model. The production within these land uses does not necessarily vary linearly with land area. Production can be increased and decreased in these land uses without increasing land area by changing other input factors, such as labor hours, or capital investments. Increases that resulted from changes in the other land uses were previously separated out of these two land uses. The remaining production, then, is not tied strongly to the production occurring across the landscape of the region. The model assumes that the level of production can be maintained within the current area footprint.

Mining industry constraint: In the model the mining industry is constrained by defining an amount of land area that can be mined each year. Current mining in the region consumes about 2000 ha of new land area per year.[68] The total annual mined area was defined as the actively mined land plus all land still in various stages of reclamation. Mined land area was modeled as requiring an average of 12.5 years to be reclaimed to an alternate use.[68] At the end of this time, the land area is considered available for other commercial use. The total mined area including active mines and land being reclaimed was was set as 31,000 ha per year and this amount of land use was held constant in the model. At this rate of mining, phosphate deposits are projected to remain in the region beyond the 50-year time horizon of this model, allowing this industry to be included in the land use analysis.

Agricultural industry constraints: Constraints were also defined for three of the agricultural industries. These constraints prevented industries that have limited export markets from increasing beyond a reasonable growth estimate. The industries constrained included vegetable production, greenhouse production, and other agriculture. These are comparatively small land uses in the region, but they have high profitability per land area. Vegetable production was constrained to have a maximum 50% growth in area. Greenhouse production and other agriculture production were considered to have more limited markets for their products and were limited to only 10% growth in area.

Results

Land Use

Table 3-1 reports total land areas for each land use category in the model. Natural areas still comprise 39.8% of the total land area, while industrial, commercial, and residential together make up only 6.9% of land area. The majority of the land area is under mining and agricultural development, with unimproved range land making up the largest single land use at 27% and citrus and mining contributing 10.4% and 8.4% of the land area. The current region has 3.9% of land area classified as open or disturbed that is not under any economic land use.

Water Balance Model

The water budgets developed for regional land uses result in each land use having a characteristic signature of water inflow and outflows. The environmental inflow in the model was rainfall, and the characteristic outflows for rainfall into ET, runoff, and recharge are given in Table 3-2. Economic inflows come from extraction of ground and surface waters. The percentage of economic inflows from different sources are given in Table 3-3, while the disposition of those inflows into outflows are given in Table 3.4.When combined, these environmental and economic flows define the water budget for each land use. Figure 3-1 shows the contribution of extracted surface and ground water to the total input flow for each land use in the region. Land uses that represent the most significant changes in input flows per hectare include vegetable farming with a 69% increase, industrial land use with a 59% increase, and power generation with a 46% increase. Figure 3-2 shows the allocation of output flows between ET, runoff, and groundwater recharge for all land uses. The figure includes the contributions to these flows from extracted ground and surface waters used in economic production processes. Significant redistributions of water to ET occur in both industrial and agricultural industries. While the power industry has large extractions of water for cooling, estimates for Florida are that only 9% of that water evaporates,[39] and the rest is returned to surface storage where it recharges groundwater. Residential and industrial wastewater flows make up the major economic contributions to surface flows.

Land Use Models

Modifying the land use models to account for indirect resource consumption resulted in significant changes to the flows within each land use. Figure 3-3 shows the percent change for the monetary value of production after indirect economic linkages had been accounted for. In this figure, the original direct value of production is shown as 100% of the initial value. Net additions or subtractions of backward, forward, and induced linkages are shown in relative scale to the original direct requirement. The commercial and industrial land uses were held constant in the model, so they did not drive any increases in other land uses in the model. Therefore, they only display economic activity that was removed and added to the other land uses. Mining, citrus, vegetable, nursery, other crops, and cattle land uses all have net positive additions from their economic linkages. The power sector and logging sector were only allocated the backward and induced linkage impacts. Forward linkage impacts were not allocated to these two industries since additional production within these two industries was not considered to drive any additional production of goods and services within the region. Accounting for indirect economic linkages created between 50% and 150% increases in output for these land uses. For most of the land uses, the induced impact created the largest change.

The indirect resource consumption for each land use was calculated by multiplying the changes in indirect outputs by the matching resource intensity. This was done for applicable backward, forward, and induced linkages for each land use. Figure 3-4 shows the percent change in resource consumption or economic impact for each land use as a result of accounting for the indirect contributions to that land use. The changes are compared in groundwater use, job provision, GHG emission, as well as emergy flow and economic output. Comparing across land uses, a wide range of changes due to indirect impacts is observed, varying from single digit decreases to an almost 900% increase in GHG emissions within the logging land use.

The economic and environmental characteristics of each regional land use were combined and then divided by the area of land use. This created the combined economic and environmental land use model that served as in input into the optimization model. Table 3-5 gives the results for the two objective functions, monetary output and emergy flow, and the variables for each land use in the model.

Optimization

The optimization of regional production resulted in land use shifts as shown in Figure 3-5. The results represent a tradeoff between economic production which requires groundwater extraction, land uses that provide groundwater recharge, and land uses that provide floodwater storage. Agriculture industries with high production value per land area increase to their internally constrained limits. The largest land use shift is a tenfold increase in irrigated cattle ranching, while citrus and un-irrigated cattle ranching experience 35% and 43% declines respectively. All upland forest and logged forest is converted into other land uses, while total wetland area actually increases in value. The model increases total wetland area by 46%, while converting all wetland area to wetland forest. These land use changes result in an additional $465M output, a 1.8% increase in economic output for the region. In addition, the region now supports a 6% larger population than before the optimization.

The initial optimization was also run with the objective of maximizing emergy throughput instead of monetary throughput. Only 4 areas of land use differed in the emergy optimized scenario from the monetary optimized scenario, and all of these varied by less than 1.5%. The increase in emergy flow was 3.9% overall, as compared with the increase in monetary flow of only1.8%.

Sensitivity Analysis

The sensitivity of optimized production to the groundwater sustainability constraint was evaluated by varying the volume of groundwater that must be recharged into the system. This constraint was varied over a range from -74% to +57% from the target constraint. Beyond this range, the optimization had no feasible solution, meaning all of the constraints could not be satisfied simultaneously. Industrial and commercial production not associated with agricultural production would have to be allowed to decrease in the region to meet any further constraints.

Figure 3-6 shows the resulting shifts in land use as the groundwater constraint is varied. Requiring less recharge resulted in increased water available for economic production. With more irrigation water available, the citrus industry expanded. Requiring more groundwater recharge resulted in land use shifts away from citrus into cattle ranching, first on improved pasture which is partially irrigated, and then to range land which has no irrigation. Higher profitability agriculture such as vegetable and nursery production remained at maximum limits until the most severe groundwater recharge restrictions were implemented. At the highest recharge restrictions, almost all irrigated agricultural production is eliminated to provide the required water flow for commercial and industrial production.

Shadow Pricing of Ecosystem Services

A result of setting up the regional optimization with sustainability measures as constraints is that shadow prices can be calculated for the ecosystem services that are constraining production. A shadow price measures the extra value that could be added to the goal function as a result of increasing a constraining resource by a single unit of that resource. The sensitivity report provided as a part of Exel's solver routine calculates a shadow price for each binding resource constraint. Only binding constraints have shadow prices, because increasing a constraint that is not limiting production does not result in any additional production capability.

In the case of the groundwater sustainability constraint, the constraint is how much water must be recharged to maintain aquifer levels. The shadow price reveals the value an additional unit of groundwater recharge has in increasing the goal function of the region. This value can be used to represent the value of the environmental service of groundwater recharge being provided by each land use to the region as a whole. It is important to note that the shadow price does not remain constant over the entire range of production. As the groundwater constraint is increased, the price per unit of groundwater changes at certain inflection points. By varying the value of the groundwater constraint used in the optimization, the range of the shadow price for the constraint can be explored, in effect giving a price curve for the constraining factor.

Figure 3-7 shows the price curves generated in the current model for both groundwater recharge and storm water storage. When the requirement for groundwater recharge is low, high water intensity activities like citrus production are selected in the model. Citrus fields have higher runoff coefficients relative to the land uses they replace, and so more storm water storage is required in the region. The shadow price of storm water storage is highest when the constraint for groundwater recharge is lowest. As the requirement for groundwater recharge is increased in the region, high water intensity land uses like citrus are replaced with lower water intensity land uses such as cattle production on pasture and rangeland. These land uses provide more storm water storage than citrus, and the need for storm water storage area in the region falls as does its shadow price. Eventually, storm water storage is no longer limiting, and the shadow price falls to zero. Groundwater recharge demonstrates a different pattern. Initially, the shadow price for groundwater recharge is very low. As the recharge requirement increases, so does the shadow price for the ecosystem service.

Discussion

Linearizing Land Uses

Linearizing the land uses in the model is a unique aspect of this model. The land uses initially are only defined by the direct impacts that take place in the land area itself. Because the resource consumption of the land uses in this model was determined using the regional EIO-LCA model, the indirect resource consumption could be calculated for each land use. For the each type of economic linkage, this indirect resource consumption is subtracted from the upstream land uses, and added instead to the land use that generates the demand for it. This accounting for indirect resource consumption within the driving land use captures resource demand that would have been missed by a conventional optimization model. Because the indirect resource consumption is subtracted from the land use it occurs in, the model avoids double counting these resources in the optimization. What would normally be perceived as nonlinearity in resource demand is now accounted for in a linear manner, allowing more accurate modeling of the region.

Accounting for backward linkages, and for induced impacts is standard practice within economic input output models and social accounting models. However, accounting for the forward linkages as in this application is not standard practice. Figure 3-3 shows that the forward linkage component is in many cases larger than the backward linkage component in the model. The meaning of this component should be considered carefully. In order to calculate this linkage the model must assume that the region will process new outputs from the land use into the same mix of products as are already produced. For example, if 30% of orange production is made into orange juice in the region, the forward linkage says that 30% of any increased production will also be made into orange juice. In reality, this depends both on markets for the product and capacity within the region. However, it can be taken as a reasonable estimate of the upper limit of what additional production could be expected to be captured within the region, and the resources required to do so. Models that include forward linkages then should be viewed as estimating the upper limit of economic development.

Forward linkages were not used for all land uses, as some forward linkages in the model may not drive any additional production. For example, additional electric power generation is not likely to drive the consumption of that power in producing new products within the region, unless new industry moves into the region. An additional consideration of forward linkages is how well the industry is represented by the national economic model. The forestry industry in the Peace River does not supply the same mix of products that are representative of the national forestry industry as a whole. Tree harvest in the Peace River is not likely to become lumber for houses or pulp for papermills, and so it will not drive the production of these products, even though the model based on the national economy may specify that. This limitation on using forward linkages could be remedied in part by developing regionally specific product allocations instead of relying on national averages. While this is impractical for all the industries in the model, if this were done for the largest industries in the region, it could increase the accuracy of the model results.

Accounting for Ecosystem Services

A key concern for sustainability models has been accounting for necessary ecosystem services. Ecosystem services are included in this model through the development of sustainability constraints. Groundwater recharge and floodwater storage are both ecosystem services that are consumed by the production of some land uses, and produced by other land uses in the model. The ability of the model to consider which services are needed and to what level they need to be provided relative to regional production is vital information for regional managers concerned with providing these services in the future.

The ability of the model to provide shadow prices for limiting services is powerful feature. Valuing ecosystem services has proven a difficult task in environmental science, as they are produce by the environment free of charge. This model provides a shadow price for any ecosystem services that are limiting in the system. The shadow price tells the regional manager how much more value of production could be generated if one additional unit of the ecosystem service were available. The shadow price is not an absolute value of the service, as it does not relay information on what it takes to provide that service. However, it is valuable information to the regional manager who must make cost-benefit calculations on providing services in the region. Shadow prices can be used to design subsidies and incentives for land owners to provide additional units of ecosystem service within the region. They can also be used to justify the cost of infrastructure investments designed to provide ecosystem services in areas where they are needed.

Choosing Goal Functions

Two goal functions were considered for this effort, maximizing emergy throughput and maximizing monetary throughput. The choice of the goal function for the region was not found to have a significant impact on the outcome of the optimization. Maximization objectives based on monetary output and emergy flow gave very similar optimization results. At first this result may appear surprising given that monetary valuation assigns zero value to land uses that have no economic output, while emergy valuation assigns the value of the ET flow of these land uses. However, comparing the value per area of the monetary and emergy flows shows that they follow the same order for the economic land uses in the region. Industrial and commercial land uses have the highest intensities, and environmental land uses have the lowest. The implication is that land uses will be substituted for each other in the same order regardless of whether the monetary flow or the emergy flow metric is optimized. However, because the relative magnitudes of the values for each land use are different between monetary and emergy evaluation, inflection points are likely to be different when using different goal functions. The similar order of land uses for monetary and emergy values may not hold true for all regions, or for the future. The order in the Peace River region is determined primarily through the energy of fossil fuels that are consumed in each region. I

Environmental land uses have both the lowest monetary and emergy values. These land uses are selected in the model based primarily on the fact that they provide more of limiting ecosystem services such as flood control and groundwater recharge per area than other land uses. Environmental land uses that provide the highest levels of limiting services are then selected. This helps to explain the reason the model selects wetland forest over upland forest, because the water storage and water recharge per area are higher for the wetland forest land use. Since the model is seeking only to maximize output, it does not value diversity of landscapes, instead it selects the land use that will give it the highest amount of the constrained variable per area.

Valuing the land uses with energy flow raises the question as to the interpretation of an emergy shadow price for a land use. Following the logic of the monetary example would suggest that the emergy shadow price represents the additional amount of emergy that could flow through the compartments of the regional system by providing one more unit of the binding constraint.

However, it should be recognized that this is summing all the emergy flow through each compartment in the model, and so emergy is being double counted within this value. The same is true for the monetary output of the region, where total money flowing through each compartment is what is being optimized, and not GDP. The implication is that the greatest value to the region is in having maximally connected compartments (or land uses in this case), as this maximizes throughput.

Comparing the composition of the emergy flows for each land use shows that energy use dominates the emergy valuation for each economic land use. This underscores the reliance even a highly agricultural region has on imported energy sources. These energy sources are a primary driving force for the production of the region. This is reflected both in the monetary and the emergy valuation of the output. Both measures seem to work as goal functions, at least in the short term. In the long term, prices for energy sources may shift dramatically in the future based on factors of supply and demand outside of the region itself. However, emergy values should maintain more stability over the long term because the energy required to make products is independent of supply and demand. Emergy valuation may prove to be a better measure for planning efforts with long time horizons and uncertain future energy costs.

Static Economic Structure

A major limitation of the current model is that it is predicting a future in which the underlying economic structure of the region remains the same and only existing land uses change linearly. New industries are not evaluated for their impact. Land use, then, is the limiting factor that is being addressed most strongly in the model. Chapter 4 begins to explore how the optimization model can be used to address changes in economic structure by introducing new land uses to the region

Table 3-1. Peace River land use areas

Land Use	Area[64–66] (ha)	% Total
Residential	48181	4.8%
Commercial	20946	2.1%
Industrial	3113	0.3%
Mining	88714	8.8%
Power	995	0.1%
Citrus	109433	10.8%
Vegetable	2930	0.3%
Nursery	5162	0.5%
All Other crops	9607	0.9%
Cattle-Pasture	27813	2.7%
Cattle-Range	285285	28.2%
Logged forest	15043	1.5%
upland forest	117805	11.6%
Wetland forest	110761	11.0%
Wetland	69583	6.9%
Lakes	40118	4.0%
Stream	3970	0.4%
Salt marsh	10308	1.0%
Open Land	41726	4.1%

Table 3-2. Water outflows from environmental inputs

Land Use	ET[35]	Run Off[35]	Recharge
Residential	57.30%	25.60%	17.10%
Commercial	49.10%	37.80%	13.20%
Industrial	40.90%	55.00%	4.10%
Mining	61.40%	34.50%	4.10%
Power	49.10%	34.50%	16.40%
Citrus	73.60%	26.20%	0.20%
Vegetable	69.50%	30.30%	0.20%
Nursery	69.50%	30.30%	0.20%
All other crops	69.50%	30.30%	0.20%
Cattle-pasture	65.50%	21.40%	13.10%
Cattle-range	61.40%	21.40%	17.20%
Logged forest	65.50%	18.10%	16.50%
Upland forest	65.50%	18.10%	16.50%
Wetland forest	69.50%	10.00%	20.50%
Wetland	73.60%	10.00%	16.40%
Lakes	85.90%	0.00%	14.10%
Stream	85.90%	14.10%	0.00%
Salt marsh	73.60%	26.40%	0.00%
Open land	61.40%	25.60%	13.10%

Table 3-3. Water inflows from economic use

Land Use	Supply[40]		Source[40]	
	Self	Public	GW	SW
Residential	20.60%	79.40%	91.10%	8.90%
Commercial	90.80%	9.20%	83.10%	16.90%
Industrial	34.30%	65.70%	95.90%	4.10%
Mining	100.00%		98.00%	2.00%
Power	100.00%		85.00%	15.00%
Citrus	100.00%		94.40%	5.60%
Vegetable	100.00%		94.40%	5.60%
Nursery	100.00%		94.40%	5.60%
All other crops	100.00%		94.40%	5.60%
Cattle-pasture	100.00%		94.40%	5.60%

Table 3-4. Water outflows from economic use

Land Use	ET[39]		Wastewater[40]		
	Self-Supplied	Public-Supplied	Vadose	Surface Water	Injected
Residential	39.00%	60.00%	61.00%	31.00%	8.00%
Commercial	80.00%	59.00%	61.00%	29.00%	10.00%
Industrial	19.00%	38.00%	62.00%	34.00%	4.00%
Mining	30.00%		100.00%		
Power	9.00%		100.00%		
Citrus	72.00%		100.00%		
Vegetable	72.00%		100.00%		
Nursery	72.00%		100.00%		
All Other crops	72.00%		100.00%		
Cattle-Pasture	72.00%		100.00%		

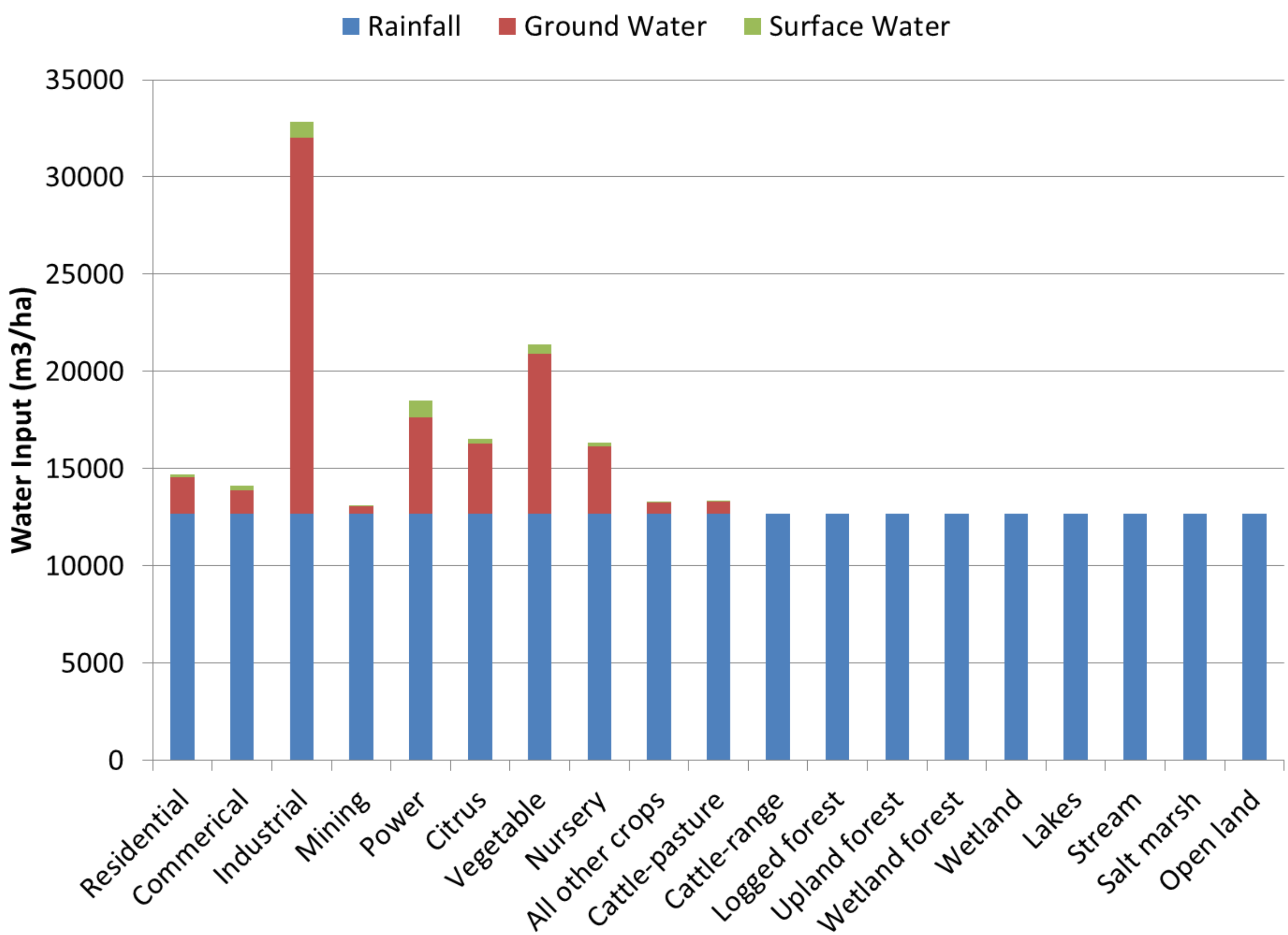

Figure 3-1. Water inflows for regional land uses showing the contribution of economic groundwater and surface water flows to the water intensity of land uses in the Peace River region.

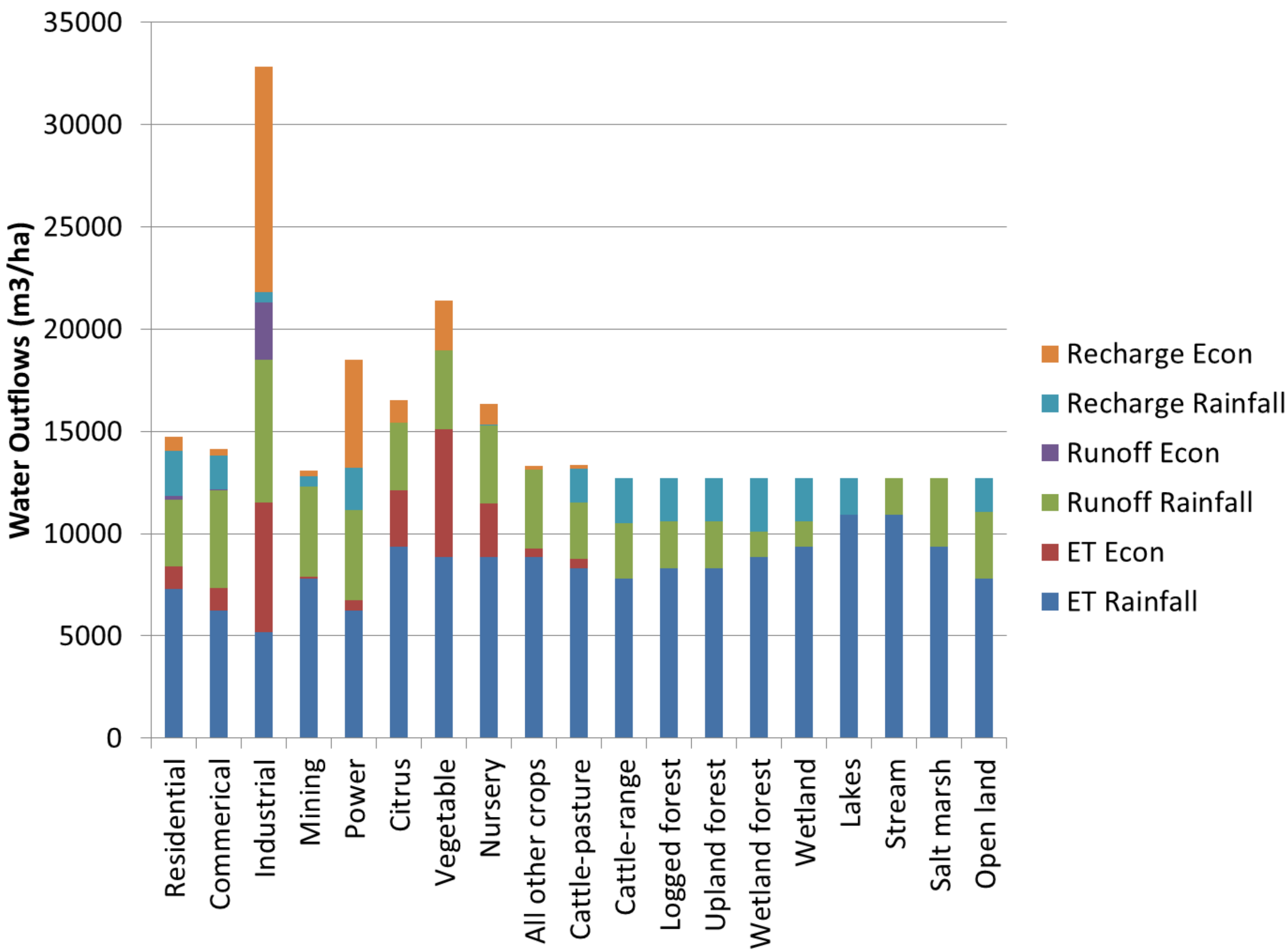

Figure 3-2. Water outflows for regional land uses showing the distribution of total flow into ET, runoff, and groundwater recharge. Each outflow is further divided to show the inflow source for that portion of the flow, whether that be rainfall or economic water inflows.

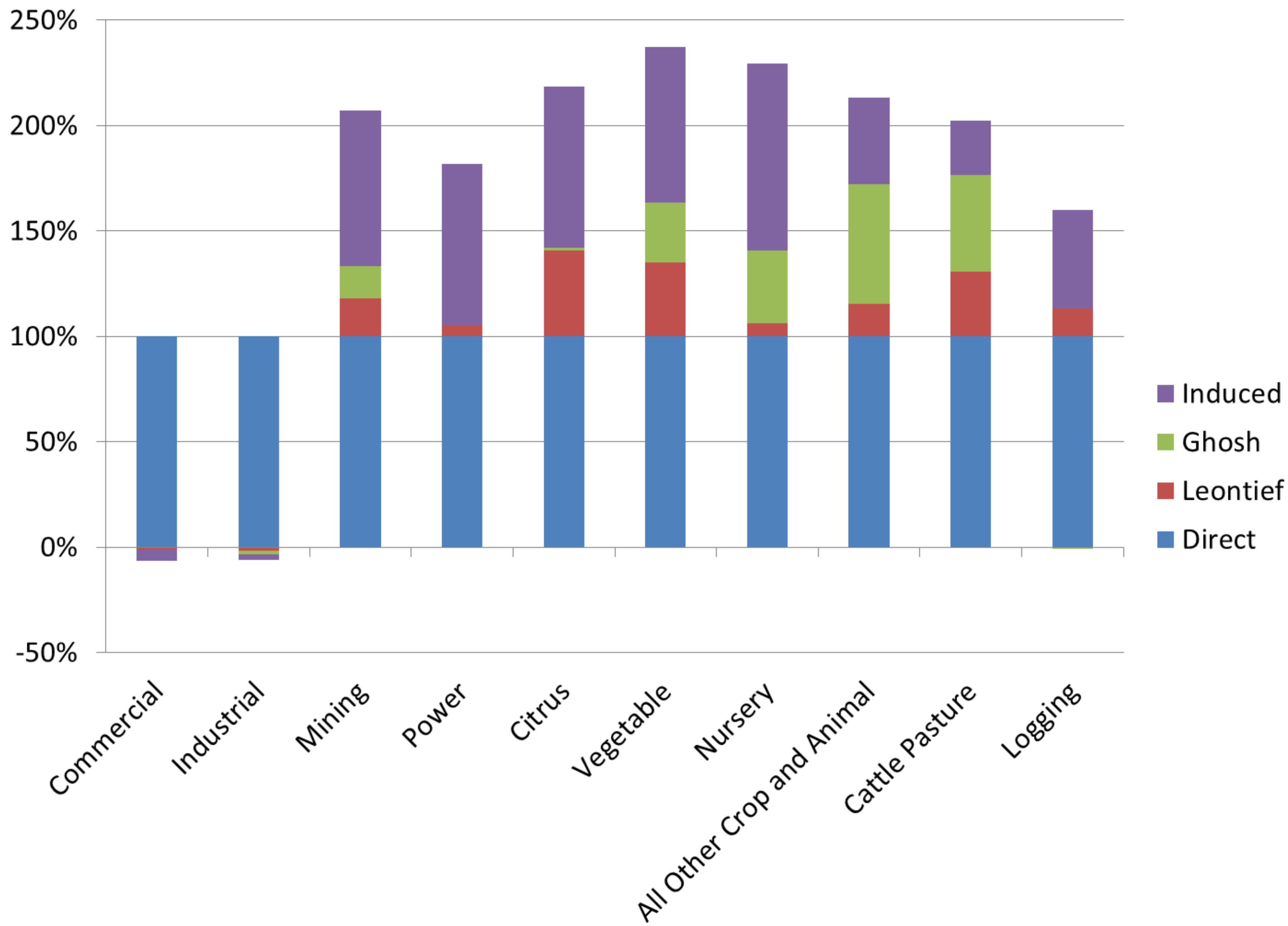

Figure 3-3. Percent change in monetary output when accounting for economic linkages within the region. Direct output measures the total economic output of the land use itself, while the three additional contributions represent economic activity occurring the other land uses but required by the direct production of the primary land use.

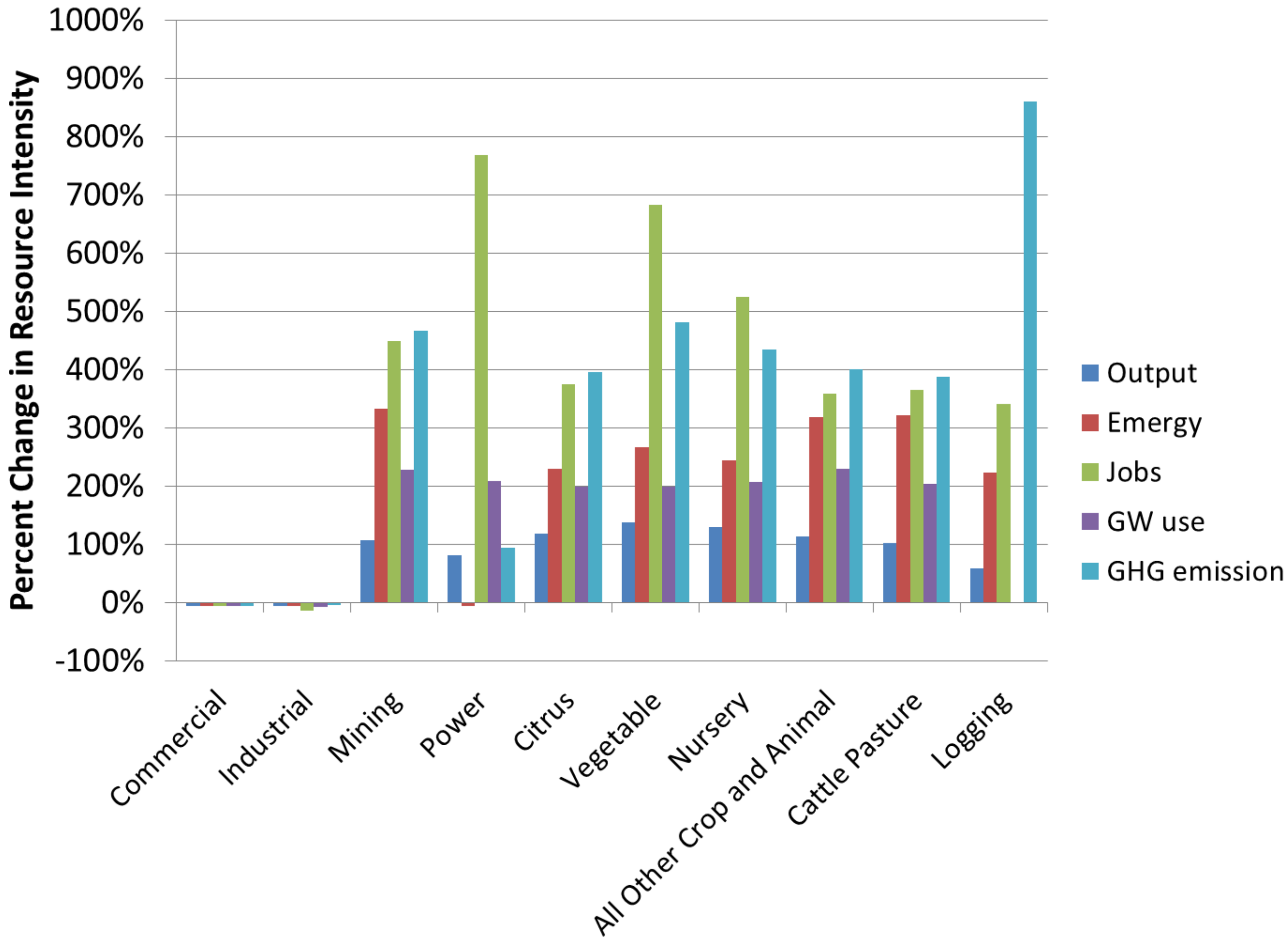

Figure 3-4. Percent change in resource intensities of land uses due to accounting for economic linkages. The changes are significant within all resource categories. Small initial values, such as logging, tend to have the largest percent increases.

Table 3-5. Land use inputs to the Peace River optimization model

Land Use	Output ($M/ha)	Emergy (seJ/ha)	Jobs (jobs/ha)	Water Balance (m^3/ha)	Flood Balance (m^3/ha)
Residential	0.0000	2.94E+17	-6.898	1151	-1016
Commercial	0.7621	6.10E+17	11.475	667	-1016
Industrial	2.3154	3.01E+18	18.221	-9410	-1016
Mining	0.0252	9.14E+16	0.200	284	-1016
Power	0.8410	3.89E+19	6.163	-210	-1016
Citrus	0.0097	1.95E+16	0.151	-2467	-1016
Veggie	0.0336	6.00E+16	0.352	-5619	-1016
Nursery	0.0263	4.97E+16	0.410	-2551	-1016
Crops	0.0078	1.55E+16	0.169	-498	-1016
Cattle-pasture	0.0025	5.40E+15	0.034	1228	-1016
Cattle-range	0.0001	4.63E+14	0.002	2184	0
Logged forest	0.0003	6.53E+14	0.006	2089	0
Upland forest	0.0000	1.62E+14	0.000	2091	0
Wet forest	0.0000	1.72E+14	0.000	2598	1524
Wetland	0.0000	1.82E+14	0.000	2078	1524
Water	0.0000	2.13E+14	0.000	1790	3048
Stream	0.0000	2.13E+14	0.000	0	3048
Salt marsh	0.0000	1.82E+14	0.000	0	0
Estuary	0.0000	2.13E+14	0.000	0	0
Open	0.0000	1.52E+14	0.000	1658	-1016

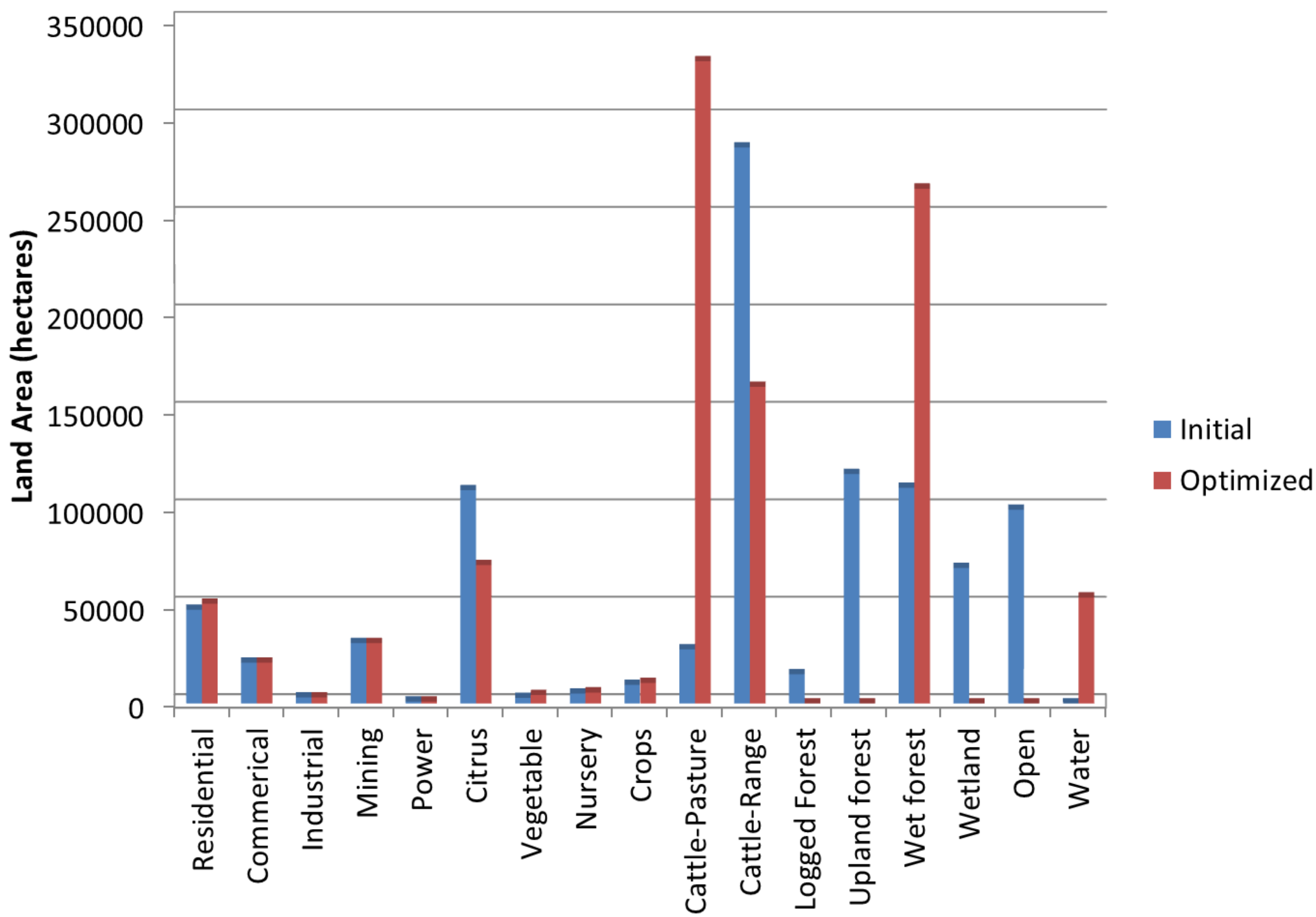

Figure 3-5. Change in land use distribution for regional optimization showing a shift away from citrus and into more cattle production.

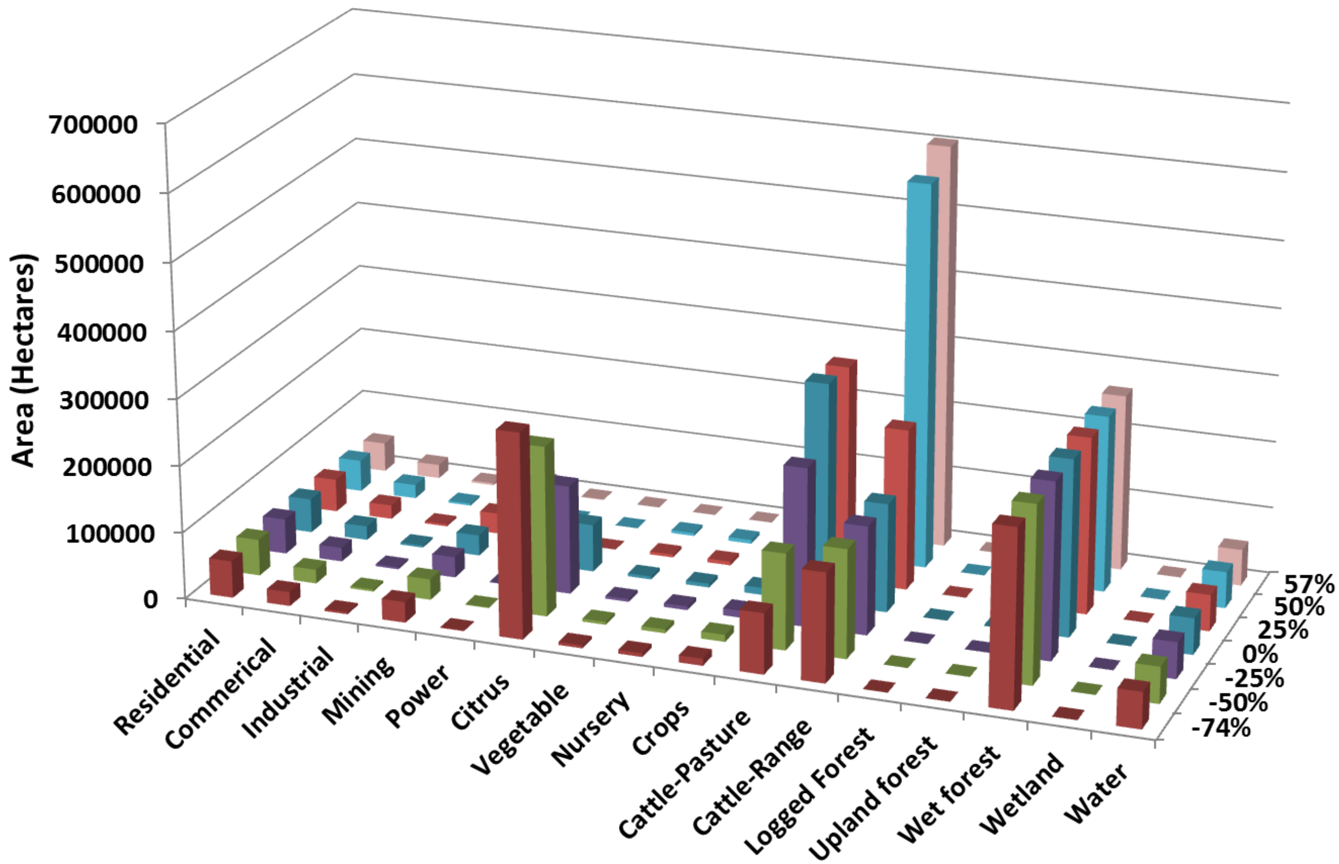

Figure 3-6. Sensitivity analysis of the groundwater recharge constraint showing how increasing the required groundwater recharge results in shifts into first pastured cattle, and the range cattle, while decreasing the required groundwater results in a shift into citrus.

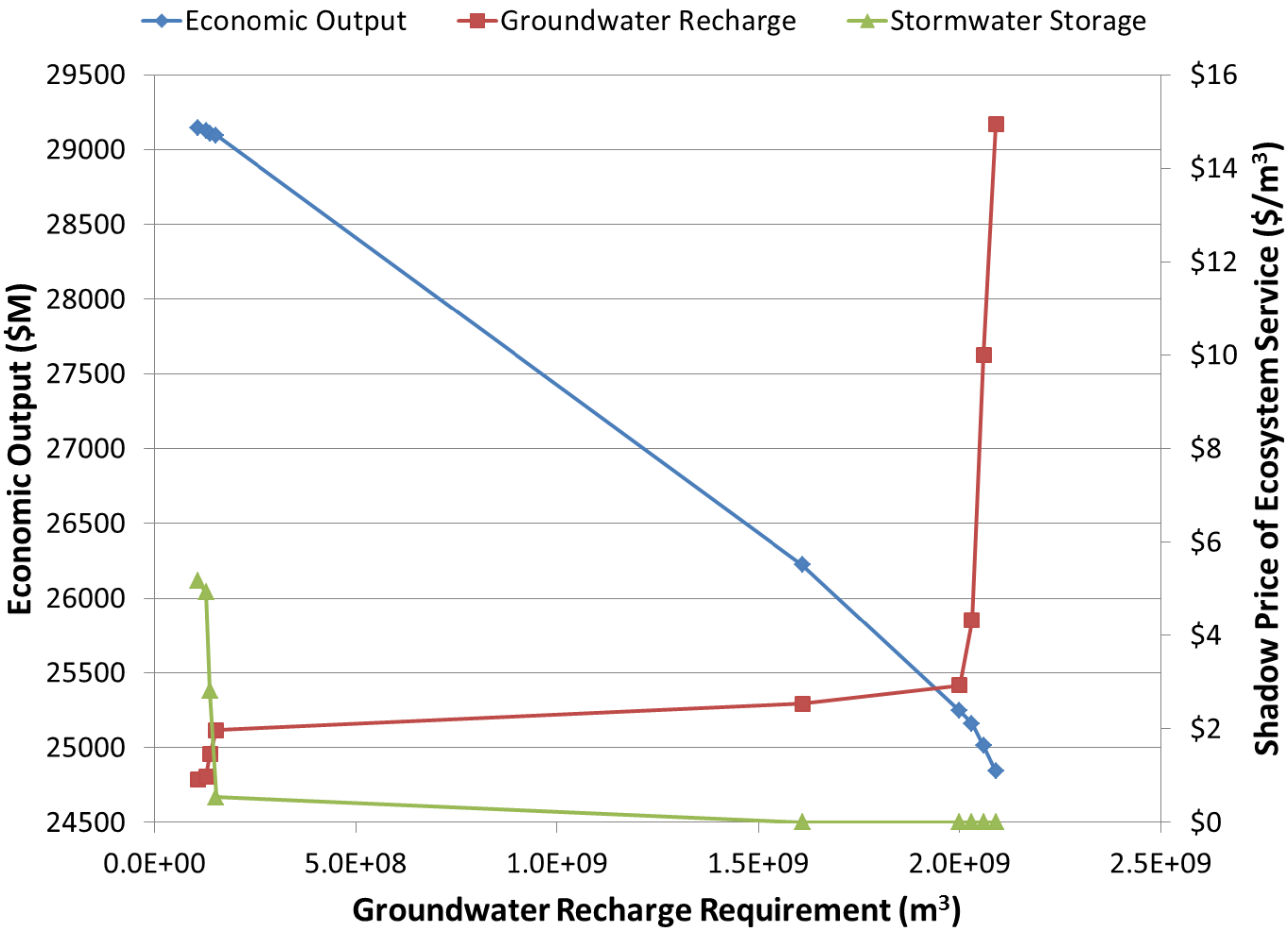

Figure 3-7. Total regional production and shadow prices for groundwater recharge and floodwater storage

CHAPTER 4
ENERGY AND CARBON BALANCE IN A REGIONAL MODEL

Introduction

This chapter outlines the addition of energy and GHG emission consideration into the optimization model for the Peace River region. This required the definition of the GHG emission characteristics of the land uses in the model. GHG emissions and energy use of the region's industries as previously defined in the regional EIO-LCA model were allocated to the region's land uses. In addition, new land uses that produce renewable energy for the region were defined based on information on recently constructed and planned alternative energy projects in the region. Sustainability constraints dealing with GHG emissions and fossil fuel use are incorporated into the optimization model, and the maximum sustainable production is recalculated with these new constraints and land uses. At the conclusion of the chapter, the results of the optimization model are reported and the impacts of the new sustainability constraints and the new renewable energy land uses are evaluated.

Energy is a key limiting resource that is required for regional production. Regional production utilizes both renewable energy sources from the sun and rain, and non-renewable sources from fossil fuels. As in most modern economies, the region's non-renewable energy is imported, and is purchased with money earned through exports. A limiting factor for a region's access to imported energy is the ratio of money received for its exports to money spent on importing energy. In the future, increased competition for energy sources, combined with decreasing supplies could substantially decrease this ratio and increase the costs of imported energy. In the future, energy security could become a significant challenge to systems seeking to maintain sustainable levels of production. While a region may achieve higher productivity using imported energy sources while energy prices are low, long term sustainability will be higher if a region can increase its reliance on internally generated energy sources.

Energy and GHG emission are closely linked, and should be considered in concert with one another. This is because fossil fuels, the major energy source in developed regions, emit greenhouse gases as they are combusted. While a greenhouse gas balance is not required to maintain sustainable production at the regional scale, a global balance of greenhouse gas emissions is important to climatic stability, which has the potential adversely impact the region. In addition, national level emission policies may eventually be translated to the regional level for implementation, producing a limiting constraint on emissions. One strategy for reducing GHG emissions is to shift to renewable energy sources that have lower GHG emissions. Part of the motivation for this chapter is to begin building analysis tools that will help regions evaluate and plan a transition to increased reliance on internal energy sources.

Methods

Energy Use of Regional Land Uses

Each land use in the Peace Region was characterized in terms of its fossil energy consumption. The energy use of each land use was calculated using the regional EIO-LCA model developed in Chapter 2. The EPA's e-GRID database[69] provided electricity production data for the Peace River region. Since data for 2002 was not available; data from 2000 was used for the region's generating stations. Industries that generate electricity for their own internal use were not included in the fuel use of the power generation industry. The electricity generated by these industries was considered to be consumed within the industry itself, and was not counted as electricity entering the regional power grid. Residential electricity and fuel use for the Peace River region was estimated using the per capita energy use of Florida multiplied by the population of the region.

GHG Emissions of Regional Land Uses

To calculate the net GHG emission for each land use in the model, the environmental carbon sequestration of each land use was estimated and added to any economic emissions to obtain a net emission value for that land use. Economic emissions for each land use were calculated using the regional EIO-LCA model from Chapter 2. Indirect emissions that occurred in other land uses but were driven by the economic activity in another land use were added to the driving land use and subtracted from the emitting land use, using the methodology described in Chapter 3 for economic linkages.

An average environmental GHG sequestration was estimated for each land use as well. Average net primary production (NPP), the difference between total production and a plant's own consumption, was used as an upper bound on how much carbon could be stored annually in a particular land use. For upland land uses, each land use was assigned an average carbon sequestration value based on a characteristic NPP for that land use.[70] NPP was then converted to metric tons of carbon dioxide equivalents ($MTCO_2e/ha/yr$) to give an equivalent GHG sequestration rate. Wet land uses, including wetlands, lakes, and streams were assigned a zero value of GHG sequestration. Wet land uses emit CH_4 and N_2O as part of their biogeochemical cycling, and although these emissions are small with respect to carbon flows, their higher warming potentials give them disproportionate impact. As a result, GHG emission and sequestration effects can cancel out in wet environments. The literature reports a wide range of values for wet land uses from net emission to net sequestration based on varying climate and hydrology conditions.[71] Based on the unresolved uncertainty associated with freshwater wetland hydrology, the assumption was made that on average the wide variations in emission and sequestration cancel out for wet land areas.

Definition of New Land Uses

For a region to increase its energy sustainability, it needs to increase the use of renewable sources of energy from within the region. There are relatively few options for renewable energy within the Peace River region. Wind and geothermal energy resources are limited within the region, and hydropower is limited because of low topographic relief. Solar insolation is high, however, and represents a significant energy source. Biomass production is also high in the region due to high insolation, plentiful rainfall, and high average annual temperatures that allow for extended growing seasons. These two resources currently represent the best options for renewable energy production in the region.

Incorporating biomass energy into the regional model requires an accounting of the carbon contained in the biomass fuel sources. Fuels derived from regionally harvested biomass re-emit their stored carbon into the atmosphere as they are consumed. The sequestration of carbon was assigned to the land use where the net primary production occurred. Re-emission of carbon was assigned to the land use where the emission occurred, which was not always the land use from which the stored carbon originated. This allocation convention allowed renewable energy sources to be substituted within the optimization model for non-renewable energy sources while still accurately tracking total GHG emissions for the region.

To evaluate the potential impact of implementing renewable technologies on a regional scale, each proposed renewable energy technology had to be transformed into a new regional land use. Economic and environmental characteristics at the landscape scale were collected using available data on existing or proposed installations. A photovoltaic solar land use was defined using data on Florida Power and Light's recently constructed DeSoto Solar Energy Complex located near the city of Arcadia within the Peace River watershed.[72] A bioethanol production land use was modeled after a proposed bioethanol plant to be built in Highlands County, just south of the Peace River region.[73] This plant is to be constructed by US Envirofuel and plans to use a combination of sugarcane and sorghum as bioethanol feed stocks. The third alternative energy source was a biomass-fueled electric power plant. Such a plant is currently under construction by US EcoGen within Polk county in the Peace River region.[74] This plant plans to use wood from eucalyptus trees grown in plantations on reclaimed mining land to produce electricity for wholesale within the region. Data to characterize the resource requirements and land use impacts of these three land uses was collected from publically available sources.[72–74]

The environmental water requirements for each new land use were also defined. The photovoltaic land use was not considered to have any continuing economic input requirements once the plant was constructed. Environmental water flows for the land use were estimated using the same values as were used for the open land use. Water requirements for growing sugarcane and sorghum in southern Florida were obtained from Evans and Cohen.[75] Sugarcane was reported to have 1100 mm of ET per year, and have an average irrigation rate of 725 mm/yr. Sweet sorghum is a much more water efficient crop, reported to have 650 mm of ET during its 120 day growing season. If the land area is left fallow between harvests, an annual ET for the land use of 825 mm/yr of ET is estimated to be required, with an average irrigation rate of 250 mm/yr. Water requirements for the eucalyptus plantation were assumed to be the same as for a Florida pine plantation, giving an annual ET of 889 mm year.

Definition of Energy and Emissions Constraints:

Two additional constraints were added to the model, a GHG emission constraint and a renewable energy constraint. Total GHG emissions are a concern at the global scale, and so any local constraints are likely to be based on implementation of policies at either the global or national level. An emissions constraint was selected to meet the proposed Kyoto protocol global policy objectives, which called for a 9% reduction from 1990 emission levels within the U.S.[76] Calculating the total reduction for the region required an estimate of both the 2002 and 1990 emissions for the state of Florida. These were calculated using the EPA's SIT model and corresponding state dataset. The growth in Florida's emissions from 1990 to 2002 was found to be an 11% increase. Adding this to the proposed 9% reduction gave a total reduction of 20% required from 2002 emission levels in order to meet the Kyoto standard. In order to transfer this standard to the regional level, the assumption was made that each region within Florida would be responsible to meet the same percentage reduction as required for the state. The initial conditions for the Peace River regional optimization model were used to calculate the region's 2002 GHG emissions, accounting for both environmental and economic emissions. The goal of a 20% reduction was applied to this value to set the emissions constraint.

A fossil fuel constraint was also developed for the region. Energy use within the model was separated into two categories: energy use requiring direct consumption of fossil fuels, which included the production of electricity, and energy use from the consumption of electricity. For both of these categories, net energy demand from a land use was assigned positive values, while net energy production was assigned negative values. This convention allowed any net renewable fuel production to offset fossil fuel demand, and net renewable electricity production to offset electricity demand. Since renewable energy production could be used to replace fossil fuel use, the constraint had the effect of limiting the region's use of fossil fuel, but not necessarily reducing the total energy use within the region. Total energy use could however decrease if required in order to meet the constraints and maximize the region's output.

An additional constraint was employed for solar electricity production. Since large scale electrical energy storage is not yet commercially viable, solar electricity is effectively constrained to provide only peaking power during the day. A constraint was employed in the optimization to limit solar electricity to account for only 10% of the total electricity production for the region. This prevented the model from assuming base electricity needs could be met with solar energy.

Results

Land Use Models

The GHG emission and energy use characteristics for the original land uses in the model were defined. The average carbon sequestration rates for the environmental part of the land uses are given in Table 4-1. Forest and Logged forest had the highest GHG sequestration rates, followed by improved pasture. Citrus and nursery land uses had intermediate sequestration values, followed by range land, open land, and mined land, the majority of which is in various stages of reclamation. Residential, commercial, industrial, and power generation land uses had decreasing amounts of sequestration, due to the increasing intensities of these land uses. Finally, vegetable and other crops were considered not to have sequestration because these crops are removed from the land use annually. Wet land uses all had zero sequestration values.

The environmental GHG sequestration values were combined with the economic GHG emissions for each land use from the EIO-LCA model. Table 4-2 gives the list of combined energy and GHG characteristics per hectare for the original land uses in the model. Of all the land uses that had an economic component, only citrus, cattle, and logging retained net sequestration characteristics after the economic emissions were accounted for. Upland forest was the only environmental land use that had net sequestration values.

The new land uses were also characterized on a per hectare basis so they could be added to the model. Table 4-3 gives the list of metrics and associated values calculated for the new land uses. Comparing these on a per hectare basis, solar electricity has the highest production value, and the highest groundwater recharge. After construction is complete, solar power generation has minimal water or fuel requirements, and no carbon emissions from electricity production. Some fossil fuels will be required for mowing during summer months, but these requirements are small, and they were considered negligible within the model.

Ethanol production is the only alternative energy land use that has an output that can substitute directly for fossil fuels in transportation activities. It is also the only renewable energy land use that has net carbon sequestration, due to the carbon retained in the ethanol it produces as an end product. While this carbon will be re-released as it is consumed in other industries, those emissions will be attributed to the consuming industry. Sugarcane bioethanol production is a high net consumer of groundwater due to sugarcane irrigation. The sorghum only bioethanol land use increased the land area needed to produce the same amount of energy, but dramatically decreases groundwater use due to sorghum's much lower water requirements.

The biomass fired electricity land use emits the carbon stored in the trees as it burns them to produce electricity. Since both the sequestration and emission of this carbon are occurring in the same land use, no net GHG emission is created. However, the harvesting of trees requires fossil fuel use, as does the initial start-up of the power plant, so the land use acquires a net GHG emission. Its GHG emission rate, however, is significantly less than the emission of the power generation land use that is based on burning fossil fuels, allowing it to decrease net regional GHG emissions if it is substituted for fossil fuel based electricity generation. The groundwater recharge of biomass fired electricity is higher than that of bioethanol, as there is no irrigation of the tree crop.

Initial Optimization

The optimization model was updated with the newly defined land uses. In the initial model run, regional output was optimized without adding GHG emission and fossil fuel constraints. The resulting land use distribution included the maximum allowable solar electricity generation in the region. Only the solar energy land use was selected in the unconstrained model run out of the new land uses. The inclusion of solar power resulted in a $14M increase in regional production over an optimized region without any new alternative energy land uses.

Greenhouse Gas Constraint

A set of model runs were performed to evaluate the impact of incorporating a greenhouse gas constraint on regional production. The initial constraint required a 20% GHG reduction, consistent with the Kyoto protocol. Under this constraint, logging land use increased from 0 to 254,615 ha, while electric power generation decreased by 2.5 %. Regional economic production dropped by $77 M, a 0.28% drop from the maximum production without the GHG constraint. For comparison, the 20% GHG reduction constraint was also evaluated without the addition of renewable energy land uses, and a $170M drop in regional production was incurred. The addition of the solar land use, then, resulted in an increase of $93 M in regional output when under the 20% GHG emission reduction constraint.

A sensitivity analysis was conducted varying the emission constraint between a 20% and 100% reduction. The results of these model runs are shown in Table 4-4. The regional output decreased by $77M for a 20% reduction and by $1,463M for a 100% reduction in GHG emissions. A regional shadow price was calculated per metric ton of carbon dioxide equivalents, and was found to increase from $90 to $413 per $MTCO_2e$ as the GHG reduction requirement increased. Figure 4-1 shows the changes in land use required to meet the GHG emission constraint for each model run. As the constraint increased, land use shifted into logging and away from citrus, pastured cattle, and power production. This allowed the landscape to sequester more carbon in the products of the logged forest. This pattern held up to the 70% reduction constraint, when sorghum based bioethanol began to be substituted for logging land use. The optimization was able to achieve a 100% reduction in GHG emission, meaning that GHG emissions were completely balanced with sequestration. However, at this most stringent constraint condition, $1.46 billion had been lost from regional economic output, and the regional population had decreased by 14%.

Fossil Fuel Constraint

A second set of model runs evaluated the fossil fuel constraint independent of the GHG constraint. The initial constraint was based on a proposed fossil fuel reduction of 20%. Under this scenario, the region added 132,752 ha of sorghum based bio-fuel land use. Total regional production decreased by $125M, which was a 0.47% loss from the maximum production without the constraint. In comparison, meeting this constraint without any offset from renewable energy sources resulted in a $315M loss to regional production. Incorporating the 20% fossil fuel offset constraint had the additional impact of reducing GHG emissions by 16%.

A sensitivity analysis was conducted varying the fossil fuel constraint between a 20% and 70% offset of non-renewable fossil fuel. The results of these model runs are shown in Table 4-5. At the 70% offset constraint, the loss in production was $1,433M, a 5.35% drop from the maximum production without this constraint. In this scenario, almost all agricultural and forest land had been converted to energy production. The 80% constraint had no solution for the optimization, as not enough land area that was not already under constraint was available to meet the additional energy production requirement required.

Figure 4-2 shows the land use shifts required to meet the increasing fossil fuel constraint in the region. Pasture land for cattle production steadily gives way to sorghum production to meet the energy requirements of the region. Because of water limitations, sugarcane bioethanol is never selected for inclusion in the region. As pastureland decreases and sorghum bioethanol increases, water runoff in the model declines, and the need for wet forest which is providing runoff storage declines. It is subsequently converted to rangeland pasture. In stark contrast to the previous model, all upland forest is removed from the model, because it does not add to the energy supply, and its ability to sequester carbon is not valued without a GHG emission constraint.

Optimization with Combined Constraints

A final optimization was performed with both the 20% GHG reduction constraint and the 20% renewable fossil fuel constraint operating simultaneously. The resulting land use distribution is given in Figure 4-3 and compared with both the initial land distribution and the optimized distribution with no energy or GHG constraints. In the fully constrained model, solar energy and sorghum based biofuels are both selected for incorporation into the region. Land use shifts away from citrus and cattle, to accommodate the significant increase in sorghum based bioethanol. Logged forest also increases due to its ability to sequester carbon. Total forested land area in the region is dramatically increased, as all freshwater wetland was converted to forested wetland to maximize water recharge. The scenario that was optimized without GHG emission or fossil fuel constraints resulted in a 1.83% increase in economic output, while the constrained scenario resulted in a slightly lower increase of 1.34%. The loss due to increased sustainability constraints was only .5% of total output, having a value of $128M. This develop scenario still represents a $352M gain from the initial economic output.

Comparison of Constraints

Figure 4-4 shows a comparison of three sustainability constraints, groundwater recharge, fossil fuel reduction, and GHG emission, varied independently of each other. The impact of each constraint is shown in terms of its effect on regional production. The graph reveals that in terms of percent change, groundwater recharge is the most limiting factor in this region. The loss in production is steeper with percent changes of groundwater recharge than percent changes in GHG emissions or fossil fuel reduction. The change in production is fairly linear for the percent changes of groundwater recharge. This is not the case for changes in energy and GHG constraints, which have fairly low impacts on regional production for small percent changes, but have large impacts as their percent changes increase.

Discussion

This chapter considers a wider picture of sustainability for the Peace River region, adding energy and emission constraints to the water constraints evaluated in Chapter 3. One of the questions that this model is designed to answer is to find where the region’s current production is in comparison to its maximum sustainable production level. Comparing the region’s economic output with the reported 2002 output shows that there is still room for development in the region. Optimization under water constraints alone resulted in a 1.8% increase in economic output. This increase comes largely from re-allocating the open land in the region, including un-reclaimed mining lands, to productive land uses. Including the GHG and fossil fuel constraints lowered this increase in economic output to 1.34%. This suggests that proposed 20% GHG emission and fossil fuel sustainability constraints could be met while still allowing room for economic growth in the region.

It should be noted that the land use shifts required to achieve this growth are substantial. The optimized solution meets the constraints through a combination of shifting land uses to renewable energy production, reducing electricity production beyond what the system itself requires, and reducing the supported population. The primary reason for the minimal economic impact is that initially, the monetary output for the new renewable energy land uses are only marginally lower than the monetary output for the land uses they are replacing. However, as sustainability requirements are increased, the gap between the value of production of the replaced land use and the renewable energy land use widens, and regional losses in production are incurred more rapidly.

Impact of Sustainability Constraints

A consideration of Figure 4.4 shows that for the initial conditions of the model, economic production is most sensitive to the groundwater constraint. The slope of the groundwater constraint is initially higher than the slope of the GHG or the fossil fuel constraint. This suggests that the actual groundwater recharge required for maintaining aquifer levels will be an important question to answer for any regional planning organization. The optimization model does not answer that question. For this model, the groundwater constraint was chose to maintain the level of recharge that was already occurring in the region for the year of the model, but this may or may not be sufficient to maintain aquifer levels over the region.

As percent changes increase for the constraints, the slope of the fossil fuel and GHG emissions constraints become steeper. Eventually, the slope of the fossil fuel constraint becomes steeper than that of the water constraint, and fossil fuel use has the potential to become the limiting production factor. However, the solution space of the model closes before the crossover point with the water constraint is reached. This lower limit to the solution space is caused by holding constant the commercial and industrial production that is not related to the other land uses. This requires that a minimum amount of water and energy resources be made available for this production. Allowing shifts in the area of these land uses would extend the solution space of the model and crossover points could be observed. This boundary on the solution space also prevents a scenario with 100% of energy coming from inside the region from being evaluated.

Implementing the renewable energy constraint has the additional effect that it results in a decrease in GHG emissions. However, the resulting land use distribution has significant differences. Implementing GHG reductions alone resulted in increases in logged forest area because of the carbon sequestration that forestry land uses provide. If the region has a high value for natural landscapes, or desires to maintain higher storages of both energy and fiber in the region, then the GHG emission constraint helps to value those landscape functions. The renewable energy constraint by itself values producing energy on the landscape at the maximum rate. It selects sorghum biomass because of the high energy yield, the low water requirement, and the higher price that it commands per hectare than other renewable energy sources.

Impact on Population

An important result of the model is that the population supported in the region declines with increased sustainability constraints. While the optimized region under only the groundwater constraint will support a 6.3% increase in population, adding the 20% GHG and fossil fuel constraints results in only a 2.5% increase in supported population. In the 70% renewable energy constraint, renewable energy land uses consume 52% of the variable land use in order to support the residential population and industrial and commercial production. While the monetary loss is only estimated to be 5% of total economic production in this scenario, the residential population loss exceeds 15%. In this case the model is trading addition population for additional production.

The model is operating under the assumption that the average residential resource consumption is always maintained, and so therefore population must decrease to meet the system's constraints. In reality, there are other options available to a region to meet these constraints. Efficiency increases in the residential resource consumption, including water, energy, and land requirements could be employed to continue support for a higher population. Allowing decreases in average standard of living would also allow the region to support a higher population in the region. Ultimately, the regional stakeholders must agree to the goal the region wants to achieve, whether that is maximizing the supported population, or maximizing the standard of living of the final population, or a balance in between. The valuable aspect of the optimization model is that it allows for an estimate of the extent to which efficiency measures would need to be employed to maintain the desired regional population at the region's maximum sustainable production level.

Impact of Renewable Energy Land Uses

The introduction of the renewable energy land uses gives the region additional options to meet both GHG emission and fossil fuel reduction constraints. These land uses generate both jobs and economic output within the region. However, depending on the land use, they can also be more resource intensive than the land uses they replace. The optimization model provides a way to evaluate the mix of renewable energy land uses that provides the best value to the region.

Including renewable energy land uses also results in a decrease in GHG emissions. However, the resulting land use distribution has significant differences. Implementing GHG reductions resulted in increases in logged forest area because of the carbon sequestration that forestry land uses provide. If the region has a high value on natural landscapes, or desires to maintain higher storages of both energy and fiber in the region, then the GHG emission constraint helps to value those landscape functions. The renewable energy constraint by itself values producing energy on the landscape at the maximum rate. It selects sorghum biomass because of the high energy yield, the low water requirement, and the higher price that transportation fuels can generate.

Groundwater recharge continues to be a limiting factor in providing renewable energy in the region. However, it should be recognized that this is due in part to technological limitations in solar energy. If solar energy could be used as base power, and not just as peaking power, then it becomes the best option for the region in terms of resource requirements. However, even if the energy storage issue were to be solved, capital requirements to implement solar remain a significant barrier.

Regional Implications

The results of the current optimization model have sobering implications for regional growth of the Peace River system. When under even partial sustainability constraints, the production capacity of the landscape is limited in its ability to provide the additional production needed to drive economic or population growth. Instead, population decrease is suggested by the model to maximize regional output. Alternative energy land uses are limited in their ability to create economic growth. Solar energy and low-water requirement bioethanol production show promise in helping meet initial renewable energy and GHG reduction goals. However, given the current renewable energy options, the land, water, and capital requirements are too large to make even an agricultural region like the Peace River fully energy independent at current resource consumption rates. Even with renewable energy land uses, the Peace River region has limited capacity for sustainable growth.

The implications of the model should be considered in light of the model's predictive capability. The model only extrapolates the current economic structure of the region. Significant economic restructuring can occur in the commercial and industrial sectors that were held constant in the model. These changes could be a future driver of economic and population growth. However, it should also be considered that any additional commercial and industrial production will require additional resource consumption. Future resource intensities may not remain constant into the future. Energy and water efficiency can be increased in many production land uses to alleviate some of the resource constraints encountered in the model. The ability of the model to forecast which resources may be most limiting as the region develops, and a shadow price for those resources, can be helpful in directing resource efficiency investments. Finally, the technology of renewable energy production can improve over time. Current technological barriers can be overcome. The optimization model can provide insight into the characteristics that renewable technologies and land uses will need to have in order to compete for resources within a region. This information could help plan both technology investments and implementation.

The regional optimization model is a useful tool to envision the outcome of system if it continues on the "business as usual" development path. The ability to forecast limitations to future production can be used to help transition smoothly to a maximum sustainable production.

Table 4-1. Carbon sequestration estimates of Peace River region land uses

Land Use	NPP (g C/m2/yr)	Carbon Stored (MT C/ha/yr)	Equivalents of CO2 (MT CO_2/ha)	Total GHG sequestered (MT CO_2/ha)
Residential	172	0.86	3.16	3.16
Commercial	27	0.13	0.49	0.49
Industrial	0	0.00	0.00	0.00
Mining	300	1.50	5.50	5.50
Power	27	0.13	0.49	0.49
Citrus	325	1.63	5.96	5.96
Vegetable	325	1.63	5.96	0.00
Nursery	325	1.63	5.96	5.96
All Other crops	325	1.63	5.96	0.00
Cattle-Pasture	400	2.00	7.33	7.33
Cattle-Range	300	1.50	5.50	5.50
Logged forest	600	3.00	11.00	11.00
Upland forest	600	3.00	11.00	11.00
Wetland forest	800	4.00	14.67	0.00
Wetland	1000	5.00	18.33	0.00
Lakes	200	1.00	3.67	0.00
Stream	200	1.00	3.67	0.00
Salt marsh	1000	5.00	18.33	0.00
Open Land	300	1.50	5.50	5.50

Table 4-2. Energy and GHG emission characterization of existing land uses

Land use	Carbon Balance (MT CO2eq/ha)	Electricity Balance (TJ/ha)	Fossil Energy Balance (TJ/ha)
Residential	-53.89	0.3432	0.8054
Commercial	-39.51	0.3756	0.5469
Industrial	-350.77	1.3759	7.2171
Mining	-11.20	0.2082	0.2673
Power	-8425.33	-46.0169	135.7594
Citrus	3.29	0.0045	0.0412
Veggie	-8.13	0.0137	0.1270
Nursery	-0.82	0.0121	0.1058
Crops	-2.72	0.0057	0.0421
Cattle-pasture	6.32	0.0020	0.0156
Cattle-range	5.44	0.0001	0.0009
Logged forest	10.93	0.0001	0.0013
Upland forest	11.00	0.0000	0.0000
Wet forest	0.00	0.0000	0.0000
Wetland	0.00	0.0000	0.0000
Water	0.00	0.0000	0.0000
Stream	0.00	0.0000	0.0000
Salt marsh	0.00	0.0000	0.0000
Estuary	0.00	0.0000	0.0000
Open	0.00	0.0000	0.0000

Table 4-3. Characterization of alternative energy land uses

Land Use	Economic Output ($M/ha)	Jobs (jobs/ha)	Water Balance (m^3/ha)	Flood Balance (m^3/ha)	Carbon Balance (MT CO_2e/ha)	Electricity Balance (TJ/ha)	Fossil Energy Balance (TJ/ha)
Biomass Electric	0.0012	0.0032	300	-1016	-0.083	-0.063	0.000
Solar	0.0314	0.0211	3307	-1016	0.000	-1.592	0.000
Sugarcane Bioethanol	0.0052	0.0042	-1357	-1016	6.125	-0.044	-0.087
Sorghum Bioethanol	0.0049	0.0040	11	-1016	4.755	-0.042	-0.071

Table 4-4. Impact of GHG emission constraint on output and shadow price

	Output ($M)	Percent change	Shadow price ($/MTCO$_2$e)	Percent change
No Constraint	26755			
20%	26678	-0.28%	90	0.0%
30%	26595	-0.59%	90	0.0%
40%	26510	-0.92%	90	0.0%
50%	26423	-1.24%	98	9.6%
60%	26329	-1.59%	98	9.6%
70%	26233	-1.95%	121	34.9%
80%	26027	-2.72%	381	325.7%
90%	25662	-4.08%	381	325.7%
100%	25292	-5.47%	416	364.0%

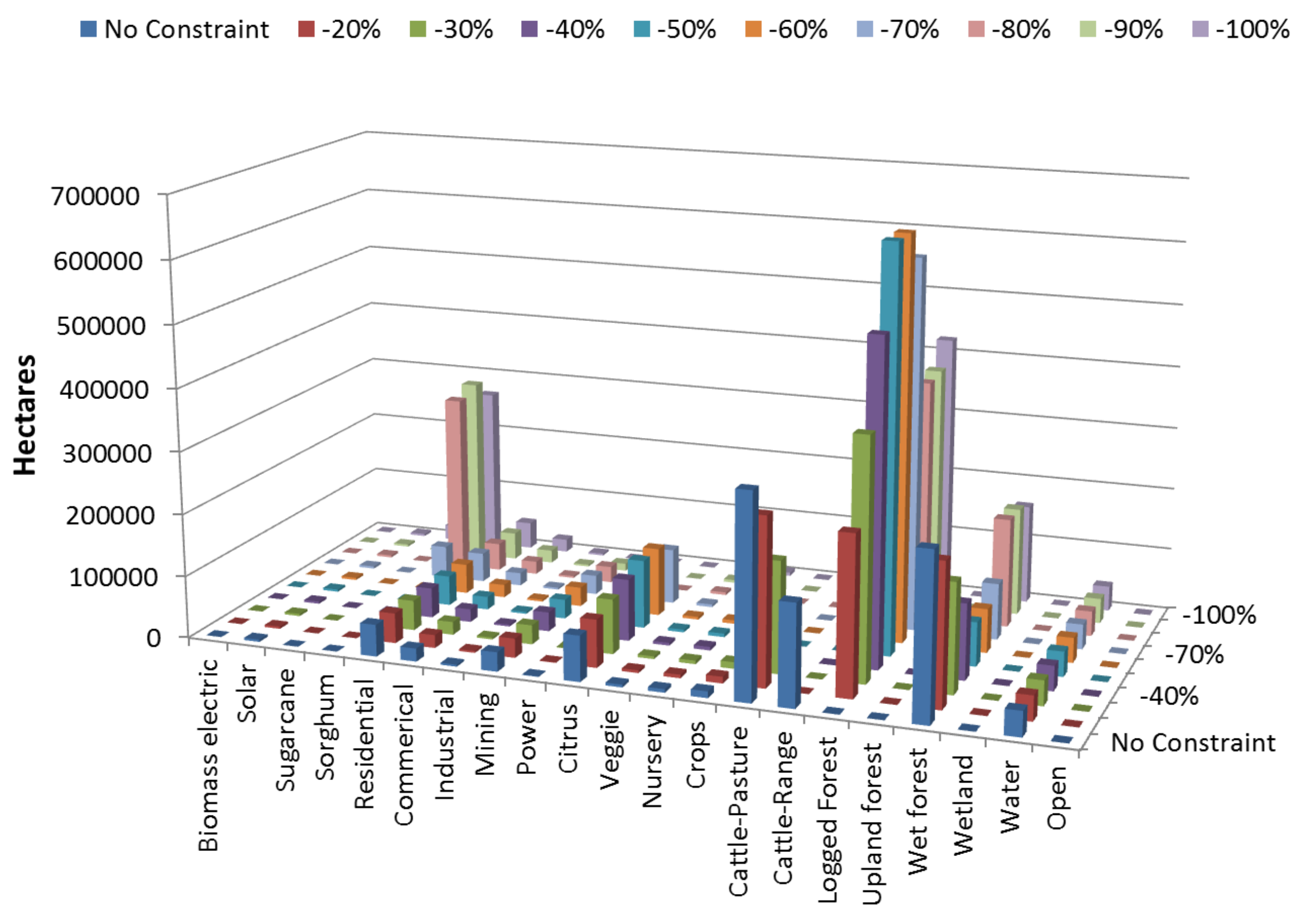

Figure 4-1. Sensitivity analysis of optimized land use distribution under GHG constraints showing increases in plantation forest and then sorghum bioethanol as the GHG constraint increases.

Table 4-5. Impact of fossil fuel constraint on regional output

Constraint	Output ($M)	Percent Change	Shadow Price ($/TJ)
No constraint	26755		
20%	26630	-0.47%	3523
30%	26551	-0.76%	6102
40%	26415	-1.27%	6102
50%	26233	-1.95%	9586
60%	25835	-3.44%	23017
70%	25322	-5.35%	23017
80%	No solution		

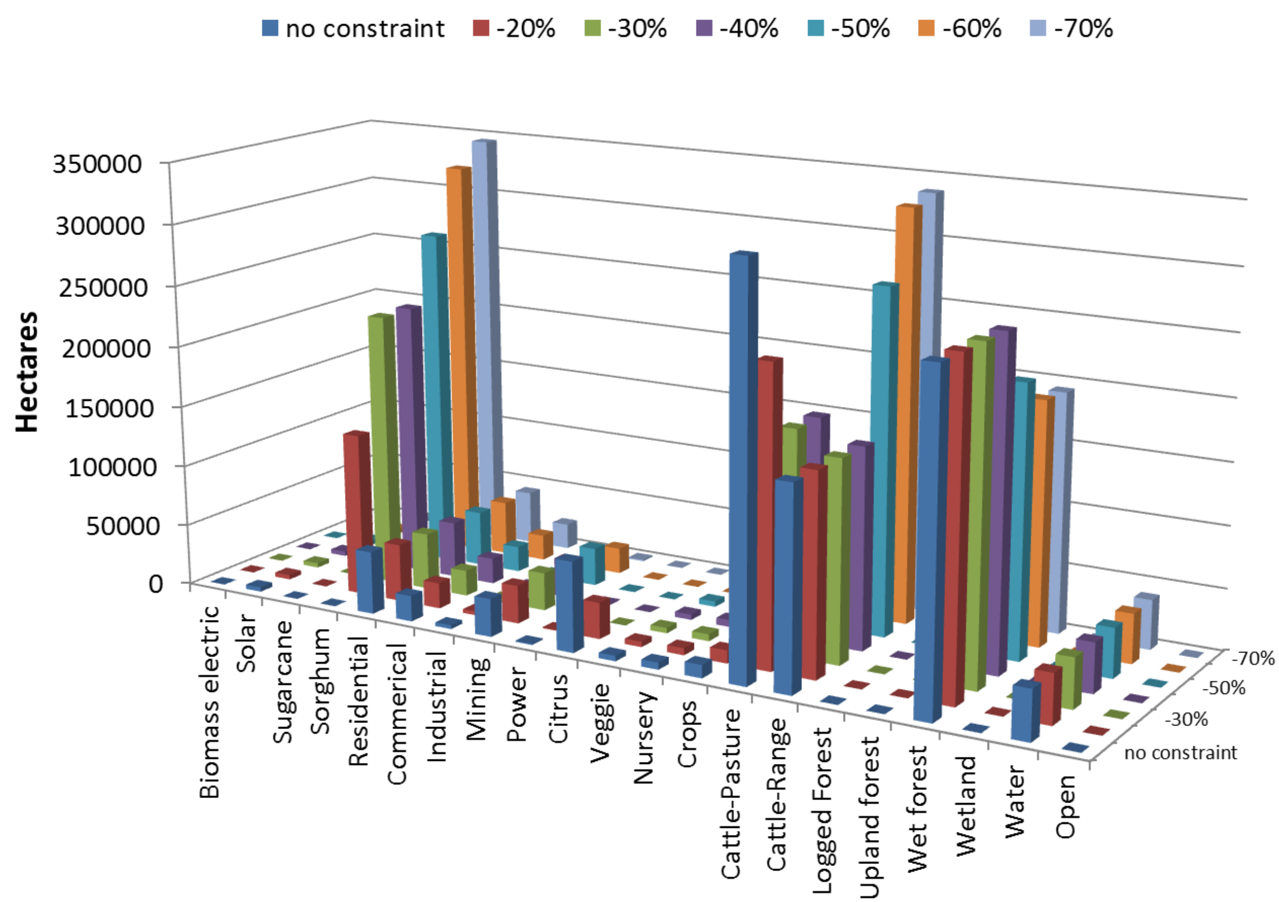

Figure 4-2. Sensitivity analysis of optimized land use distribution under fossil fuel constraint showing a loss of citrus and pastured cattle and an increase in sorghum bioethanol to meet fossil fuel reductions.

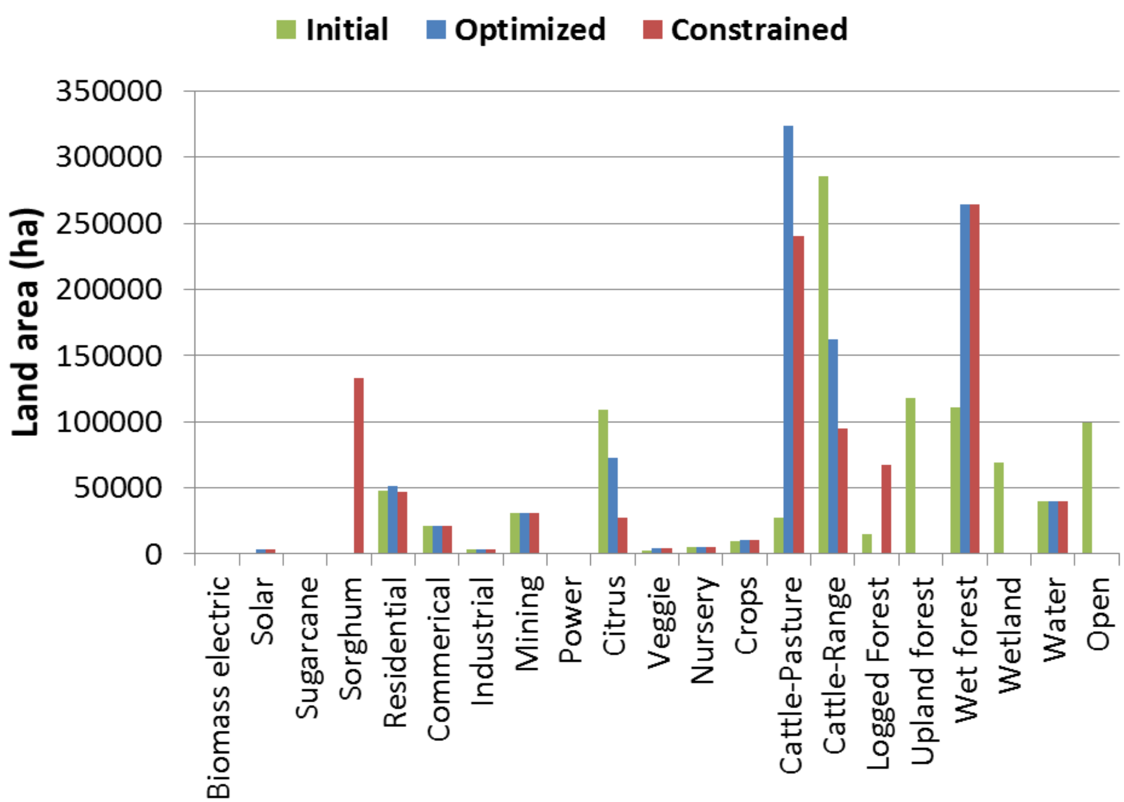

Figure 4-3. Comparison of initial, optimized, and fully constrained land use

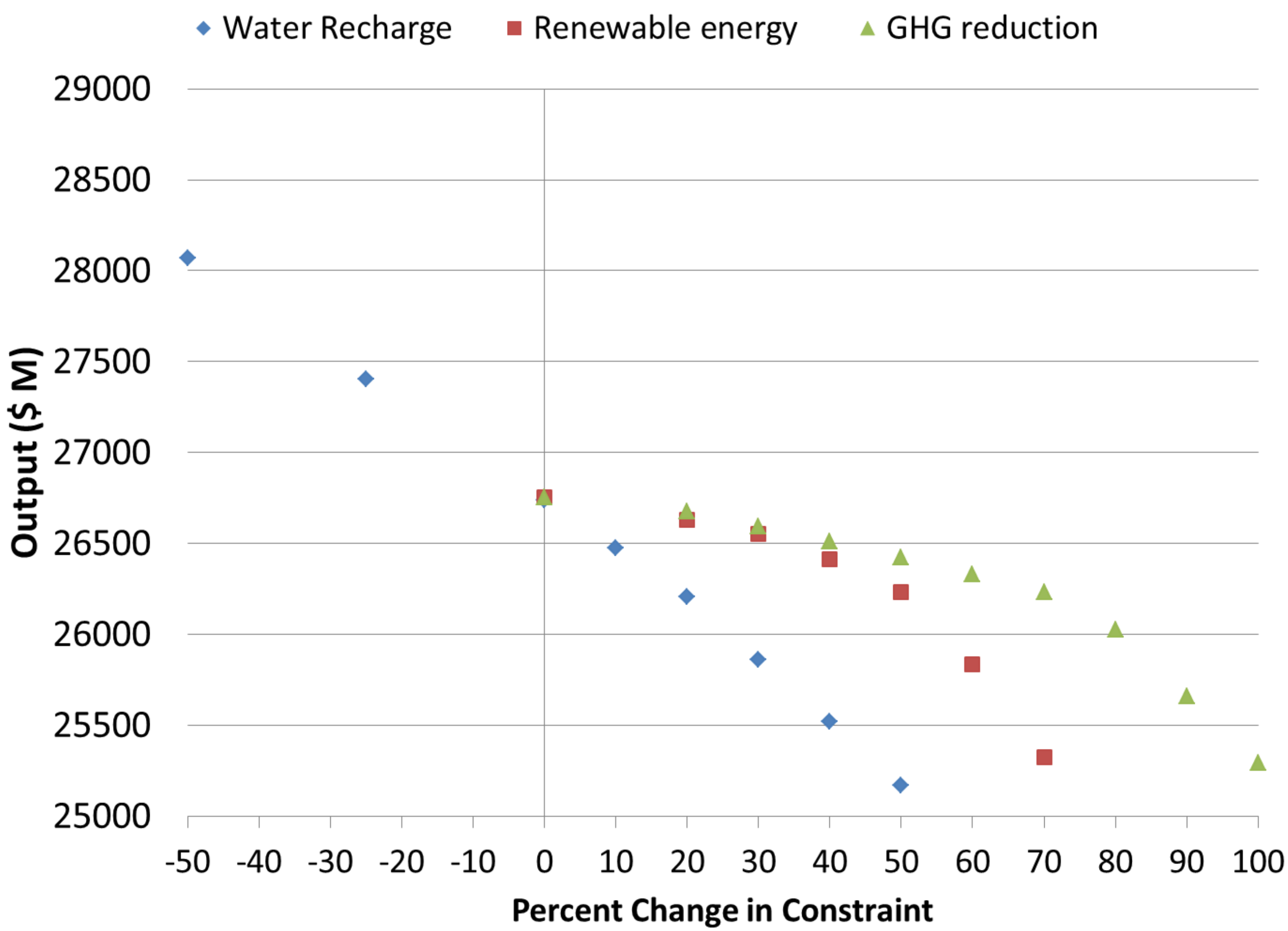

Figure 4-4. Impact of sustainability constraints on regional output showing the region is initially most sensitive to percent changes in groundwater recharge constraints. GHG emission and fossil fuel constraints initially display a smaller sensitivity, but increase in sensitivity as constraints are increased.

CHAPTER 5
EVALUATING THE MODEL

Contributions of the Model

The combination of EIO-LCA with a land use optimization model provides a novel approach to regional sustainability modeling that addresses several shortcomings of other available methods. The contributions of this work include a method for building a regional EIO-LCA model, and a method of constructing a linear programming model that both captures sustainability constraints and accounts for internal interactions between the model components.

The regional EIO-LCA model is attractive for use in regional planning in that it can be implemented quickly with modest effort. The use of commercially available economic modeling software combined with publically available data can dramatically lower the time and cost required to develop the regional model, without sacrificing too much regional specificity. The region's total resource flows are accurately modeled by using a top-down allocation scheme. The resource flows that comprise the largest portions of the total flow are specifically allocated, while state and national averages are used to estimate the remaining flows.

The use of the commercially available economic-input output model provides standardized economic categories so that results are easily comparable with other regions, and regions can also be scaled easily to larger geographic areas. The commercial software also provides for readily available annual updates of the economic model. Public resource consumption data varies in collection timeframes, but is generally updated every four to five years. This allows for the possibility of updating the model at regular intervals. A time series of regional EIO-LCA models could give insight into how the economic structure is changing over time, and the rate at which resource efficiency may be increasing in certain industries. By analyzing these trends over time, projections can be made as to what future resource intensities of certain industries may become, allowing for increasingly accurate optimization results. Construction of a time series of models can also provide an estimate of the uncertainties involved in the calculated resource intensities, allowing for uncertainty analysis to be conducted within the model.

The way the linear optimization model is conceived helps to resolve several challenges inherent in other modeling techniques. In order to move away from having multiple decision criteria to evaluate, a single objective function is selected. That objective is for the region to maximize its productivity, to be as productive as it can be within the limits of the system. While regional stakeholders will need to agree to this objective, it has potential to be a common starting point of agreement even between those who disagree over the meaning of sustainable development. Selecting a single objective function has the advantage that it removes sustainability as the end goal of the system, and instead sustainability considerations become the constraints in the model. This gives more flexibility in how the sustainability constraints are handled.

Sustainability constraints for a region can be levied from outside the system as national and state policy, or they can be selected from inside the system by stakeholders that want certain aspects of their system to be sustained into the future. A valuable aspect of this model is that the required sustainability constraints themselves do not necessarily have to be known with certainty before model implementation. The sustainability constraint can be added to the model and the impact of different levels of constraint can be evaluated in a sensitivity analysis. In multi-criteria decision models, sustainability considerations are made into systems goals, and these goals must be weighted relative to the other goals prior to running the model. The current construct allows for the sustainability constraints to operate concurrently in the model without an externally imposed hierarchy.

There remain theoretical considerations as to how the productivity of the region should be measured. As was discussed in chapter 3, both monetary and emergy valuations were considered, and no difference in outcome was noted. The use of monetary measures makes the model translate more easily into terms that regional planners will be familiar with. Emergy should be further explored as a stable measure of output over the long term. The use of total throughput as a production measure includes the flows that travel through different land uses multiple times. It would be possible to build the model and use value added or GDP as a measure instead and avoid double counting. The decision to use total throughput instead of GDP was based on a desire to capture the internal cycling within the region. Regions with higher levels of internal cycling will be more resilient in the face of external disturbances. This represents a theoretical question that deserves additional attention, and could be an avenue for future work.

A significant contribution to sustainability science is the method of constructing land uses so that they account for the indirect effects they have within the region. Accounting for the indirect resource use helps to evaluate all the tradeoffs that must be made in the system when a major resource becomes limiting. The use of both backward and forward linkages in the model helps to maximize the benefit the region could see from increases in land uses. The optimized region then represents an upper bound on system production based on the region's ability to continue to process its products into higher value added products.

There are many opportunities to expand and improve the capabilities of the model. The current model operates with just 16 economic land uses when including the renewable energy land uses, and only 4 variable environmental land uses. A more detailed model with additional land uses would increase the number of variable economic interactions considered in the model. Commercial and industrial sectors which are currently highly aggregated could be separated into additional land uses within the model. The residential sector could also be separated into low, medium, and high intensity housing. The model, however, is fundamentally limited to land uses that have resource requirements that change linearly with land area, and so many industries will need to remain aggregated.

Once the regional model is developed, it remains flexible in its ability to accommodate new information. It can continue to be updated with new land uses and land use characteristics as this information comes available. The wide-scale implementation of best management practices may significantly shift the resource consumption of certain land uses in the future. Within the model, any land use can be divided into a land use utilizing old practices, and a land use utilizing new management practices to evaluate the impact of best management practice within the region. In the same way, renewable energy land uses can be updated as technology improves efficiency and yield.

Additional work can also be done to make the model better reflect the region in question. IMPLAN models can be modified with regional data to better tailor the interactions of the region. More specific data on regional industries will allow models to be refined to more closely match the economic characteristics of a region. The resource consumption of major regional industries can also be further tailored with the use of detailed studies of these industries, or through the use of estimates of similar industries using process-based LCA. This data can be incorporated in the place of national average estimates to increase the accuracy of the regional model.

A final area for extension of the model is the array of sustainability constraints that are considered. The current implantation of the regional model was limited in scope to water, energy, and GHG emissions. In a highly agricultural region, soil conservation and nutrient availability can be important limiting factors to production as well. A more in depth analysis would consider carbon and nutrient storage in the region's soils. In addition, the eutrophication of streams and lakes in the region is of concern and could also be addressed with information on nutrient use and emission from each land use. Data is also available on regulated air emissions from certain industries in the region that could be considered.

Limitations of the Model

The regional model has several important limitations, and the interpretation of the results should incorporate an understanding of these limits. The current model has no spatial analysis. Only total area and average land use characteristics are considered, and the impacts of spatial relationships are neglected. While the simplification of regional interactions is necessary to build a useful model, lack of a spatial component ignores many important questions. For example, the location of groundwater recharge has a major impact on its ability to maintain sustainable aquifer levels within the region. Groundwater recharge needs to be spread appropriately across the region to maintain aquifer levels. While it was considered to be beyond the scope of this modeling effort, spatial modeling is necessary to fully understand the spatial constraints of the system.

An additional drawback of the model is that does not include any analysis of the impact of loss of diversity within the region. Two kinds of diversity should be considered. Biodiversity within the region is not valued as an ecosystem service by the current set of constraints. While it could be assumed that natural areas in the region will be appropriately managed for biodiversity, there is not yet any mechanism for ensuring that an appropriate mix of habitats is provided. The result is that entire land uses can be eliminated in the optimization, i.e. upland forest, or herbaceous wetland. One way to address this shortcoming is to add constraints that provide minimum levels of certain habitat types in the region that help ensure the maintenance of diverse plant and animal life. A second kind of diversity to consider is the diversity of economic activity. A system that devotes all its land use to one type of activity is more likely to suffer from rapid changes in market conditions, or natural disasters and climatic variation. The inclusion of a metric to weigh the stability of the optimized system would help regional planners decide how much optimization they want to pursue at the expense of system stability.

Finally, not all factors have been included in the evaluation of land uses. Capital costs of developing the land use are important but not fully included in the current model. Although regional productivity may be increased by a particular land use, high capital costs or low return rates on that capital investment could stand in the way of their development, particularly if the land use is dependent on external sources of capital. In the current regional model, the photovoltaic solar land use appears to be an obvious choice for development, and it competes economically with current land uses. This is because the high capital cost of installing solar was not evaluated by the model. Capital costs should be better integrated into future implementations of the model.

Conclusion

The regional EIO-LCA optimization model can be a useful tool to evaluate future options for a region's development. It provides value in that it incorporates both the environmental and economic spheres, and explicitly considers both limiting resource consumption and sustainability constraints. The model is simple in its form, and does not explicitly account for certain nonlinear interactions within regions. However, because the model is constructed so that it bounds the possible solution space, it is still possible to explore the limits of available development options. The model provides a much needed link between the complex environmental interactions, and the complex economic interactions within a region.

Finally, the model provides a means to estimate the maximum sustainable production level for a region. While acknowledging that much information is still uncertain about the future of the system, it still gives regional planners a picture of what a future system would look like based on an extrapolation of the current organization. This allows important questions to be explored in terms of the goals of system development and resource constraints that will be encountered along the way.

APPENDIX A
REGIONAL WATER ALLOCATION

This appendix outlines the steps that were taken to develop the regional water intensities for Florida and the Peace River region. The first step was to collect data from government reports on total water use for each region. Water use for the state of Florida is reported every 5 years by the USGS. The closest data set was the year 2000 water use report. The total consumption data is reported in Table A-1. Matching Florida economic data for the year 2000 was obtained from IMPLAN software. IMPLAN's year 2000 data was reported in an older industry categorization scheme and a bridge table was used to match industries between the year 2000 and the year 2002 categories.

The second step was to develop water intensities for individual industries. USGS estimates of water use had sufficient category resolution that water use could be matched directly with 13 agricultural industries, 4 mining industries, and the electric power industry. Table A-2 gives the USGS data for agricultural industries.

The rest of the industrial and commercial water use was highly aggregated and could not be directly allocated to corresponding IO industries. Instead, correction factors were developed to adjust national water intensities into regional water intensities. The correction factors ensured that the water use of each economic sector summed to the USGS reported value for that sector. The procedure was to multiply the regional economic output by the national water intensity for the corresponding industry. The resulting water use was summed for all industries in an economic sector. The USGS reported water use for that sector was then divided by the calculated water use from the national water intensities.

$$R\ Correction\ Factor = \frac{USGS\ Sector\ Total\quad (gal)}{\sum_{i=1}^{n}(Sector\ Output_i(\$) \times National\ R_i(gal/\$))} \tag{A-1}$$

This percent difference in totals was used as a correction factor for all the industries within that economic sector.

$$National\ R_i \quad \times Sector\ Correction\ Factor = Regional\ R_i \tag{A-2}$$

This allocation method was carried out separately for self- supply water and public supply water sources as the economic aggregation was reported differently for these two sources. The allocation of the self-supplied water subcategories of food production, pulp/paper, chemicals, and other manufacturing helped to differentiate some of the high water use industries in Florida from national averages.

Self-supplied water for the residential sector was estimated in the USGS report by assuming that residential per capita water use was the same as publicly supplied per capita water use. The per capita water use is then multiplied by the population of Florida that is not served by a public water supply system to calculate total water use. Consumed water intensities were calculated by multiplying the water intensity by Florida average consumption percentages as reported in Table A-3.

A water intensity vector was also developed for the Peace River region. Water use is reported individually for each county in the Peace River region by the SWFWMD. The reported data is given in Table A-4. Correction factors for Polk and Charlotte County were developed since they have areas outside the SWFWMD that needed to be accounted for. The list of correction factors is given in Table A-5. Wastewater disposition was included in the Peace River water budget model, and the values for the Peace river region are given in Table A-6.

Table A-1. Florida water use adapted from Marella[39]

Sector	Subsector	Industrial (gals)	Electric Power (gals)	Commercial (gals)	Residential (gals)
Public Supply		3.56E+10		3.11E+11	5.43E+11
Industrial Self-supply					
	Agriculture	1.43E+12			
	Mining	6.80E+10			
	Chemical industry	4.12E+10			
	Paper industry	5.56E+10			
	Food manufacturing	1.24E+10			
	Other manufacturing	8.24E+09			
Electric Power Self-Supply			4.60E+12		
Commercial Self-supply					
	Golf courses			1.08E+11	
	Other recreation			4.21E+10	
	Other commercial			2.06E+10	
Residential Self-Supply					7.25E+10
Total		1.65E+12	4.60E+12	4.82E+11	5.43E+11

Table A-2. Florida's agricultural water use adopted from Marella[39]

Industry	Crop Type	Ground Water (gals)	Surface Water (gals)	Reclaimed Water (gals)	Total Water Use (gals)	Water withdrawn (gals)
Oilseed farming		3.61E+08	2.92E+07		3.91E+08	3.91E+08
	Soybeans	3.61E+08	2.92E+07		3.91E+08	3.91E+08
Grain farming		1.28E+10	1.29E+10	2.30E+08	2.59E+10	2.57E+10
	Field corn	1.24E+10	6.83E+08	2.30E+08	1.33E+10	1.30E+10
	Rice	0.00E+00	1.21E+10		1.21E+10	1.21E+10
	Sorghum	3.32E+08	4.75E+07		3.80E+08	3.80E+08
	Wheat	1.06E+08	1.10E+07		1.17E+08	1.17E+08
Vegetable and melon farming		1.12E+11	4.57E+10	1.20E+09	1.59E+11	1.58E+11
	Vegetables	1.03E+11	4.33E+10	1.20E+09	1.48E+11	1.46E+11
	Potatoes	9.34E+09	2.41E+09		1.17E+10	1.17E+10
Tree nut farming		3.03E+08	3.65E+07		3.39E+08	3.39E+08
	Pecans	3.03E+08	3.65E+07		3.39E+08	3.39E+08
Fruit farming		3.98E+11	2.82E+11	6.94E+09	6.87E+11	6.80E+11
	Blueberries	4.38E+08	1.10E+07		4.49E+08	4.49E+08
	Citrus	3.85E+11	2.81E+11	6.94E+09	6.73E+11	6.66E+11
	Grapes	1.17E+08	1.83E+07		1.35E+08	1.35E+08
	Peaches	3.65E+06			3.65E+06	3.65E+06
	Strawberries	4.78E+09	1.83E+08		4.96E+09	4.96E+09
	Miscellaneous	6.75E+09	1.22E+09		7.97E+09	7.97E+09
	Non-specific fruit	5.66E+08	4.38E+07		6.10E+08	6.10E+08
Greenhouse and nursery production		1.03E+11	4.59E+10	1.63E+09	1.51E+11	1.49E+11
	Field grown	1.99E+10	4.16E+09	1.09E+09	2.51E+10	2.41E+10
	Greenhouse grown	5.11E+08	2.88E+08		7.99E+08	7.99E+08
	Container grown	3.81E+10	9.63E+09	5.40E+08	4.82E+10	4.77E+10
	Sod	4.49E+10	3.18E+10		7.67E+10	7.67E+10

Table A-2. continued

Industry	Crop Type	Ground Water (gals)	Surface Water (gals)	Reclaimed Water (gals)	Total Water Use (gals)	Water withdrawn (gals)
Tobacco farming		1.94E+09	3.65E+07		1.97E+09	1.97E+09
	Tobacco	1.94E+09	3.65E+07		1.97E+09	1.97E+09
Cotton farming		3.01E+09	2.88E+08		3.30E+09	3.30E+09
	Cotton	3.01E+09	2.88E+08		3.30E+09	3.30E+09
Sugarcane and sugar beet farming		1.13E+10	3.01E+11		3.13E+11	3.13E+11
	Sugarcane	1.13E+10	3.01E+11		3.13E+11	3.13E+11
All other crop farming		6.85E+10	1.65E+10	2.28E+10	1.08E+11	8.50E+10
	Peanuts	7.34E+09	4.60E+08		7.80E+09	7.80E+09
	Pasture hay	5.88E+10	1.53E+10	5.37E+08	7.46E+10	7.41E+10
	Other (grasses)			1.59E+10	1.60E+10	0.00E+00
	Miscellaneous	2.40E+09	7.34E+08	6.37E+09	9.50E+09	3.13E+09
Cattle ranching and farming		1.13E+10	5.51E+08		1.19E+10	1.19E+10
	Livestock	1.13E+10	5.51E+08		1.19E+10	1.19E+10
Animal production, except cattle and poultry		2.85E+09	7.67E+07		2.93E+09	2.93E+09
	Fish farming	2.85E+09	7.67E+07		2.93E+09	2.93E+09
State Totals		7.26E+11	7.06E+11	3.28E+10	1.46E+12	1.43E+12

Table A-3. Average water consumption by sector[39]

Category	% Consumption
Public Supply	38.7%
Residential Self-Supply	38.7%
Industrial-Commercial Self-Supply	19.1%
Agricultural Self-Supply	69.5%
Recreational Irrigation	80.0%
Power Generation	9.0%

Table A-4. Peace River region water withdraws[40]

Sector	Subsector	Charlotte (gals)	De Soto (gals)	Hardee (gals)	Polk (gals)	Total (gals)
Public Supply						
	Residential	3.63E+09	3.11E+08	3.76E+08	1.76E+10	2.19E+10
	Commercial	1.01E+09	1.65E+08	1.36E+08	4.53E+09	5.85E+09
	Industrial	9.39E+07	2.92E+07	1.65E+07	5.83E+08	7.23E+08
	Recreation	5.64E+07	0.00E+00	0.00E+00	2.67E+08	3.23E+08
	Public Use	7.81E+08	8.27E+07	8.68E+07	3.74E+09	4.69E+09
Agriculture Self-Supply						
	Citrus	1.70E+10	2.53E+10	1.83E+10	4.96E+10	1.10E+11
	Other Crops	1.87E+08	9.53E+07	2.05E+08	1.43E+08	6.30E+08
	Nursery	8.75E+08	1.34E+09	1.16E+09	1.60E+09	4.97E+09
	Vegetable	3.22E+09	9.32E+08	1.92E+09	6.75E+08	6.74E+09
	Pasture	6.33E+08	1.19E+09	1.16E+09	9.51E+08	3.93E+09
	Livestock	9.51E+06	4.02E+08	3.47E+08	9.79E+08	1.74E+09
Mining Self Supply						
	Limestone	0.00E+00	0.00E+00	0.00E+00	2.15E+07	2.15E+07
	Peat	0.00E+00	0.00E+00	0.00E+00	2.56E+06	2.56E+06
	Phosphate	0.00E+00	0.00E+00	2.90E+08	8.35E+09	8.64E+09
	Sand & Shell	2.12E+08	6.24E+07	0.00E+00	1.03E+09	1.30E+09
	Other	6.28E+07	5.48E+06	0.00E+00	4.00E+08	4.68E+08
Industrial and Commercial Self-Supply						
	Manufacturing	2.17E+08	0.00E+00	3.65E+05	8.35E+09	8.57E+09
	Food Processing	0.00E+00	1.50E+07	3.83E+07	9.47E+08	1.00E+09
	Commercial	0.00E+00	0.00E+00	0.00E+00	1.86E+06	1.86E+06
	Power	0.00E+00	9.49E+06	7.12E+07	3.69E+09	3.77E+09
	Other Industry	6.59E+06	0.00E+00	0.00E+00	4.37E+08	4.43E+08
Recreational Self-Supply						
	Parks	1.82E+08	3.29E+06	1.57E+07	1.86E+09	2.06E+09
	Golf	6.94E+08	5.29E+07	8.83E+07	1.83E+09	2.67E+09
	Other Recreation	2.56E+06	0.00E+00	1.83E+06	6.19E+08	6.23E+08
Residential Self-Supply						
	Residential	1.38E+09	7.17E+08	3.74E+08	5.16E+09	7.63E+09
Total Water Use		3.03E+10	3.07E+10	2.46E+10	1.13E+11	1.99E+11

Table A-5. Peace River region water use correction factors

County	Agriculture Self-Supply	Industry Self-Supply	Domestic Self-Supply	Recreation Self-Supply	Public Supply
Charlotte	4.34	18.04	1.24	1.00	1.00
Polk	1.23	1.01	2.55	1.09	1.04

Table A-6. Peace River region wastewater disposition[39]

	Charlotte (gals)	De Soto (gals)	Hardee (gals)	Polk (gals)	Total (gals)
Surface Applied	1.75E+09	8.98E+07	1.32E+08	6.32E+09	8.30E+09
Deep Injection	1.18E+09	0.00E+00	0.00E+00	0.00E+00	1.18E+09
Stream	0.00E+00	2.14E+08	2.73E+08	3.63E+09	4.11E+09
Total Wastewater Treated	2.93E+09	3.03E+08	4.05E+08	9.95E+09	1.36E+10
Percent Disposition					
Surface Applied	59.8%	29.6%	32.5%	63.6%	61.1%
Deep Injection	40.2%	0.0%	0.0%	0.0%	8.7%
Stream	0.0%	70.4%	67.5%	36.4%	30.3%

APPENDIX B
REGIONAL ENERGY ALLOCATION

This appendix outlines the steps that were taken to develop the regional energy intensities for Florida and the Peace River region. The first step was to collect data from government reports on total energy use for each region. Total energy use for Florida is given in Table B-1 adapted from the SEDS database. This data was used to set the total energy use for the state.

The next step in developing the energy intensity vector was to disaggregate energy use by fuel type. Fuel oils and kerosene purchases are reported by state for several transport and industrial subsectors in the EIA's Fuel Oil and Kerosene Sales (FOKS) report. Fuel totals in this data set were not the same as values reported in the SEDS database. The reported values were corrected so that they added to SEDS totals. This was done by calculating each fuel use category's percentage of total reported fuel use and then multiplying each category's percentage by the SEDS total. A comparison of SEDS and FOKS values and the correction factors used is given in Table B-2.

After adjustment to SEDS values, fuel use was allocated to specific transportation industries. Jet fuel and aviation gasoline from the SEDS report were allocated entirely to the "air transport" industry. Rail fuels reported in the FOKS report were directly allocated to "rail transport". Farm, oil, and off-highway fuels were removed from the transportation sector and allocated to the industrial sector. Military fuel use was removed from the transportation sector and assigned to the commercial sector as part of government fuel use. Vessel bunkering fuels were allocated between two transportation industries, "water transport", which includes freight and cruise ships, and “commercial fishing” which is part of the industrial sector. Since no state level data existed to allocate these fuels, several assumptions were made in their allocation. Residual fuels were allocated entirely to “water transport” as only large vessels are equipped to use this type of fuel. Commercial fishing fuel use was calculated by multiplying the national energy intensity by Florida’s commercial fishing industry economic output. The resulting commercial fishing industry fuel use was subtracted from the vessel bunkering distillate total, and the remaining distillate fuel was allocated to water transport.

The highway fuels reported in the FOKS report required additional data for further allocation. Federal Highway Administration (FHWA) data was used to allocate highway-related fuel use. The FHWA reports state estimates of highway use of gasoline in Table MF-21[77] and off-road gasoline use in Table MF-24.[78] The FHWA data includes all gasoline sales, including gasoline additives such as ethanol, and aviation gasoline. Transport ethanol and aviation gasoline use from the SEDS table were added together along with commercial, industrial, and transportation gasoline use from the SEDS table in order to arrive at a total energy value of 982,015 TJ for all gasoline consumed in Florida. The FHWA’s total was higher than the SEDS total and all FHWA categories of fuel use were adjusted to match SED’s values as shown in Table A-3.

Off road fuel use was estimated by the FHWA using empirically-based models for agricultural, construction, and industrial/commercial vehicles. For the regional model, these fuels were removed from the transportation industries, and allocated to their respective industrial, commercial, and residential categories. Data from the Transportation Energy Data Book (TEDB) was used to allocate fuel use between vehicle types. The TEDB reports highway energy use by mode of transport and fuel type for the entire U.S. Florida does not report energy use by vehicle type, and so national percentages of energy use by vehicle type were used for an initial allocation of Florida's highway energy use between automobiles, light trucks, motorcycles, buses, and medium and heavy trucks. Table A-4 gives the data from the TEDB and the share of energy use that each fuel represents.

The 2002 Vehicle Inventory and Use Survey [47] was used to adjust national highway energy use to better reflect Florida energy use. The VIUS is a national survey instrument used to determine national truck inventories and uses. Survey data is reported by state, and was analyzed to estimate truck fuel use by industry category and fuel type. Estimates of fuel use derived from the survey data are included in Table B-5. These estimates are then used to tailor the TEDB allocation of truck and automobile use to Florida conditions as shown in Table B-6.

The Florida VIUS fuel use estimates that light trucks account for only 37% of gasoline use, as opposed to national averages of 40%. The gasoline powered heavy trucks are estimated to account for only .6% of Florida's trucks as opposed to national averages of 3.5%. The resulting 6% difference in total gasoline use is assumed to be accounted for by increased automobile use within Florida from 56% to 62%. For diesel fuel, light trucks jump from a national average of 5% to over 10% of total diesel fuel. However, heavy trucks account for only 38% of diesel fuel use, as opposed to the national average of 90%. It is unreasonable to assume that diesel automobiles account for this 42% difference in fuel use. The more likely explanation is that the heavy trucks that consume the missing fuel are long haul vehicles traveling between states and are not registered in the state of Florida. These vehicles would not be reported within Florida's VIUS survey. These heavy trucks would not be included in the economic output of Florida's truck transport industry either, and so this fuel is removed from the total diesel fuel use and not allocated to any other sectors. This assumption can be checked by using IMPLAN's S/D ratio for truck transport, which estimates that 83% of truck transport is supplied by local businesses.

The national energy intensity vector assumes all automobile, motorcycle, and light truck fuel use is for personal transport, and removes their fuel use entirely from the sector. Light trucks, however, are often used in the self-provided transport of industries. The state level VIUS data can be used to separate transport-industry provided and self-provided transport within both the light and heavy duty truck categories. Table B-7 shows the fuel use associated with VIUS industrial categories. The agricultural, construction, mining, and manufacturing categories are removed from the transportation sector and assigned to the industrial sector. All service truck fuel use is removed and assigned to the commercial sector. Personal transportation fuel use is removed and assigned to the residential sector. The remaining VIUS categories of "For hire transportation/warehouse" and "Vehicle rental services" are assigned to the truck transport industry. The remaining automobile and motorcycle use is allocated to the residential category, as this is the predominant use and no other data sets are available to allocate this category.

Buses are used primarily within two transportation industries, "transit and ground passenger transport" and "sightseeing transport". The national energy intensity vector allocates the fuel use based on the percentage of economic output of these two industries. In Florida, over 80% of the revenue for Florida's sightseeing industry comes from water transport, and only 20% comes from land transport (U.S. Economic Census, 2002)

The water transport portion of the sightseeing industry is considered to come entirely from gasoline powered watercraft. Marine gasoline fuel use is allocated to sightseeing by the ratio of commercial to privately registered boats in Florida. This allocation assumes that privately owned and commercial boats have similar usage patterns and fuel consumption. Once commercial marine gasoline use is calculated, the remainder of gasoline marine fuels are removed from the transport sector and allocated to residential recreational use. The assumptions involved are necessarily crude, and introduce large uncertainty in the water transport industries. Better methods are sought for their allocation.

Pipeline transport represents natural gas, crude oil, and water transportation. In Florida, all pipeline transport is natural gas transportation. The EIA reports the natural gas consumed in pipeline transportation, and this value was allocated to pipelines. The transportation electricity use reported for Florida was also allocated entirely to pipeline use, as no electric rail existed in Florida in 2002.

The final three transport industries have no state level data available. The national energy intensities are used for these industries. Their petroleum fuel use is assumed to be truck transport, while natural gas and electric usage is assumed to be for facilities and are subtracted from the commercial use categories.

This method gives Florida industries within a sector the same relative resource use per dollar as the national model within a defined sector. However, it allows changes in the percentage of resource use that each sector represents of Florida’s total. The sector totals sum to Florida’s total use, and the sector’s percentage of total consumption is unique to the state.

Table B-1. Florida energy use 2002 adopted from SEDS[43]

Fuel	Residential (TJ)	Commercial (TJ)	Industrial[a] (TJ)	Transportation (TJ)	Power (TJ)	Totals (TJ)
Coal	30	223	32289	0	725989	758532
Natural Gas	16515	60924	90308	12647	564069	744463
Distillate Fuel	574	15765	43443	224765	22704	307251
Residual Fuel	0	470	10531	69164	285684	365850
Motor Gasoline	0	2178	13460	1016749	0	1032386
Kerosene	379	93	10	0	0	482
LPG	7638	10125	2570	651	0	20984
Aviation Gas	0	0	0	2618	0	2618
Jet Fuel	0	0	0	161567	0	161567
Other Petroluem[b]	0	0	13240	4862	0	18102
Petroleum Coke	0	0	0	0	50006	50006
Biomass	5095	1370	98022	39	47430	151956
Geothermal	2108	632	0	0	0	2740
Solar	29407	0	0	0	0	29407
Nuclear	0	0	0	0	370903	370903
Hydroelectric	0	0	0	0	2003	2003
Purchased Electricity	389031	299441	68194	211	0	756877
Totals	450778	391223	372067	1493272	2068787	4776126

[a]The industrial values report estimates of fuels with feedstock use removed

[b]Other Petroleum includes asphalt and road oil, lubricants, pentanes, napthas, and waxes

Table B-2. Comparison of SEDS and FOKS energy values

Sector	Subsector	Distillate Fuel SEDS[43] (TJ)	FOKS[45] (TJ)	Difference %	Adjusted (TJ)	Residual Fuel SEDS[43] (TJ)	FOKS[45] (TJ)	Difference %
Residential		574	591	2.9%				
Commercial		15765	16215	2.9%		470	505	7.3%
Industrial		43443	45256	4.2%		10531	10949	4.0%
	Oil		32		31			
	Farm		19535		18714			
	Off Highway		18237		17471			
	Other		325		312			
Transport		224765	231180	2.78%		69164	74215	7.3%
	Railroad		11413		11096			
	Vessel Bunker		22411		21790		74215	
	On Highway		196510		191057			
	Military		846		822			
Power		22704	18320	-19.3%		285684	285924	0.1%
Total		307251	311562			365850	371593	

Table B-3. Adjustment of Florida gasoline use

Sectors	Subsectors	Subsectors	EIA SEDS[a] (TJ)	Table MF-21[77] (TJ)	Table MF-24[78] (TJ)	% Total	Adjusted Value (TJ)
Highway Use				1010967		96.51%	998971
	Private & Commercial			997152		95.20%	985320
	Public - Federal Civilian			1185		0.11%	1171
	Public - State & Local			12629		1.21%	12479
Non-Highway Use							
	Private & Commercial			35900		3.43%	35474
		Agriculture			3874	10.79%	3828
		Aviation			3295	9.18%	3256
		Commercial & Industrial			5266	14.67%	5204
		Construction			4473	12.46%	4420
		Marine			17394	48.45%	17188
		Miscellaneous			1597	4.45%	1578
	Public - State & Local			606		0.06%	598
Total			1035043	1047472			1035043

[a]EIA SEDS total includes aviation gasoline and ethanol

Table B-4. Average highway fuel use adopted from TEDB[46]

	Gasoline TBTU	Diesel TBTU	LPG TBTU	NG TBTU	Total TBTU	Gasoline %	Diesel %	LPG %
Light vehicles	15871.1	310.6	10		16191.7	96.5%	6.3%	37.2%
Automobiles	9273.9	52.0	0		9325.9	56.4%	1.1%	0.0%
Light trucks	6573.3	258.6	10		6841.9	40.0%	5.3%	37.2%
Motorcycles	23.9				23.9	0.1%		
Buses	6.7	171.7	0.2	11.6	191.1	0.0%	3.5%	0.7%
Transit	0.2	77.5	0.2	11.6	90.4	0.0%	1.6%	0.7%
Intercity		29.2			29.2		0.6%	
School	6.5	65.0			71.5	0.0%	1.3%	
Medium/heavy trucks	569.7	4440.4	16.7		5026.8	3.5%	90.2%	62.1%
HIGHWAY TOTAL	16447.5	4922.7	26.9	11.6	21409.6	100.0%	100.0%	100.0%

Table B-5. Modification of highway fuel use with VIUS data

	TEDB US Avg Gasoline %	FL VIUS Adjusted Gasoline %	FL VIUS Adjusted Gasoline TJ	TEDB US Avg Diesel %	FL VIUS Adjusted Diesel %	FL VIUS Adjusted Diesel TJ
Total Highway Fuel			998971			191057
Automobiles	56.38%	59.88%	598184	1.06%	1.06%	2018
Light trucks	39.97%	39.28%	392351	5.25%	10.98%	20979.32
Motorcycles	0.15%	0.15%	1452			
Buses	0.04%	0.05%	456	3.49%	4.14%	7901
Transit	0.001%	0.006%	61	1.57%	2.22%	4245
Intercity				0.59%		
School	0.04%		395	1.32%		
Med/heavy trucks	3.46%	0.65%	6528	90.20%	40.06%	76538.66
Total Accounted	100.00%	100.00%		100.00%	56.23%	
Unaccounted			0		43.77%	83620

Table B-6. Florida truck fuel use from 2002 VIUS[47]

Sector	Subsector	Gasoline TJ	Diesel TJ	LPG TJ	Total Petro TJ
Truck Transportation		39793	31028	109	70930
	For hire transportation/warehousing	11511	14626	40	
	Vehicle rental services	11430	9347	38	
	Not reported	16852	7055	31	
Industrial		50854	27804	32	78689
	Agriculture, forestry, fishing	4692	4130	10	
	Mining	31	1113	0	
	Utilities	4374	1858	8	
	Construction	34464	17100	14	
	Manufacturing	7293	3602	0	
Commercial		36021	24035	77	60133
	Wholesale trade	5319	7104	26	
	Retail trade	8561	5985	21	
	Information services	61	105	0	
	Administrative/support services	4529	5925	17	
	Recreation services	45	77	0	
	Hospitality services	2954	3226	8	
	Other services	14552	1614	5	
Residential		272211	14651	0	286863
	Personal transportation	272211	14651	0	
TOTAL		398879	97518	218	496615

Table B-7. Energy use of Florida's transportation industries

Transport Industry	LPG TJ	Gasoline TJ	Aviation Gas TJ	Jet Fuel TJ	Diesel TJ	Residual TJ	Total Petroleum TJ	NG TJ
Air transportation		638	2618	161567			164823	
Rail transportation					11096		11096	
Water transportation					20029	69164	89193	
Truck transportation	404	36372			29694		66470	1144
Transit and ground passenger transport	5	456			6768		7229	10
Pipeline transportation								11493
Scenic and sightseeing transportation		4297			1133		5430	
Postal service		2557			998		3555	
Couriers and messengers		24033			9378		33411	
Warehousing and storage		863			337		1200	
Totals	409	69217	2618	161567	79432	69164	382406	12647

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BIOGRAPHICAL SKETCH

David Pfahler completed a Bachelor of Arts in chemistry from Cedarville University and entered the US Air Force as an officer in 1997. David's first assignment was in the Air Force Research Laboratory in Kirkland AFB, New Mexico. He helped develop chemical lasers during his three years there. In his second assignment, he completed a Master of Science in chemistry from the University of Florida. David then worked in the Air Force Research Laboratory at Wright Patterson AFB, Ohio developing energy systems for Air Force applications. In June 2007, David left the Air Force and was selected as an associate for the NSF-Integrative Graduate Education and Research Traineeship (IGERT) program in adaptive management of water, wetlands, and watersheds.