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Energy, environment, and sustainability: a hierarchical analysis of south Louisiana

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ENERGY, ENVIRONMENT, AND SUSTAINABILITY: A HIERARCHICAL ANALYSIS OF SOUTH LOUISIANA

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by
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DEDICATION

This dissertation is dedicated to: The people of south Louisiana

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During the course of my studies at LSU, I was supported by many friends, family and strangers. I am grateful to all of them, but especially to JJ, my parents, and brother, the Day family, Dr. Robert Lane, Dr. Richard Keim, my committee members, and fellow graduate students in the School of Renewable Natural Resources and the Department of Oceanography and Coastal Sciences.

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ABSTRACT

This dissertation details research into the sustainability of industrial, human, and natural systems in south Louisiana. Chapter 1 is a general introduction. Chapter 2 calculates the energy return on financial investment (EROFI) of oil and gas production in the ultra-deepwater Gulf of Mexico (GoM) in 2009 and the Macondo Prospect (Mississippi Canyon Block 252). I calculated a preliminary Energy Return on Investment (EROI) using a range of energy intensity ratios. The EROFI for ultra-deepwater oil and gas at the wellhead was roughly 0.85 gallons, per dollar. These estimates of EROI for 2009 ultra-deepwater oil and natural gas at the wellhead ranged from 7–22:1. The EROFI of the Macondo Prospect oil reserves ranged from $84 to $140 to produce a barrel, and EROI ranged from 4–16:1. The lower end of these EROI ranges (i.e., 4 to 7:1) is more accurate because these values were derived using energy intensities averaged across the domestic oil and gas industry. Extraction costs of ultra-deepwater energy reserves in the GoM come at increasing energetic and economic cost to society.

In Chapter 3, I estimated the annual greenhouse gas emissions primarily from energy usage at Louisiana State University (LSU). Total energy use is 2.43 million MMBtu resulting in per capita GHG emissions of 6.1 Metric Tons CO_2e, which is low compared to many other universities. Chapter 4 estimates the carbon storage of two bottomland hardwood forests located in the Lower Mississippi Alluvial Valley. Carbon storage varied with microtopography. Carbon storage was greatest on drier ridge sites compared to swale sites. The forested area required to mitigate the 162,742 MT CO_2e emitted by the LSU campus community in fiscal year 2007-2008 is estimated to be 12,937 to 23,150 hectares. The low end of this range is based on storage rates at the Ben

Hur ridge study site and the high end of this range is based on storage rates measured at the St. Gabriel swale study site. Management for maximum carbon sequestration could lower the amount of land necessary to offset carbon emissions by the university. Chapter 5 contains the summary and conclusions.

CHAPTER 1

GENERAL INTRODUCTION

Preface

This dissertation details research into the sustainability of industrial, human, and natural systems in south Louisiana. Three systems were analyzed with regard to energy production, consumption, and carbon storage. Chapter 1 is an introduction to two critical challenges facing industrial society in the 21st century: climate change and fossil energy scarcity. Chapter 2 is an analysis of the net energy available from ultra-deepwater oil and gas extraction in the Gulf of Mexico in 2009. Chapter 3 is an analysis of energy consumption and the resulting greenhouse gas emissions of Louisiana State University's (LSU) main campus during fiscal year 2007. Chapter 4 is an analysis of the carbon storage potential of four bottomland hardwood forest sites located along the Lower Mississippi Alluvial Valley floodplain in East Baton Rouge and Ascension parishes.

This introductory chapter provides background information on the source to sink dynamics of energy flows in south Louisiana investigated in this dissertation. Climate change and energy scarcity are discussed to provide global, national, and local context for the research presented in Chapters 2-4. Results and conclusions from these chapters are summarized in Chapter 5.

Introduction

There is increasing evidence that humans are approaching the capacity of the earth's resources to sustain continued global human population growth and continued socio-economic growth (Goodland 1995, Hall and Day 2009; Rockstrom et al. 2009, Brown et al. 2011). The exponential growth in human population over the last two centuries has been the result of the industrial revolution and concomitant increases in

resource accessibility as a result of increases in the availability and affordability of fossil fuels (Moses and Brown 2003). In effect, humans have transitioned from an empty world to a full world (Daly 2005; Costanza 2008; Day et al. 2009; Fig.1). Figure 1b is used in the introduction and in chapter 2-4 to highlight those aspects of the industrial, human, and natural economy that are investigated in each chapter.

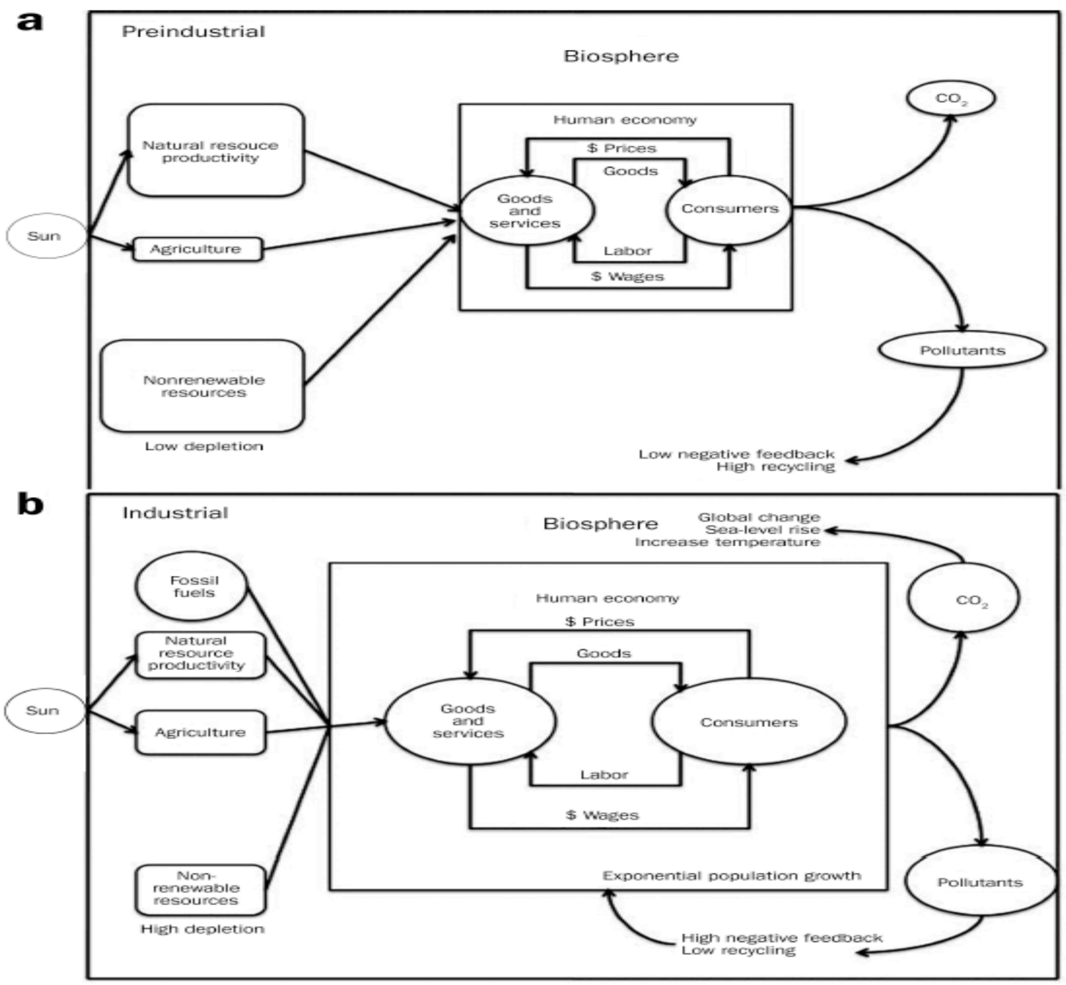

Figure 1. Conceptual diagram of the economic system and the biosphere for empty and full world scenarios. Fig. 1a represents this relationship in an empty world. Fig. 1b represents this relationship in a full world. The economic system is a subset of the biosphere and is absolutely dependent for its functioning on biosphere sources and sinks. The economic system has grown dramatically over the last two centuries. Adapted from Day et al. 2009. Ecology in Times of Scarcity. Bioscience. Vol.59 No.4 Pgs.321-331

Cheap, abundant fossil fuels combined with advances in technology to extract and produce resources, along with foreign trade policy decisions have allowed for the globalization of the world economy (Rudra and Jensen 2011; Chomsky 1994). The globalized market economy functions based on the principles of supply and demand to deliver products to consumers who have the means to pay the market price for goods (Krugman and Wells 2009). These markets are based on neo-classical economic models that foresee continued growth into the foreseeable future (Solow 1956; Swan 1956). Ever-increasing fluxes of material and energy inputs are required to meet the increasing demand of a growing world population and increasing per capita consumption. One of the major problems with this theory is its failure to account for how economic processes consume resources and generate wastes (Gorgescu-Rogen 1971, Daly and Farley 2004, Hall and Klitgaard 2006, 2011). Resource depletion, especially as it is related to peak oil and waste generation in the form of greenhouse gas emissions, are two market externalities generally unaccounted for by neo-classical economic models that directly impact humans and threaten the human carrying capacity of Earth.

Peak oil is the time when global production of conventional crude oil reaches a maximum and begins to decline. The production profile of non-renewable resources such as oil generally follows a well-defined bell-shaped curve that was first used to accurately predict peak oil production in the U.S. (Hubbert 1969; Bardi 2009). Estimates of when the global peak of non-renewable energy will occur differ (Campbell and Laherrere 1998; Deffeyes 2001; Simmons 2005; Bentley 2010), but production of conventional crude oil globally reached an all time high in 2006 and further additions to production have come in the form of crude + condensate + natural gas liquids (C+C+NGL). Currently, for each

barrel of oil being produced, less than 0.5 barrels is being discovered (Deffeyes 2001; Bentley 2010, Figure 2).

The Hubbert approach is based on the concept that oil discoveries in an area generally precede peak production by 30-40 years. For example, U.S. oil discovery peaked about 1940. World oil discoveries peaked by 1970 and have been falling since and recent success has been very low, despite increased drilling efforts (Campbell and Laherrere 1998, ASPO 2008, Figure 2) and most estimates since 1965 of ultimately recoverable oil have been about 2 trillion barrels (Hall et al. 2003). Global production increased exponentially until about 1970 but the rate of increase has declined since. Most importantly, production is now 2-3 times the discovery rate, and current production is mainly from reservoirs discovered 30 to 40 years ago. Four hundred or so giant and supergiant oil fields provide roughly 80% of the world's petroleum, the vast majority of which were found before 1960 (Skrebowski 2004). Of these, roughly one quarter are declining in production at an average rate of about 4% annually. Also world oil demand is increasing especially in China and India putting further pressure on oil supply.

The Alberta tar sands, Bakken shale oil in North Dakota, and other non-conventional sources have contributed to production increases since 2006. Part of the explanation for the recent increase in unconventional production has been a dramatic run-up in the price of oil over the last decade. The price per barrel for oil in 1998 was less than $20/barrel. A decade later, the price increased seven-fold, reaching an all time high in July 2008 of $147/barrel (U. S. EIA 2011).

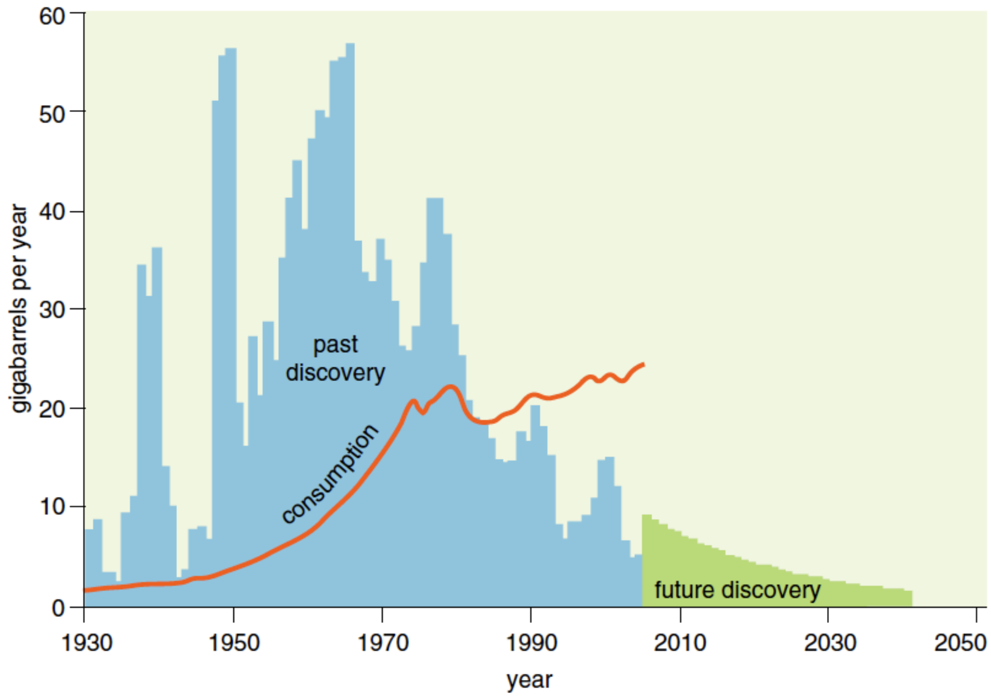

Figure 2. Graph of global oil discoveries and consumption through time. The rate of annual global oil consumption has been greater than the rate of annual discoveries since the mid-1980's. The gap between consumption and discoveries is predicted to continue widening into the near future. Adapted from Hall and Day 2009 and ASPO.

The price increase has made non-conventional sources economically attractive although the many of the reserves have been known since before the 1950's (Maugh 1977; Maugh 1978, Murphy and Hall 2011). Unconventional reserves provide lower net energy than most of the conventional reserves produced up until now (Murphy and Hall 2010). The energy quality, measured as the amount of economic output generated per unit of energy input, of unconventional reserves is less than conventional reserves (Cleveland et al. 2000). More energy must be used to extract, process, and refine low EROI fuels into a usable form than high EROI fuels. In addition to non-conventional sources, energy extraction is moving into more extreme environments such as the Arctic and ultra-deepwater in pursuit of additional reserves that are more energy intensive

(Krajick 2007; Kerr et al. 2010; Tainter and Patzek 2011). Accurate estimates of the net energy available in remaining conventional and unconventional reserves may allow for more informed decision-making with regard to energy policymaking. These developments are important to society because it is the surplus energy provided from the energy extraction sector that allows for economic growth and productivity (Cleveland et al. 1984).

Since so much of the economy depends upon the widespread availability of cheap fossil fuels for the production and distribution of goods, the onset of peak oil and the decline in net energy available to society has profound implications for overall societal well being (Hall and Day 2009; Hall et al. 2009; Murphy and Hall 2011). Concurrently, waste in the form of greenhouse gases (GHGs), produced through the combustion of fossil fuels from industrial society and land use change, are entering the atmosphere at a rate greater than marine and terrestrial ecosystem's assimilative capacity (IPCC 2007).

Anthropogenic fossil fuel consumption has led to an increase in greenhouse gases (GHG) in the atmosphere (IPCC 2007). The atmospheric concentration of GHGs such as carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons has increased dramatically since the industrial era began in the early 19^{th} century (IPCC 2007). Prior to the industrial revolution atmospheric CO_2 concentrations were about 280 ppm. Currently, the CO_2 concentration in the atmosphere is about 390 ppm and rising (NOAA 2010, Fig.3). Increased levels of GHGs in the atmosphere have led to an increase in the thermal equilibrium of the planet as a result of the increased amount of infrared radiation absorbed by these gases in the atmosphere (IPCC 2007). Since the 19^{th}

century, the global average temperature of the Earth has increased by 0.7°C (Mann et al. 200).

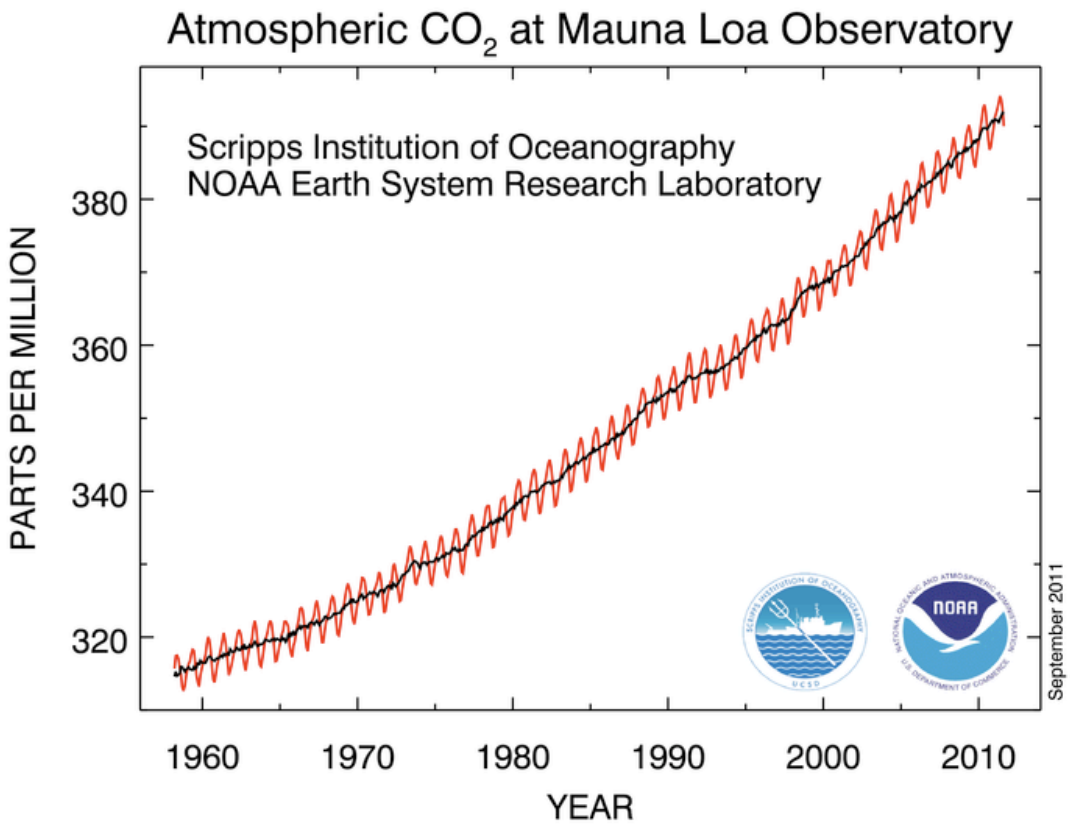

Figure 3. Monthly mean atmospheric CO_2 concentration measured at Mauna Loa Observatory, Hawaii. (NOAA 2010)

Effects of increased greenhouse gas concentrations in the atmosphere include increases in global average surface air temperature, global average sea level, and a decrease in snow cover in the Northern Hemisphere (Brohan et al. 2006; Vermeer and Rahmstorf 2009; Frei and Gong 2005). Changes in precipitation regimes are expected to have an impact on agriculture (IPCC 2007). Droughts and flooding may negatively impact agriculture and could lead to a rise in the price of agricultural commodities and further exacerbate food insecurity in vulnerable areas (Godfray et al. 2010). Climate is a

dominant physical factor affecting global ecosystems (Odum and Barrett 2005). The effects of climate change are highly diverse and wide ranging in biological ecosystems (Walther et al. 2002).

Declining net energy and climate change are major problems facing society. The relationship between the two problems can be viewed as a positive feedback cycle (Wiener 1948; Forrester 1971; Odum 1972) because the population continues to pursue more difficult energy reserves to meet growing demand, financial and energy costs rise, thereby increasing the amount of pollution emitted to get the necessary energy to meet demand. In other words, the system requires a given amount of energy and as that energy becomes more difficult to obtain, populations will experience increased energy costs and increased atmospheric pollution. This pollution impacts ecosystem services provided by nature. These ecosystem services are very valuable to the human economy. For example, Batker et al. (2010) reported that the annual values of ecosystem goods and services for the Mississippi delta ranged between 12 and 40 billion dollars.

One of these ecosystem services is the potential for forests to store carbon (Murray 2009). The preservation of this ecosystem service is posited as a mitigation technique in order to reduce atmospheric CO_2 concentrations (IPCC 2007). The carbon trading schemes developed by the European Union and as part of the failed Waxman-Markey legislation allow for the trading of forest carbon credits by carbon credit investors and polluting entities who may be fined for excess emissions (EU ETS 2011; H.R. 2454 2008). Forest carbon stock assessments are occurring worldwide to accurately assess the global carbon storage potential and bring carbon credits to market (Gibbs et al. 2007; McKinley et al. 2011). The methodologies used in reducing emissions from

deforestation in developing countries (REDD) and the U.S. Forest Inventory Analysis (FIA) assessments are being updated and refined based on new information from different regions and forest types (Birdsey 1996, Smith et al. 2006, Jenkins et al. 2003; Shoch et al. 2009). Forest growth models have been developed to estimate future carbon storage rates as a result of different climate change scenarios (Aber and Federer 1992; Wang 2011). Measuring forest growth and predicting forest growth from climate can benefit from tree ring analyses to determine the effects of periodic changes in climate on tree growth. This technique was employed for this study at four bottomland hardwood (BLH) forest sites in south Louisiana to determine live biomass forest carbon stocks.

The studies compiled in this dissertation were conducted from a systems ecology perspective with a focus on sustainability. Systems ecology is the study of whole ecosystems and includes measurements of overall performance as well as a study of the details of systems design by which the overall behavior is produced from separate parts and mechanisms (Odum 1983). Sustainability science is a growing discipline in which scientists from various fields are working to integrate research across disciplines in an attempt to formulate solutions to problems facing society. According to the National Academy of Sciences (NAS) "Sustainability science is an emerging field of research dealing with the interactions between natural and social systems, and with how those interactions affect the challenge of sustainability: meeting the needs of present and future generations while substantially reducing poverty and conserving the planet's life support systems" (NAS 2011).

The sustainability of a system depends on the maintenance of energy flows and system structure. In turn, sustainability is dependent on the functioning of each

component part of the system to maintain overall system functioning. Energy flows in systems develop characteristic webs of energy transformation, feedback interaction, and recycling (Odum 1983). The webs form a hierarchy of converging transformations (i.e. transformation of sunlight energy by primary producers forming the basis of a complex trophic foodweb). Understanding energy availability and the rate processes in each step of the energy transformation hierarchy allows for management of system sustainability. Flows of low-quality energy are abundant and widely dispersed, and individual units are small in size (Odum 1983). Higher-quality units and their flows, although less in total energy flow, are more concentrated and have higher embodied energy and each unit is larger in size with a larger territory from which it receives energy and feeds back its actions (Odum 1983).

This research examines the sustainability of three systems in Louisiana and the northern Gulf of Mexico: industrial, human, and natural. The systems are component parts of the larger regional economy and ecosystem. The studies are defined by temporal and spatial boundaries. The temporal boundary for each of the three studies is one calendar year. The spatial boundaries are defined as the ultra-deepwater (>5,000 ft.) of the Gulf of Mexico, Louisiana State University's main campus in Baton Rouge, Louisiana, and two bottomland hardwood forest sites located in the south Louisiana portion of the Lower Mississippi Alluvial Valley. The studies share energy flows from source to sink as a common theme.

Fossil fuels are the source of the vast majority of energy used to power the modern industrial economy, but their importance to the economy and environment is often understated. Humans are mining the lithosphere for fossil fuels, combusting these

fuels to perform work, and emitting the waste products into the atmosphere. Traditional economic accounting of extraction, consumption, and emission of waste does not fully account for the depletion of the finite fossil fuel resource base at the source. Changes in atmospheric composition that occur as a result of economic activity are also ignored and considered a market externality, though their deleterious effects are well documented (IPCC 2007).

The overarching goal of this dissertation is to define and examine energy and carbon flows from source to sink in three systems operating in south Louisiana. The three systems selected in this study are important parts of the economy of south Louisiana. The oil and gas sector of the economy contributes significantly to the state and federal budgets and to the U.S. economy in general each year, as do the employment opportunities it provides to the residents of Louisiana. Louisiana State University generates over one billion dollars a year to the local economy. LSU not only provides employment to residents in the region but also serves as the state's flagship University and is threatened by declining energy production in the northern Gulf of Mexico since it's budget relies heavily on state revenues generated in part from the oil and gas sector. The LSU community, especially cash-strapped students, is also vulnerable to rises in the price of energy as disposable income declines and more of their disposable income must be spent on basic necessities. Furthermore, the LSU AgCenter owns a considerable amount of LMAV bottomland hardwood forests that could potentially be utilized for carbon mitigation to offset annual GHG emissions from the main campus. Such carbon mitigation could provide revenue to the university directly through sales on the carbon credit markets, or indirectly through an experiential education curriculum that encourages

student involvement in forest management on LSU AgCenter property. Thus, projections for climate change and energy availability in the future pose threats to the sustainability of economic activity and the industrial, human, and natural systems in south Louisiana.

At the largest scale, it is clear that energy is going to become more scarce and expensive. Based on this, I looked at the energy and financial profitability of drilling in the ultra-deepwater GoM, the last remaining significant conventional energy reservoir in the region. Society will have to become more efficient in its use of energy, or operate on less, because fossil fuel energy is becoming more expensive.

It is also becoming increasingly clear that anthropogenic sources of GHG emissions are leading to global climate change. Humans can decrease GHG emissions as a means to slow climate change and maintain a climate suitable for human habitation into the future. I chose to study LSU because administrative officials were seeking to have the inventory completed in-house as part of a graduate student research project. LSU provided me with a study area the size of a small city. Information regarding the energy requirements of the University was readily available and administrative support was provided.

After completing the GHG emissions inventory for the campus, I began investigating ways to mitigate annual greenhouse gas emissions. The forests owned by the LSU AgCenter provided an opportunity to study the carbon storage capacity of LSU AgCenter owned lands and potential forest management strategies that could enhance carbon storage on sites. The results of the study suggest that considerable carbon storage potential exists on LSU AgCenter owned properties and that active

management with carbon storage as a goal can maximize the potential of these sites to mitigate against campus GHG emissions.

Energy in the U.S. and Louisiana

Fossil fuels account for approximately 81% of global primary energy use (EIA 2008). Crude oil accounts for 34% of this total while natural gas accounts for 21% (EIA 2008). Domestic crude oil production peaked in the U.S. at 3.5 billion barrels per year in 1970 before declining to 1.9 billion barrels in 2009 (U.S. EIA 2011). In Louisiana, crude oil production peaked in 1970 at 470.5 million barrels and declined to 50 million barrels per year in 2009 (EIA 2011). Since the depletion of domestic onshore oil wells, offshore production has increased and production has moved into deeper water (Fig. 4).

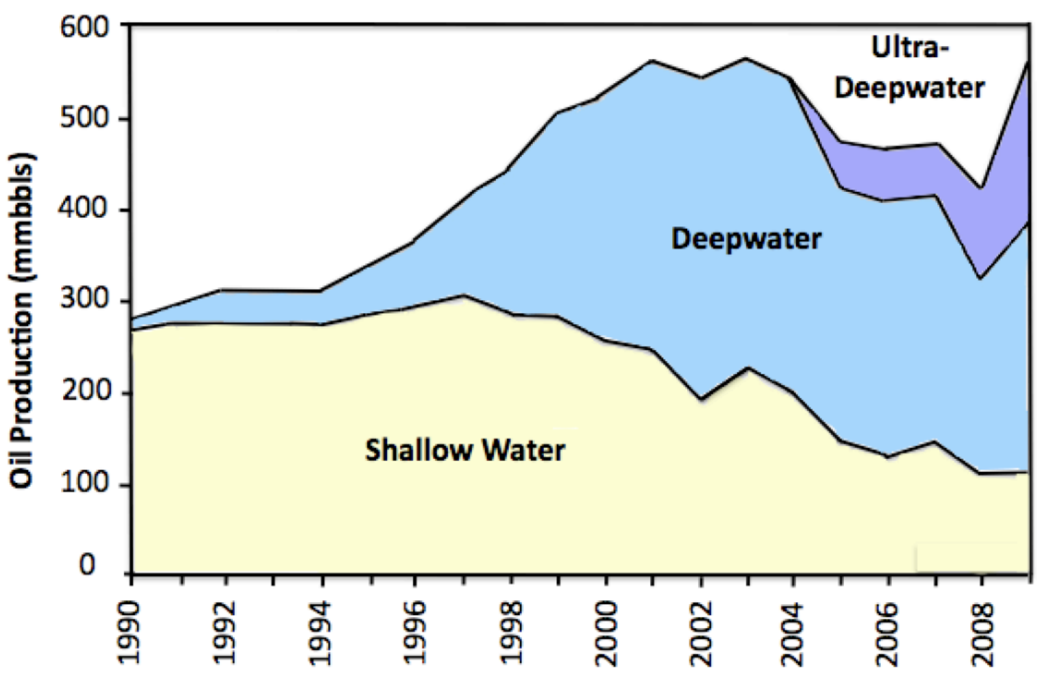

Figure 4. Oil production in the Gulf of Mexico (GoM) Federal Offshore region including lease condensate Source: Minerals Management Service (MMS), Energy Information Administration, Office of Oil and Gas (2010). (mmbbls equals million barrels per year).

Deep-water reserves in the federal outer-continental shelf are now being accessed at greater energy and economic costs to producers. The first freestanding structure that produced oil in the Gulf of Mexico was erected in 1938 in the shallow water 1.5 miles from the city of Cameron, Louisiana. The first "out-of-sight-of-land" platform was deployed in 18 feet of water, 10.5 miles from shore in 1947 (Priest 2007). In 2010 a typical offshore well in the federal OCS, such as the Macondo Prospect, was located in over 5,000 feet of water and approximately 41 miles from shore (Berman ASPO 2010).

The fossil fuel industry has been a major player in the Louisiana economy for over a century. Oil and natural gas production accounted for approximately 15% of state revenues in FY 2008-2009 and approximately 25% of state economic activity while directly and indirectly employing tens of thousands of state workers (TP 2009; Hertsgaard 2010). Only sales and income taxes contribute a higher percentage to state revenues. Louisiana has 19 operating petroleum refineries. East Baton Rouge parish is home to the Exxon Mobil refinery, the second largest oil refinery in the nation, and ninth largest in the world. The refinery can refine more than a half million barrels of oil per day (U.S. EIA 2011).

The sustainability of the industry in the state and the nation is dependent upon continued access to petroleum resources to maintain production at current levels. Continued depletion of older, existing wells, the decline in the number and size of oil discoveries nationally and globally, and increased consumption in foreign markets such as China and India, pose significant obstacles to the long-term sustainability of the industry in Louisiana (Kaiser 2010, Deffeyes 2010, Loaiciga 2011, Hertsgaard 2010). Since the peak in domestic crude oil production in 1970, the U.S. has offset domestic

production through imports from foreign producers (Smil 2011). The advent of peak conventional crude oil production globally, suggests that declining availability of resources will limit economic processes that demand perpetually increasing oil resources. At the same time, the economic and energy costs to obtain these resources will continue to increase further impacting economic growth (Murphy and Hall 2011).

Energy Return on Investment for Oil and Gas in the Ultra-deepwater Gulf of Mexico

Chapter 2 is an analysis of the energy return on financial and energy investment for the ultra-deepwater energy sector operating in the Gulf of Mexico in 2009. Energy return on financial investment (EROFI) is an estimate of the financial cost for the production of a barrel of oil, or of natural gas expressed as a barrel of oil equivalent (BOE). EROFI is the amount of money expended by an energy producing entity divided by the amount of energy produced. An energy producing entity must produce energy at sufficient economic profit while paying the costs of the supply chain of labor, materials, and transport to maintain a profitable business (Kaiser 2010; King and Hall 2011). Profitability is, however, related directly to the supply chain costs. The entity fails to be financially profitable when the incurred costs are greater than the price of the product being sold. EROFI analysis provides insight into the base price for which a barrel of oil must be sold to maintain economic profitability.

Energy return on investment (EROI) analysis differs from EROFI in that energy units are substituted for the monetary expenditures accounted for in the EROFI equation. EROI is a tool used to measure the net energy of an energy supply process (Cleveland et al. 1984). The net energy of an energy source is the amount of energy returned to society

divided by the energy required to get that energy (Hall et al. 2009). An energy source becomes an energy sink when the amount of energy used in extraction is greater than the extracted amount of energy (EROI <1:1). EROI for finding oil and gas decreased exponentially from 1200:1 in 1919 to 5:1 in 2007 (Guilford et al 2011). The EROI for domestic oil and gas production was about 20:1 from 1919 to 1972, before declining to 8:1 in 1982 (Guilford 2011). Today, the EROI of domestic oil production is about 10:1, or 10 units of output for every unit of input (Guilford et al 2011, Cleveland 2005). Production is a more energy intensive process than exploration, hence the higher EROI for discoveries.

EROI is important to a society because it provides a measure of the surplus energy gained from an energy source that can be diverted to other sectors of the economy to produce goods and services in addition to those required for energy extraction. Decreasing EROI increases the proportion of economic output that goes into the energy extraction sector of the economy leaving less economic and energy available for non-energy extraction sectors. The trend towards low EROI fuels reduces the quantity and affordability of the fuel supply (Hall and Day 2009). I developed EROFI and EROI estimates of ultra-deepwater GoM crude oil and natural gas production in 2009 to estimate the monetary and energy returns on the costs of a critical industry whose sustainability is ultimately limited by the availability of a non-renewable declining resource base. After production, ultra-deepwater GoM fossil fuels are transported, refined, and distributed to end users.

Louisiana State University Greenhouse Gas Inventory

The combustion of fossil fuels results in climate changing greenhouse gas emissions entering the atmosphere (IPCC 2007). The production of such wastes is an externality not counted in traditional economic models. In recent years, there have been efforts to move away from such energy sources and limit greenhouse gas (GHG) emissions from entering the atmosphere to prevent further damage to the earth's climate system (UNFCCC 1997). Initial steps to address this issue by higher educational institutions began with greenhouse gas emissions inventories (Association for the Advancement of Sustainability in Higher Education 2010). Chapter 3 details the emissions inventory for LSU that was conducted in 2008-2009.

Total greenhouse gas emissions in the United States in 2008 were estimated to be 7,053 Million MT carbon dioxide equivalents (CO_2 e) (U.S. EIA 2009). The U.S. produces between 22% and 25% of total GHG emissions globally. Average annual per capita emissions for the years 2001-2005 were approximately 20 tons CO_2 per U.S. citizen (World Resources Institute 2009). While most countries have lower average per capita emissions than the U.S., a few, such as Qatar and other Middle Eastern countries, have higher per capita emissions.

Louisiana produces the highest amount of industrial greenhouse gases per capita in the United States (Gurney et al. 2003). East Baton Rouge parish produces more GHG emissions than any of the other 63 parishes in the state. Louisiana State University is a public higher education institution located in Baton Rouge Louisiana with a total campus community of 33,235 in FY 2007-2008. The vast majority of energy used on campus

comes from the combustion of fossil fuels in the form of natural gas and transportation fuels such as gasoline and diesel. The price of energy rises as fossil fuel availability and associated net energy declines. Decreasing consumption of such fuels could allow for the limited budget of the University to be allocated towards other uses while decreasing overall impact to the environment.

An assessment of greenhouse gases emitted as a result of annual energy consumption by the LSU-Baton Rouge main campus community was conducted during for FY 2007. The study catalogued the sources of emissions as well as the overall distribution of emissions using three different scopes, on-campus direct, off-campus direct, and indirect emissions that result from daily activities attributed to the functioning of the university and it's community members. The Clean Air-Cool Planet campus carbon calculator was used to inventory and generate overall emissions estimates based on data collected from numerous departments and individuals across campus. The methods were similar to those used at hundreds of other higher educational universities across the country and the inventory methodology has been used as the standard for conducting assessments nationwide (Association for the Advancement of Sustainability in Higher Education 2010).

The GHG inventory assessment is one of the first steps on the path towards sustainability in higher education. The assessment allows for a broader understanding of the energy inputs required for the campus to function as well as the resulting waste stream produced from campus energy consumption. Defining and understanding these consumption patterns could motivate the implementation of polices and incentives that decrease energy consumption while decreasing greenhouse gas emissions from campus

activities. In addition to the main campus, the LSU AgCenter owns more than 24,000 acres of agricultural and forested lands throughout Louisiana. Greenhouse gas emissions can be mitigated by decreasing combustion of fossil fuels as well as enhancing carbon storage on agricultural and forest lands. Study sites for Chapter 4 were selected in nearby bottomland hardwood forests. These sites were chosen since bottomland hardwood forests in the Lower Mississippi Alluvial Valley have been shown to have high carbon storage potential (Shoch et al. 2009) and are the dominant forest type in the region.

Carbon Storage in Bottomland Hardwood Forests

Land use change in the form of agricultural expansion was the largest source of carbon released to the atmosphere from about 1860 until the late 1970's (Houghton et al. 1983). It is only since the late 1970's that fossil fuel combustion has overtaken land use change as the leading contributor to carbon in the atmosphere (Lal et al. 1998). The two main ways that land use change contributes to atmospheric carbon is through the burning and decomposition of biomass and the release of soil organic carbon following the cultivation of forests and agricultural fields (Lal et al. 1998). The once expansive LMAV forests have been reduced by conversion to agriculture (MacDonald 1979) and more recently as a result of urban development (Sharitz and Mitsch 1993).

U.S. forests are a net carbon sink estimated to sequester approximately 162-256Tg of carbon annually (McKinley et al. 2011). This is equal to approximately 10% of carbon produced from the combustion fossil fuels consumed annually in the country (Birdsey et al. 2006). Recent research suggests that per unit forest area, Louisiana forests were a carbon source from 1992-2001 (Zheng et al. 2011).

Bottomland hardwood forests occupy floodplains of the southeastern U.S. Louisiana contains the greatest coverage of bottomland hardwood forests in the LMAV, although it is estimated only 30% of the original 6.5 million ha remain (Dahl 1990, Hefner et al. 1994, Battaglia et al. 2002). The remaining forests in the region are often highly fragmented with diminished ecosystem functioning due to hydrologic alteration and invasion of exotic species (Kellison et al. 1998).

There have been several attempts to quantify the carbon stocks in the South Central Region of the U.S. and in the LMAV (Birdsey 1996, Smith et al. 2006, Shoch et al. 2009, Wang et al. 2011). However these studies have generally looked at even aged afforested and plantation forests on the regional and state level scale and do not provide detailed assessments of individual uneven-aged stands in the LMAV. The purpose of this paper is to examine the carbon stocks of four microtopographically different uneven-aged forest stands in south Louisiana.

Preliminary estimates suggest 268 million metric tons of carbon is stored in all biomass components of Louisiana's forests (Xu and Wang 2007). Between 1991 and 2003 carbon loss was greatest in oak-gum-cypress forests (Xu and Wang 2007). These forests are typical of bottomland hardwood forests in the LMAV in Louisiana. Louisiana forests currently function as a carbon sink and the continued decline of carbon storage as an ecosystem service may have negative implications for the future (Wang et al. 2011).

The creation of carbon markets is often posited as a way to reduce forest carbon losses as a result of deforestation and land-use change (IPCC 2007). Such markets attempt to put a monetary price on the storage of carbon in terrestrial forest

environments. These markets currently exist on a volunteer basis in the U.S. and rely upon accurate estimates of the carbon storage potential of different forested systems for carbon price valuation. Credits are sold based on the additional amount of carbon stored each year in a forest based on management practices and conservation of carbon storage as an ecosystem service value in forests. Carbon finance in the lower Mississippi valley has subsidized afforestation of at least 31,300 ha of agricultural land as of 2008 (Shoch et al. 2009).

The purpose of this dissertation is to research energy and carbon flows in industrial, human, and natural systems in south Louisiana. Systems within south Louisiana were chosen because they operate at different size scales, are representative of similar functioning industrial, human, and natural systems outside the region, and are interconnected. Based on these assumptions, the following objectives were pursued:

1. Estimate the energy return on financial and energy investment for ultra-deepwater oil and natural gas in the federally regulated outer-continental shelf region of the Gulf of Mexico for production year 2009.
2. Inventory the greenhouse gas emissions produced by activities on the Louisiana State University main campus for FY 2007-2008
3. Estimate the carbon storage capacity of four uneven-aged bottomland hardwood forest stands in the LMAV of south Louisiana

These objectives add to the growing body of literature that allows for the understanding of tradeoffs associated with the pursuit of energy extraction, consumption, and storage. These analyses may be used to increase the sustainable management of

resources by society and help to maintain a climate that is within the bounds of human habitability. The long-term sustainability of each system relies on interdependent biophysical and socio-economic forcings that when interrupted, may lead to a decline in the functional capacity of one system or another. Understanding the interdependencies within each system may help to preserve the functioning of the system over time. Understanding the limits of each system may provide guidance on potential alternative paths towards long-term sustainability.

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CHAPTER 2

ULTRA-DEEPWATER GULF OF MEXICO OIL AND GAS: ENERGY RETURN ON FINANCIAL INVESTMENT AND A PRELIMINARY ASSESSMENT OF ENERGY RETURN ON ENERGY INVESTMENT*

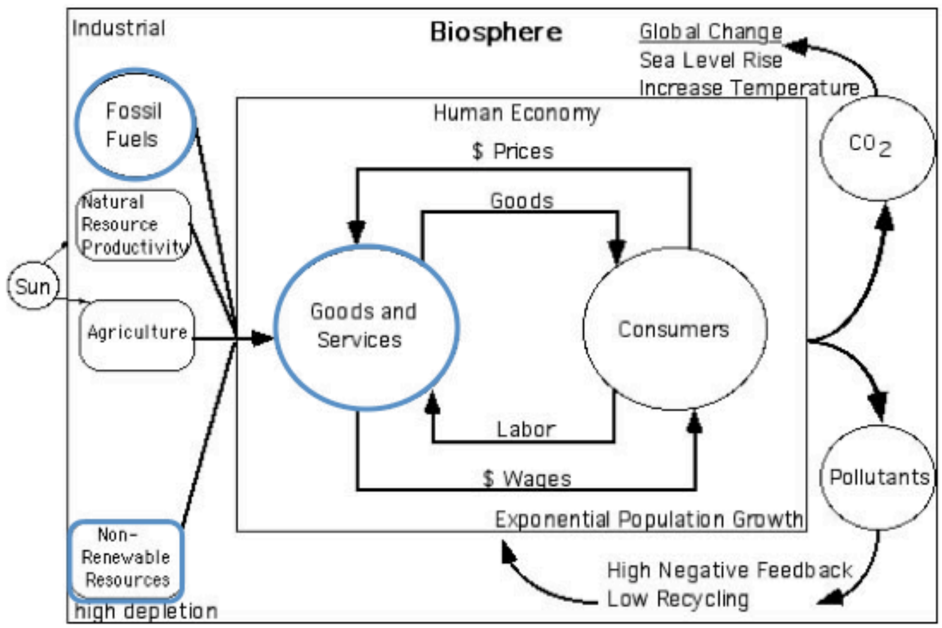

Figure 5. Conceptual diagram of the economic system and the biosphere for the full world scenario. The blue highlighting designates aspects (fossil fuels and non-renewable resource goods and services) of the industrial production side of the economy that are discussed in Chapter 2.

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Introduction

Since the early 1970s, domestic oil production rates in the U.S. have decreased, and domestic demand has been met increasingly by oil imports. Domestic oil is becoming scarcer and more difficult to produce because of reservoir depletion and a sharp decrease in the number of large, easily accessible discoveries onshore or in shallow coastal environments (Hofmeister 2008; Robertson 2008; Hall and Day 2009). Consequently, deepwater and ultra-deepwater Gulf of Mexico (GoM) oil has become increasingly important to U.S. domestic oil production over the last 20 years (Kaiser et al. 2010). Not surprisingly, energy extraction in the ultra-deepwater environment requires more financial and energy resources than from onshore or in shallow-water environments. Drilling costs increase exponentially with depth in the ultra-deepwater environment (Ultra-Deepwater Advisory Committee 2009). The increase in energy and financial costs reduces net energy available to society. The recent era of deepwater drilling often is associated with the notion of national energy independence and has been touted as a potential solution to decrease dependency on imports. However, proven oil reserves in the federal waters of the GoM (approximately 3.5 billion barrels at year-end 2008) are inadequate to support national domestic oil consumption for even one year (U.S. Central Intelligence Agency 2010; U.S. Energy Information Agency 2010). Production of deep and ultra-deepwater reserves has become profitable in part because of government subsidies and relatively high oil prices over the last decade (U.S. Department of Energy 2000; U.S. Minerals Management Service 2009a; U.S. Energy Information Agency 2010).

The purpose of this paper is to calculate explicitly the Energy Return on Financial Investment (EROFI) (King and Hall 2011) of oil and gas production in the ultra-deepwater Gulf of Mexico (GoM) for 2009 and the EROFI of oil in the Macondo Prospect. The Macondo Prospect, also known as Mississippi Canyon 252, is an ultra-deepwater oil and gas deposit located in the northern GoM. The deposit was being drilled on April 20, 2010 when the Deepwater Horizon oil rig exploded and collapsed into the northern GoM and is representative of other ultra-deepwater wells (Berman 2010). I also derived preliminary EROI estimates based on a range of energy intensity ratios (King and Hall 2011; Guilford and Hall 2011) to provide a range of estimates for EROI in the ultra-deepwater GoM and Macondo Prospect.

The EROFI is an estimate of the financial cost for the production of a barrel of oil or natural gas expressed as barrel of oil equivalent (BOE). One BOE is equal to 5,800 cubic feet of natural gas. EROFI is the amount of money expended by an energy producing entity divided by the amount of energy produced. An energy producing entity must produce energy at sufficient economic profit while paying off the costs of the supply chain of labor, materials, and transport in order to maintain a profitable business (King and Hall 2011). Profitability is, however, related directly to the supply chain costs. The entity fails to be financially profitable when the incurred costs are greater than the price of the product being sold. EROFI analysis provides an estimate of the base price for which a barrel of oil must be sold in order to maintain economic profitability. EROI analysis is a tool used to measure the net energy of an energy supply process (Cleveland et al. 1984). The net energy of an energy source is the amount of energy returned to society divided by the energy required to get that energy (Hall et al. 2009). An energy

source becomes an energy sink when the amount of energy used in extraction is greater than the extracted amount of energy (EROI < 1:1). In 1930, the average domestic oil discovery yielded at least 100 units of energy equivalent output production for every unit of input, and that oil could be produced at a return of about 30 for one. (Guilford et al. 2011; Cleveland 2005). Today, the average net energy measured by EROI of domestic oil production has declined to about 10:1, or 10 units of output for every unit of input (Guilford et al. 2011; Cleveland 2005).

Gately (2007) reported without explicit quantification that the energy return on investment (EROI) for deepwater and ultra-deepwater oil was low, decreased with an increase in water depth, and less than 10:1. Gately (2007) estimated EROI for deepwater (depths of 900 m +) GoM using production data from the Minerals Management Service (MMS, now Bureau of Ocean Energy Management, Regulation and Enforcement) combined with previously published operational dollar cost estimates (Dismukes et al 2003) and energy intensity factors that allow for the conversion from dollars to energy units (Costanza and Herendeen 1984). EROI, including only direct costs at 900m+ water depths, ranged from 10–27:1 for the years 2000–2004 and 3–9:1 for the same years when including indirect costs of production (Gately 2007). The energy intensity factors used in past studies may be inaccurate because of changes in technology, advances in energy efficiency, and the scale of offshore operations since they were first proposed (Costanza and Herendeen 1984; Gately 2010). Unfortunately it is impossible to verify the accuracy of Gately's conclusions (2007) or to recreate either analysis because no data were given.

The importance of EROI to a society is that the analysis provides a measure of the surplus energy gained from an energy source that can be diverted to other sectors of the

economy to produce goods and services other than those required for energy extraction. Decreasing EROI increases the proportion of economic output that goes into the energy extraction sector of the economy leaving fewer economic and energy resources available for non-energy extraction sectors. Net energy and the associated surplus energy to society, declines with declining EROI. The trend towards low EROI fuels reduces the quantity and affordability of the fuel supply (Hall and Day 2009).

This paper presents a non-comprehensive analysis of the EROFI for ultra-deepwater oil and gas in the GoM in 2009 and potential Macondo Prospect reserves using updated financial data. In particular, data that have become available in the wake of the Deepwater Horizon oil rig disaster are used to increase understanding of the EROFI for energy production in the federally regulated ultra-deepwater outer continental shelf of the GoM. The analysis is non-comprehensive because it estimates EROFI and EROI without including all of the indirect energy inputs that go into the production process (i.e. labor costs, auxiliary services costs, environmental costs). In addition, the EROFI and EROI estimates are for energy extraction at the well-head and do not include the financial or energy resources required to transport, refine, and distribute the energy to end users. It is necessary to convert financial inputs to energy inputs using energy intensity ratios to estimate the energy return on energy investment in the ultra-deepwater GoM in 2009 because of a lack of access to accurate, comprehensive ultra-deepwater energy input production data.

GoM Oil Production

GoM federal offshore oil production on the outer continental shelf (OCS) accounted for approximately 29% of total U.S. oil production in 2009. Deepwater and ultra-deepwater GoM areas contributed to 80% of total federal offshore GoM oil in 2009 (U.S. Minerals Management Service 2010). Deepwater (1,000–5,000 ft.) oil production in the GoM became a major part of U.S. domestic energy production in 1998 when shallow water production began to decline. Deepwater production peaked in 2004 and has been in decline ever since. Ultra-deepwater (> 5,000 ft.) production has helped to offset the deepwater production decline in a similar manner as deepwater production had previously offset shallow-water production in the late 1990s (Fig. 6).

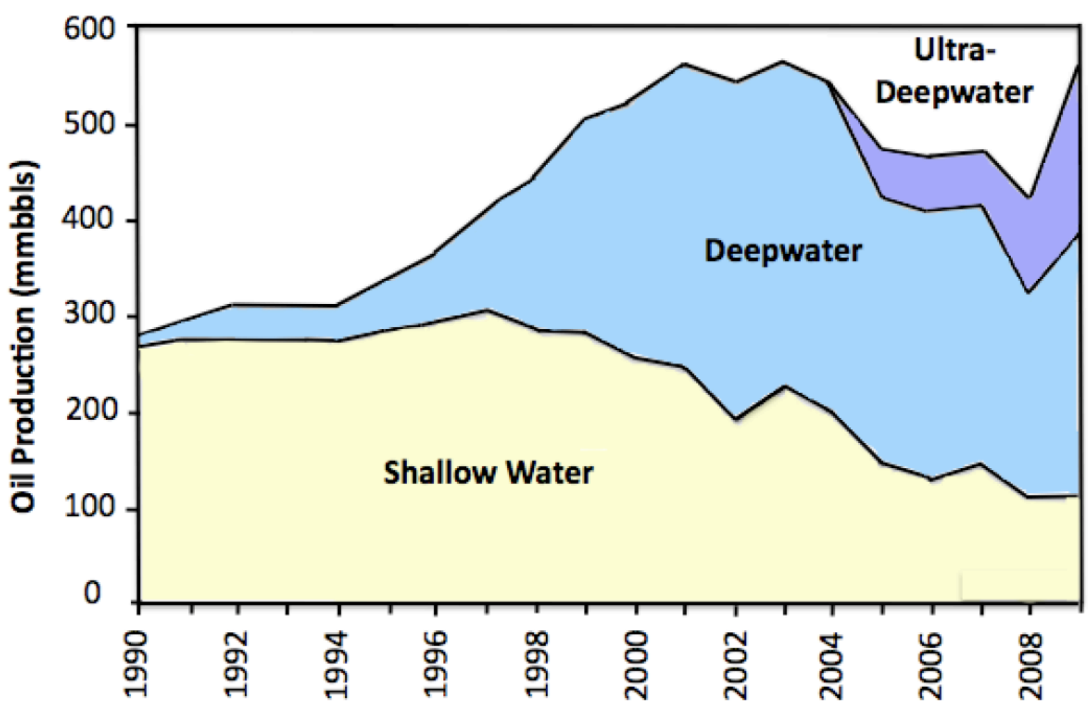

Figure 6**.** Oil production in the Gulf of Mexico (GoM) Federal Offshore region including lease condensate Source: Minerals Management Service (MMS), Energy Information Administration, Office of Oil and Gas (2010). (mmbbls equals million barrels per year).

Federal offshore production, formerly declining from 2007 to 2008, increased by 33% (over 147 million barrels) between 2008 and 2009 (U.S. Energy Information Agency 2010; IHS CERA 2010). The increase in production for 2009, however, reflects not only production from the new projects that came online, but also the addition of volumes that were shut-in during 2008 as a result of hurricane activity (U.S. Minerals Management Service 2009a). For oil, 75-percent of the increase in production in 2009 is a reflection of shut-in volumes coming back online (USA Minerals Management Service 2009a).

The economic profitability of deep and ultra-deepwater production is dependent upon, among other things, the price of oil and costs associated with exploration, production, transportation, processing, and delivery to end use as well as government subsidies. Past studies (Anderson and Boulanger 2002) concluded that a discovery containing at least about 1 billion barrels recoverable is required to support extracting ultra-deepwater oil, which may cost upwards of $1 to $2 billion dollars (22). Larger reservoirs generally yield higher production rates per well, thereby increasing net energy and financial profitability because less energy and money is required to extract oil from a larger reservoir (King and Hall 2009).

GoM Rig Counts

The number of oil drilling rigs in Federal OCS waters affects the energy return on financial and energy investment. Increasing drilling effort does not always lead to an increase in production (Hall et al. 2009). An increase in the number of rigs increases the financial costs of energy extraction, as more energy, labor, and

raw materials are required per unit of energy produced. So long as rigs are adding proportional supply to the total energy produced, they can to offset the increased financial and energy costs of ultra-deepwater projects.

The lifespan of a rig affects the amortized cost of the rig. Rigs have a lifespan of about ten years before a major work over is required (National Subsea Research Institute 2010; Sharma et al. 2010). Most ultra-deepwater drilling rigs were constructed within the last twenty years, as was the nine year-old Deepwater Horizon. The long-term leasing contract process allows rig construction costs to be recouped over a period of years and insures rig utilization. Rigs are mobile and often produce oil from several different fields over the course of their operational lifetime.

Daily operating costs for deepwater rigs have doubled over the course of the last decade partly as a result of increasing energy costs required by production operations for larger floating rigs often located 100+ miles from shore. Global investment trends provide evidence for continued deepwater production and decreased shallow and mid-water production (Triepke 2010).

Macondo Prospect Reserves and Cost Estimates

The Macondo Prospect is an oil and gas reservoir located in Mississippi Canyon Block 252 in the northern GoM just southeast of the mouth of the Mississippi River. The reservoir is in water depths greater than 4,900 ft. (1,700 m) and located more than 17,700 ft. beneath the ocean floor. BP officials estimated that there were approximately 50–100 million barrels of oil associated with the Macondo Prospect (Klump 2010; Scherer 2010). Oil companies usually extract

Typically only about 30% of the oil in a reservoir can be recovered due to the geologic constraints of the reservoir and economics of the extraction process (Scherer 2010). Based on this estimate, I estimated that the reservoir would yield about 30% of the total reserves or between 15 million and 50 million barrels. Higher available reserve estimates, result in lower EROFI and higher EROI values, and increase the time necessary for extraction.

The average construction cost of floater rigs in operation in 2009 was $565 million dollars per rig (Jefferies & Co. Offshore Drilling Monthly 2009). At the time of its demise, the Deepwater Horizon was leased for three years at a total cost of $544 million, which equates to a bare rig daily lease rate of $496,800/day. The average daily operations cost for U.S. GoM semi-submersible rigs, including crew, gear, and vessel support operations for 2009 was approximately the same as the daily lease rate (Rigzone Inc. 2011). Thus, total daily operational cost was $993,600. This estimate is consistent with industry-wide costs for similar deepwater oil rigs (Leimkuhler 2010).

Energy Intensity Ratios

The energy intensity ratio is the amount of energy required to produce $1 of GDP (or of some component of GDP) in a given year. The energy intensity ratio allows converting from financial costs to energy costs in this and other studies. The energy intensity ratio of production is correlated to effort, one variable of which is the number of rigs employed in production (Hall and Cleveland 1981). Other variables affecting energy intensity include the size and energy requirements of rigs and support vessels as well as

the depth of resource deposits and distance offshore. Energy intensity ratios can be used to estimate approximate costs for many fuels where economic but not energy data are available (King and Hall 2011; Hall et al. 2009; Murphy et al. 2011), which was the case for our study. Energy intensity ratios, for the economy as a whole and for individual industrial sectors, change because of inflation, as a result of material availability, and through efficiency gains. The mean energy intensity ratio for the U.S. economy in 2005 was approximately 8.3 Megajoules (MJ) per $1 USD. The oil and gas industry is an energy intensive sector with an estimated energy intensity ratio of 20 MJ per $1 USD in 2005, while heavy construction during the same period was estimated to be 14 MJ per $1 USD (Hall et al. 2009). Advances in energy efficiency and the steady decline in energy intensity ratios over time provide the rationale for estimates used in this study (U.S. Energy Information Agency 2011). Previous research has shown that energy intensity ratios serve as an effective proxy in determining the EROI of various energy sources (King 2010).

The objectives of this study were threefold: (1) To derive estimates of the energy return on financial investment for oil and oil + natural gas in the ultra-deepwater GoM in 2009 based on production and financial cost data; (2) To derive estimates of the energy return on financial investment for oil and oil+natural gas in the ultra-deepwater GoM in 2009 based on the same data plus estimates of energy intensities; and (3) To derive an estimate of the energy return on both financial and energy investment for the estimated total oil reserves of the Macondo Prospect based on industry stated estimates of reserves and financial cost data.

Methods

The methodology employed in this paper is based on the second order comprehensive EROI ($EROI_{stnd}$) protocol described by Murphy et al. (2011) and previously by Mulder and Hagens (2008). The $EROI_{stnd}$ includes direct and indirect energy and material inputs for extraction whereas the first order EROI ($EROI_{1,d}$) includes only direct energy and material inputs. I used the $EROI_{stnd}$ methodology so that the study results could be easily compared to the EROI research performed on other energy resources (Murphy et al. 2011). I calculated energy return on financial investment based on King and Hall (2011). The EROFI for potential reserves in the Macondo Prospect was estimated based on annual costs multiplied by the number of years it would take to extract the reserves and divided into the energy output of the estimated size of reserves. The EROFI for total energy produced in the ultra-deepwater GoM in 2009 was determined by dividing the total estimated financial costs for ultra-deepwater operations in 2009, into the total amount of oil and gas recovered from the ultra-deepwater in 2009. EROI estimates were then estimated using energy intensity ratios established for 2005 combined with production cost data adjusted for inflation at 4% per year. Financial input data includes rig construction and operation costs along with exploration costs. Energy output is based on an estimated 30% extraction of Macondo oil reserve estimates and total reported 2009 GoM ultra-deepwater oil and natural gas production.

The Macondo Prospect is an average ultra-deepwater well with respect to depth and location (Berman 2010). I use the Macondo Prospect as a proxy for similar sized ultra-deepwater GoM reserves. The period of time required to extract the Macondo reserves is important to the analysis. Increased extraction efficiency decreases operating

and production costs that positively impact EROFI. The production profile curve is the amount of energy extracted from a well over time. A constant flow rate production profile would result in a higher energy return because of a shorter time for total production. However, virtually all producing wells follow a bell-shaped production profile based on the three phases of ramp-up, plateau, and decline (Kaiser et al. 2010). I calculated EROFI and EROI values for constant and bell-shaped production profiles to demonstrate this difference. The constant production profile curve provides an optimal extraction scenario that is unlikely to occur, but useful in demonstrating potential returns on investment. The bell-shaped profiles were generated using the MMS full potential scenario forecast methods based on past deepwater GoM production wells [41-42] as follows.

For total recoverable reserves of 50 million barrels in the Macondo Prospect and 30% extraction efficiency, 15 million barrels of oil would be pumped in 600 days if a constant flow rate of 25,000 bpd were assumed. If all of the 50 million barrels were recoverable at the same constant flow rate, it would take 2000 days. Peak production is based on the estimated ultimately recoverable reserves using the MMS full potential scenario forecast equation:

$$\text{Peak Rate} = (0.00027455) \times (\text{ultimate recoverable reserves}) + 9000$$

where the peak rate is in barrels of oil equivalent (BOE) per day and the ultimate recoverable reserves are in BOE (U.S. Minerals Management Service 2007; 2009).

The parameters in this equation were derived by plotting maximum production rates of known fields against the ultimate recoverable reserves of those fields, and

performing a linear regression between reserves and production (U.S. Minerals Management Service 2007; 2009). These reserve estimates are on a field-by-field basis, thus MMS assumed that this relation, based on historic field trends, could be applied on a project basis (U.S. Minerals Management Service 2007; 2009). This equation is generally applied to reserves of 200 million barrels of oil equivalents and more and assuming peak production lasts for four years (U.S. Minerals Management Service 2007; 2009).. For our analysis, I assumed peak flow rates lasted two years because Macondo reserve estimates were one half to one quarter of 200 million barrels and then declined at 12%/year (U.S. Minerals Management Service 2009a). During the first year of operation, production was assumed at half its peak rate (U.S. Minerals Management Service 2007; 2009a;2009b].

Ultra-deepwater GoM production in 2009, was 182 million barrels of oil and 572 billion cubic feet of natural gas (U.S. Minerals Management Service 2009a); equivalent to an oil+natural gas total of 291 million BOE. Production costs were based on published rig counts and rig construction costs (Table 1) (Offshore Drilling Monthly 2010; Triepke 2009). At any given time there were 25–30 rigs producing in ultra-deepwater (Triepke 2009). Amortized rig construction costs are based on the number of years it takes to drill a well and extract the resource**.**

I used published energy intensity ratios to derive the EROI values from the EROFI. The energy intensities are rough estimates of the energy used to undertake any economic activity derived from the national mean ratio of GDP to energy (Hall et al. 2009). These ratios can be used to estimate rough costs for many fuels where economic but not energy data are available (Murphy and Hall 2010) and are based on non-quality

Table 1. Estimated 2009 production costs for the Macondo Prospect and ultra-deepwater GoM rigs.

Study	# of Rigs	Amortized Construction Cost	Operating Cost	Exploration Cost	Total Cost per Year
Macondo Prospect	1	$62.2 million per year for nine years	$1 million per day	$1 million per day for 100 days	$527.2 million
Ultra-Deepwater GoM	25–30	$56.5 million per year, per rig, for 10 years	$1 million per day per rig	$1 million per day, per rig, for 100 days	$13–15.7 billion

corrected thermal equivalents (Cleveland 2005). The EROI calculation is limited by available data and is an estimate at the wellhead and not at the point of end use. Estimates of the energy intensity ratio of U.S. oil and gas extraction averaged across all domestic fields and well depths was 9.87 MJ/$ in 1997, 14.5 MJ/$ in 2002, and 20 MJ/$ in 2005 (Hall et al. 2009; Carnegie Mellon 2011). This increase was not due to the energy intensity per dollar increasing, but because more of the downstream energy requirements were included in the higher energy intensity values. Based on these reports, I used energy intensity ratios of 7, 12, and 18 MJ to carry out a sensitivity analysis of the impact of different energy intensity ratios on EROI. These ratio estimates are less than those reported in 2002 due to increases in economic efficiency between 2002 and 2009.

Energy output was based on 1 barrel of oil = 6.11 Gigajoules. EROFI costs were expressed in 2009 USD$. EROI was based on 2009 USD$ costs, corrected for inflation

using a factor of 1.10 (Bureau of Labor Statistics 2011), and presented in 2005 USD$ to maintain consistency with the energy intensity ratios used in the analysis. Total energy inputs were the summation of 10-year amortized rig construction costs, 100-day exploration costs per rig, and operational costs converted to energy units using the three different energy intensity ratios. Construction, operational, and exploration costs were summed and were then converted to energy units using the three energy intensity ratios described above. A number of costs were not included because data were not available. Costs not accounted for were rig and operator insurance costs, costs associated with enhanced recovery techniques and costs associated with dry holes. However, these costs are substantial (Weglein 2004). When included, these costs would increase EROFI and decrease EROI beyond estimates provided below.

Results

The financial cost per barrel of ultra-deepwater oil in the GoM at the well-head ranged from $71/barrel to $86/barrel depending on the number of rigs deployed in production. The EROFI for oil + natural gas at the well-head in the GoM in 2009 ranged from 0.019 to 0.022 barrels (BOE), or roughly 0.85 gallons, per dollar, based on the number of rigs deployed in production.

The financial cost at the well-head per barrel of oil available in the Macondo Prospect based on the constant flow rate production profile, was $62/barrel assuming 15 million barrels produced per day, or $45/barrel if producing 50 million barrels over 2000 days. The EROFI at the well-head was $141/barrel of oil in the Macondo Prospect if 15 million barrels were produced over 4 years, or $84/barrel if producing 50 million barrels over 8 years.

The preliminary EROI based on financial costs and subsequent sensitivity analysis using three different energy intensity ratios ranged from 4:1 to 14:1 for 2009 total GoM ultra deepwater oil production while the EROI for total oil plus natural gas production in the ultra-deepwater GoM in 2009 was slightly higher at 7:1–22:1. The EROI for the Macondo Prospect using the MMS full potential scenario forecast varied from 4:1 to 16:1. The EROI of the constant flow rate scenarios for producing 15 and 50 million barrels in the Macondo Prospect at 25,000 bpd are given in Table 2.

Table 2. Calculated EROFI and EROI of Macondo Prospect oil reserves, as reported by BP (Klump 2010), assuming a constant production rate of 25,000 bpd. The EROI is calculated using three different energy intensity ratios (7MJ/$, 12MJ/$, 18MJ/$) and two different reserve estimates. MJ/$ = Megajoules/U.S. dollar. All values are inflation adjusted.

Time (days)	Total Reserves (millions of barrels)	EROFI (2009 USD$/bbl)	Energy Intensity Ratio (MJ/$)	EROI
600	15	$62	7	18:1
			12	10:1
			18	7:1
2000	50	$59	7	20:1
			12	12:1
			18	8:1

Applying the MMS full potential scenario forecast equation to Macondo field reserves yielded a peak rate of 13,118 barrels/day for 15 million barrels and 22,728 barrels/day for 50 million barrels. If 15 million barrels were recovered, the well would be depleted within four years and if 50 million barrels were recovered, the well would be

Table 3. Estimated EROFI and EROI of potential Macondo Prospect oil reserves using three different energy intensity ratios (7MJ/$, 12MJ/$, 18MJ/$), two different reserve scenario estimates, and a flow rate based on the MMS full potential scenario forecast equation (MMS 2009). MJ/$ = Megajoules/U.S. dollar. All values are inflation adjusted.

Time (years)	Total Reserves (millions of barrels)	EROFI (2009 USD $/bbl)	Energy Intensity Ratio (MJ/$)	EROI
			7	9:1
4	15	$141	12	6:1
			18	4:1
			7	16:1
8	50	$84	12	9:1
			18	6:1

depleted within eight years. The EROI using the MMS production equation for one well producing total reserves of 15 and 50 million barrels, respectively, from the Macondo field for four years and eight years, respectively, are presented in Table 3.

EROI estimates of 2009 ultra-deepwater oil production are based on operating costs of $1 million per day and 10 year annualized rig costs of $56.5 million/year plus $100 million dollars in exploratory drilling per rig. EROI estimates based on low (25 rigs), average (27 rigs), and high (30 rigs) rig counts are given in Table 4. The EROI of oil and natural gas (BOE) produced in the ultra-deepwater of the GoM in 2009 is shown in Table 5. Again, EROI is based on low (25 rigs), average (27 rigs), and high (30 rigs) rig counts as given in Table 4. The range of EROI estimates for the Macondo Prospect and 2009 ultra-deepwater production are presented in Figure 7.

Table 4. Estimated EROFI and EROI of 2009 Federal GoM Ultra-deepwater oil using three different energy intensity ratios (7 MJ/$, 12 MJ/$, 18 MJ/$) and three different rig count scenario estimates. MJ/$ = Megajoules/U.S. dollar. All values are inflation adjusted.

# of rigs	EROFI (2009 USD $/bbl)	Energy Intensity Ratio (MJ/$)	EROI
25 (low)	$71	7	14:1
		12	8:1
		18	5:1
27 (avg.)	$77	7	13:1
		12	7:1
		18	5:1
30 (high)	$86	7	11:1
		12	7:1
		18	4:1

Table 5. EROFI and EROI of Federal GoM Ultra-deepwater energy using three different energy intensity ratios (7MJ/$, 12MJ/$, 18MJ/$) and three different rig count scenario estimates. MJ/$ = Megajoules/U.S. dollar. All values are inflation adjusted.

# of rigs	EROFI (2009 USD $/bbl)	Energy Intensity Ratio (MJ/$)	EROI
25 (low)	$45	7	22:1
		12	12:1
		18	9:1
27 (avg.)	$48	7	18:1
		12	12:1
		18	8:1
30 (high)	$54	7	18:1
		12	11:1
		18	7:1

Discussion

Our values for EROFI at the well-head ranged from $45/barrel to $141/barrel. By comparison, production costs for Mideast and North Africa oil ranges from $6/barrel to $28/barrel and for the United States overall roughly twice that (International Energy Agency 2008). These values for the GOM indicate that if these resources are used as the basis of US oil use, then the price of oil would have to be in the range of current prices, which maybe too high to sustain economic growth (King and Hall 2011; Hall et al. 2009). The sensitivity analysis yielded EROI values ranging from 4–22:1. The lower end of this range of EROI may be more accurate since these values were derived using energy intensity ratios for the oil and gas industry. Increasing rig counts and time required for extraction negatively influenced EROI for the United States as a whole. EROI for

domestic oil and gas has declined from 100:1 for discoveries in 1930 and about 30:1 for production in the 1950s–1970s to about 10:1 in 2005–7 (Cleveland et al. 1984, Cleveland 2005).

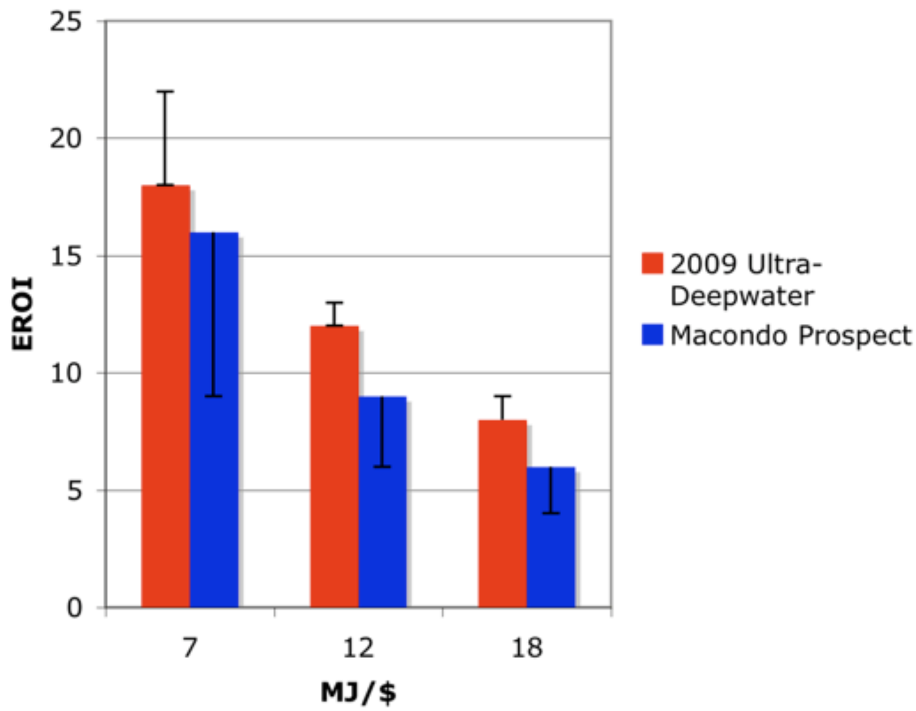

Figure 7. Standard EROI for the Macondo Prospect and 2009 ultra-deepwater total oil plus gas production calculated from EROFI using different energy intensity ratios and adjusted for inflation at a rate of 4%/year. EROI is based on 2005 energy intensity ratios and costs in 2005 dollars. Error bars reflect potential daily production flow rates for Macondo data and different rig counts for 2009 data (see text for discussion).

EROI values presented in this study are in the lower range of previously published estimates for domestic oil production, especially when high energy intensities are used. The EROI for oil and gas at the well-head in ultra-deepwater in 2009 ranged from 7–22:1, while the EROI for oil alone in ultra-deepwater was 4–14:1. Most of the variability was our choice of energy intensities used per dollar. The Macondo Prospect EROI for oil alone using the MMS production profile curve yielded a similar EROI of 4–

16:1 based on estimates of varying reserve sizes, costs associated with extraction, and the energy intensity associated with extraction costs. The constant flow rate scenario for the Macondo Prospect yielded similar results in the range of 7–20:1. These values fit the trend of decreasing EROI over time as oil was produced from increasingly expensive fields.

Our EROI values can be compared to other reports of EROI for energy production processes including 80:1 for coal, 12–18:1 for imported oil, 5:1 or less for shale oil, 1.6 to 6.8:1 for solar, 18:1 for wind, 1.3:1 for biodiesel, 0.8 to 10:1 for sugarcane ethanol, and 0.8 to 1.6:1 for corn-based ethanol (Hall and Day 2009; Murphy and Hall 2010). GoM ultra-deepwater oil in 2009 is compared to previous estimates of EROI for domestic, foreign, and tar sands oil in Figure 8. The graphic demonstrates that the EROI of oil has declined over time in the U.S. and from foreign sources. In addition, the graphic shows unconventional reserves such as the tar sands contain a lower EROI than conventional domestic and foreign sources of oil.

The EROI values of this study were based on financially-derived energy costs of production at the well-head only, and did not include all of the indirect costs of delivery to end use. Thus, these estimates are conservative. If all indirect costs were included in the EROI calculations, then EROI would decrease. The lack of indirect cost estimates underscores the need to make accessible better energy accounting information so that more refined analyses of the EROI of ultra-deepwater energy extraction can be conducted. Unfortunately, funding is being cut for the U.S. Energy Information Agency, the agency charged with providing such information to the public (U.S. Energy

Information Agency 2011). The lack of data availability regarding energy extraction costs in the GoM makes it difficult for the individuals, interest groups, and political

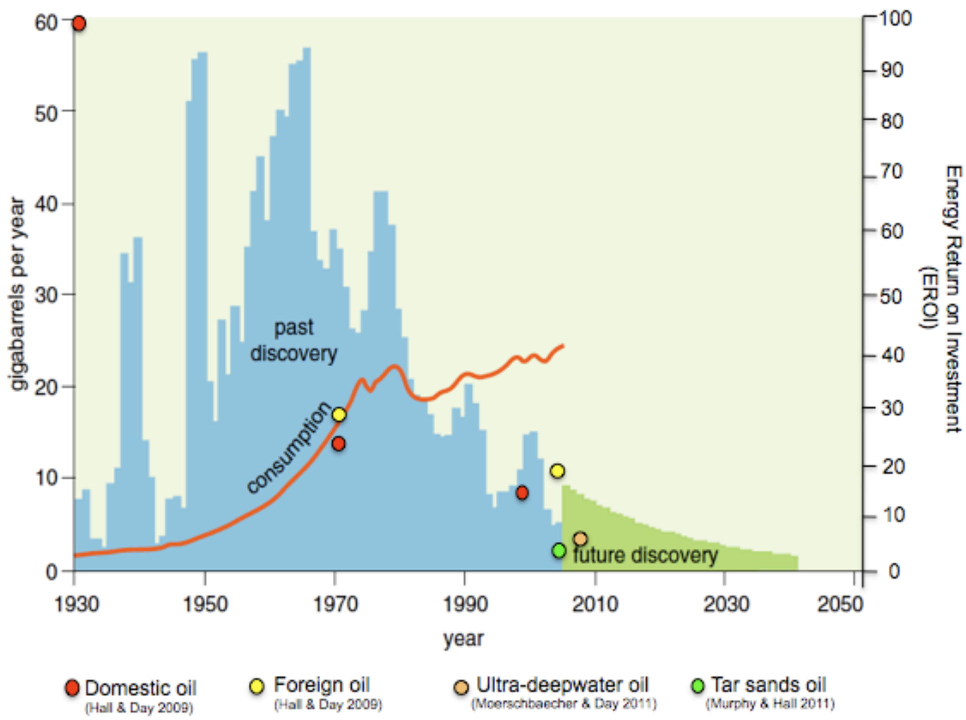

Figure 8. Graph of global oil discoveries and consumption through time. Colored dots represent EROI values of domestic oil, foreign oil, tar sands oil, and ultra-deepwater GoM oil from this study and previously published values.

representatives to make wise decisions regarding offshore energy policy. Informed decision-making on energy policy is essential to the long-term sustainability of society.

One of the energy costs only partially included in this study is the number of exploratory *vs*. development wells in ultra-deepwater in 2009. The number of exploratory *vs*. development wells drilled in 2009 was not factored into the EROI calculations of this study because data were unavailable. In addition, the insurance costs associated with rigs operating in ultra-deepwater were not included but are estimated by market analysts to range between 10–35% of the present value of the rig (Slanis 2010). For a $500 million

dollar rig, that would add between \$50–\$175 million in insurance costs per year of operation. If all of these costs were included it might decrease the EROI by perhaps 25 percent.

More expensive, higher capacity rigs produce higher EROI oil when producing from large reservoirs with high daily flow rates. As daily production declines from the plateau phase, the EROI of the well decreases since the same operational and infrastructural costs are being utilized to produce less oil and gas. Technological advancement may increase efficiency of extraction over time, thereby increasing energy return on investment but technology comes at the cost of research and development funding. A difficult situation arises when drilling contractors are prevented from accessing the resource either through federal regulation, as happened in 2010, or as a result of declining oil prices and decreasing production profitability.

Subsidy statutes applying to deepwater energy production, that circumvent the fair market value provision, are mainly the result of the Deepwater Royalty Relief Act (DWRRA) and the Energy Policy Act of 2005. The Deepwater Royalty Relief Act granted exploration leases issued between 1996 and 2000 an exemption from paying the government royalties on oil produced by wells that would not otherwise be economically viable. The program has been extended since its original expiration date in 2000. In addition, the Energy Policy Act put an oil-price threshold below which producers would not have to pay the government royalties thereby providing further incentive for companies to drill in the offshore GoM.

Another indirect cost not accounted for in this study includes the cost of the loss of the value of ecosystem services as a result of federal offshore energy production. Air and water pollution attributed to the oil and gas industry are market externalities that in reality have costs borne by society.

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CHAPTER 3

THE GREENHOUSE GAS INVENTORY OF LOUISIANA STATE UNIVERSITY: A CASE STUDY OF THE REQUIREMENTS OF PUBLIC HIGHER EDUCATION IN THE UNITED STATES

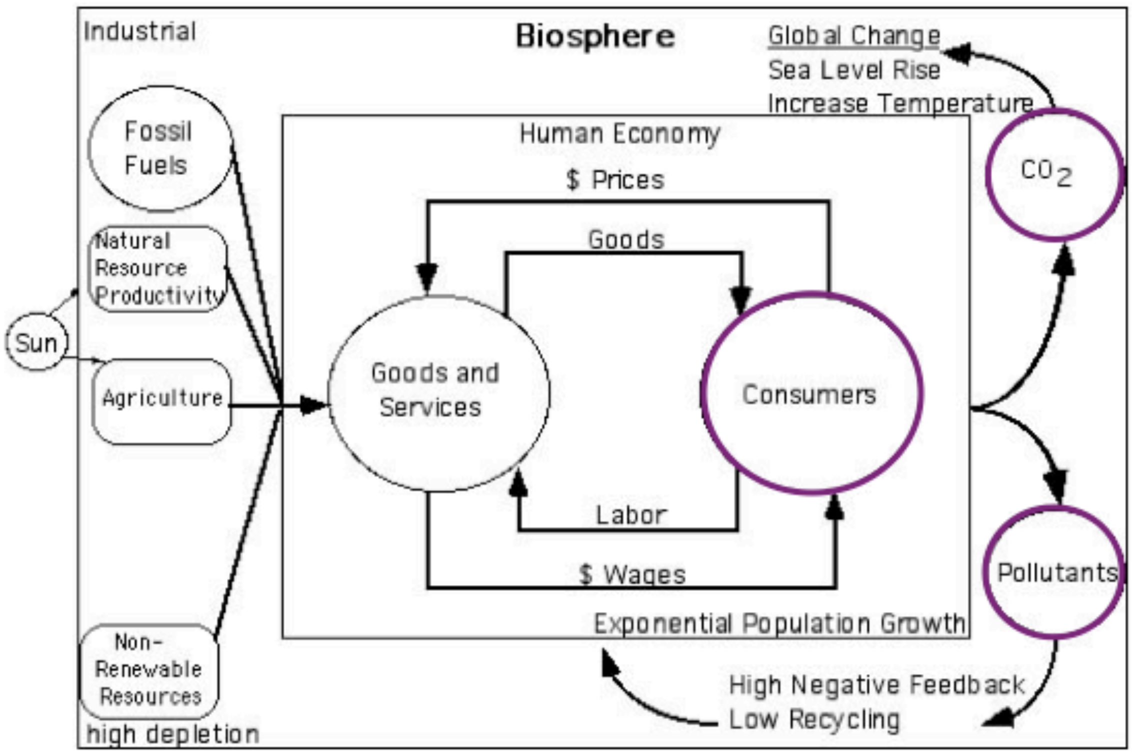

Figure 9. Conceptual diagram of the economic system and the biosphere for the full world scenario. The purple highlighting designates aspects (consumers and waste products) of the human consumption components of the economy that are discussed in Chapter 2.

Introduction

Resource consumption and sustainability are growing concerns for public higher education institutions and society (Zilahy et al. 2009) (Hall et al. 2009). Climate change and increasing energy scarcity also pose threats to modern society (Hall and Day 2009). To deal with these concerns, an increasing number of higher education institutions have begun to inventory energy consumption and greenhouse gas (GHG) emissions (American College and University Presidents Climate Commitment 2009). These inventories can play an important role in defining institutional energy requirements, highlighting options for energy conservation, and in assessing the environmental costs of resource consumption.

Anthropogenic fossil fuel consumption has led to an increase in greenhouse gases (GHG) in the atmosphere (Intergovernmental Panel on Climate Change 2007). The concentration of GHGs such as carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons have increased dramatically since the industrial era began in the early 19th century (Intergovernmental Panel on Climate Change 2007). Prior to the industrial revolution atmospheric CO_2 concentrations were about 280 ppm. Currently, CO_2 concentrations in the atmosphere are about 390 ppm and rising (National Oceanographic and Atmospheric Administration 2010). Greenhouse gas production and sea level rise are tracking the higher IPCC scenarios (McCarthy 2009).

Increased levels of GHGs in the atmosphere have increased in the thermal equilibrium of the planet as a result of the increased amount of infrared radiation absorbed by these gases in the atmosphere (Intergovernmental Panel on Climate Change 2007). Effects of increased greenhouse gas concentrations in the atmosphere include increases in global average surface air temperature, global average sea level, and a

decrease in snow cover in the Northern Hemisphere (Brohan et al 2006; Vermeer and Rahmstorf 2009; Frei and Gong 2005; Odum and Barrett 2005). Precipitation changes are expected to decrease water availability in the western U.S. and alter agricultural production throughout the interior U.S. (Intergovernmental Panel on Climate Change 2007). Climate is a dominant physical factor affecting global ecosystems (Odum and Barrett 2005). The effects of climate change are highly diverse and wide ranging in biological ecosystems (Walther et al. 2002). A basic assumption of this paper is that anthropogenically induced climate change is real.

Total greenhouse gas emissions in the United States in 2008 were estimated to be 7,053 million Metric Tons (MT) carbon dioxide equivalents (CO_2e) (Energy Information Agency 2008). The U.S. produces between 22% and 25% of total GHG emissions globally. Average annual per capita emissions for the years 2001–2005 were approximately 20 tons CO_2 per U.S. citizen while global average annual per capita emissions ranged from 3.9 to 5.8 tons CO_2 per year (World Resources Institute Climate Analysis Indicator Tool 2009). While most countries have lower average per capita emissions than the U.S., a few, such as Qatar and other Middle Eastern countries, have higher per capita emissions.

The state of Louisiana was the eighth largest producer of total GHG emissions in the U.S. in 2005 with a total of 191.56 million MT CO_2 (Environmental Protection Agency 2008). The majority of these emissions come from private sector industrial activities within the state. In 2005, Louisiana was the second largest producer of industrial GHG emissions in the U.S. with a total of 93.3 million MT CO_2e (Environmental Protection Agency 2008). Total per capita emissions in Louisiana in

2002 were 13.76 MT CO_2 (Gurney et al. 2010). East Baton Rouge Parish, where LSU is located, produced the highest total amount of greenhouse gas emissions (approximately 27 million MT CO_2e) of all parishes within the state in 2002, mainly because of heavy industry (Gurney et al. 2010). The majority of emissions in East Baton Rouge Parish are the result of industrial activities such as petrochemical refineries and chemical manufacturing plants. However, Louisiana forests and coastal wetlands provide carbon storage that has the potential to offset some of the state's emissions (Chmura et al. 2003; Rybczyk et al. 2002).

As a coastal state with about 30,000 km^2 of coastal area including approximately 30% of the total coastal marsh area in the lower 48 states (Barras et al. 2010; Louisiana Department of Natural Resources 2010), Louisiana is presently, and will continue to experience the effects of climate change into the future (Day 2005; Blum 2009). Local effects include increasing salinization of surface waters (Intergovernmental Panel on Climate Change 2007), water constraints on thermal power plants used for electricity production (Blum et al. 2007), large-scale infrastructure damage (namely the energy and transport sectors) and state revenue losses due to extreme weather events (*i.e.*, hurricanes) (Kafalenos et al. 2008), relative sea level rise between one and two meters by 2100 leading to 10,000–13,500 km^2 of coastal land loss by 2100 (Blum 2009; Bates et al. 2008; Bull et al 2007; Kafalenos et al. 2008; Day et al. 2007), a significant increase in days with peak temperatures over 90 °F and fewer freezing days (Melillo and Peterson 2009), and increased incidents of large scale population mortality (more than 1,800 individuals died as a result of Hurricanes Katrina and Rita in 2005) (Nicholls et al 2007).

LSU and Greenhouse Gas Emissions

Louisiana State University Agricultural and Mechanical College (LSU A&M) is a public land grant university located in Baton Rouge, Louisiana, USA. LSU is "committed to being a responsible institution dedicated to the pursuit of truth and the advancement of learning while upholding the highest standards of performance in an academic and social environment" (LSU A&M 1995). LSU decided to address its contribution to atmospheric greenhouse gas pollution by commissioning an inventory of greenhouse gas emissions on the main campus during the 2008–2009 school year. This is recognized as a required initial step in understanding and reducing the annual GHG emissions of the University. Many have used the term "carbon footprint" for this type of analysis for universities (American College and University Presidents Climate Commitment 2009). However, this is less accurate than "carbon weight" (Hammond 2007). Reduction of GHG emissions is a way of reducing the rate and magnitude of change resulting from global climate change (Intergovernmental Panel on Climate Change 2007). The GHG inventory provides a baseline estimate of emissions resulting from activity on the main campus. The University's decision to inventory and assume responsibility for GHG emissions and their effects on climate are in line with both international (Kyoto Protocol) and domestic policy (United States House Resoluton 2454 2010) concerning global climate change.

This report details the GHG emissions resulting primarily from direct energy usage for the LSU A&M main campus for fiscal year (FY) 2007–2008. The purpose of this report is to provide the campus community and the public with an accurate estimate of campus GHG emissions, the sources of those emissions, and potential measures that

may be implemented to reduce emissions in the future. Further, it is hoped that this effort will serve as an example for other universities as they move towards lowering their GHG emissions.

GHG Protocol Calculators are “the most widely-used international accounting tool for government and business leaders to quantify and manage greenhouse gas emissions” (World Business Council for Sustainable Development and World Resources Institute 2010). The GHG Protocol Calculators are a series of tools that measure individual elements of emission sources. The Clean Air Cool Planet (CACP) campus carbon calculator utilizes the GHG accounting standards set forth by the World Business Council for Sustainable Development and the World Resources Institute (CACP 2010) in the GHG Protocol Initiative. The CACP calculator is backed by the American Colleges and Universities President’s Climate Commitment (ACUPCC) and is the most widely utilized campus emissions calculator in U.S. higher education.

I recognize that the CACP calculator accounts for direct greenhouse gas emissions and some indirect emissions but does not include all the energy requirements to sustain the students, faculty, and staff on and off campus. However, the results of the emissions inventory provide a baseline for the implementation of informed emissions reduction strategies. The use of the CACP calculator also allows a comparison with other universities based on common boundaries and a common protocol tool. Comparisons with higher educational institutions in other countries are not included in this paper due to a shortage of data and the lack of an internationally recognized assessment tool.

Objectives

The overall objective was to create an accurate inventory of direct and specific

indirect annual GHG emissions on the LSU-Baton Rouge main campus for FY 2007–2008. Specific objectives included:

1. Define Organizational, Operational, and Temporal boundaries of the study.

2. Collect campus energy consumption data from campus personnel.

3. Enter data into the carbon calculator.

4. Analyze the data and summarize results to determine the major contributors to campus GHG emissions.

5. Conduct a comparative analysis of data from similar-sized higher-education institutions to compare differences and similarities between institutions.

6. Develop alternative scenarios and management implications to decrease campus emissions.

Methods

The CACP calculator is a Microsoft excel based spreadsheet that provides procedural protocols and a framework for investigation of campus GHG emissions. The calculator is based on IPCC workbooks for national inventories and the methodologies and calculators of the GHG Protocol Initiative. It has been adapted for higher education institutional use (ACUPCC 2009) and inventories produced by the calculator are compatible with current standards used to craft the proposed national cap and trade policy (U.S. House Resolution 2454 2010; CACP 2010). The CACP campus carbon calculator allows for standardized accounting of customized fuel mix information used for campus electricity generation. This is an important aspect of the calculator because campus electricity generation often accounts for greater than 50% of total campus emissions and is highly variable based on region and production source (Association for the

Advancement of Sustainability in Higher Education 2010; CACP 2010). The CACP campus carbon calculator allows for the accounting of all six-greenhouse gases specified by the Kyoto Protocol. The standards identify organizational (spatial), temporal, and operational boundaries along with the scope of emissions to prevent ‘double counting’ (CACP 2010). All calculations were performed using version 6.1 of the calculator.

The organizational boundary of the study includes the LSU Agricultural and Mechanical college main campus in Baton Rouge (approx. 1000 acres). The vast majority of campus buildings rely on the campus powerhouse and co-generation facility for electricity, natural gas, and heating ventilation and air-conditioning (HVAC) services. All campus athletic fields, stadiums, and campus dining facilities are accounted for in this study.

According to the LSU Office of Budget and Planning, the total university operating budget was $436.6 million in FY 2007. The research budget was $56.9 million of the total budget. The total campus community population of faculty, staff, and students was 33,235. The study does not account for members of the community employed by auxiliary services, such as contract laborers. Total building space on campus was 11.2 million square feet (ft^2). Net research building space was 531,811 ft^2.

Figure 10. Map of the LSU A&M main campus included in this study. The map in the upper left is the state of Louisiana with a red star denoting Baton Rouge. Red circles connected to a letter denote facilities that receive partial or no services accounted for in this GHG inventory. Details described in text. (A) Edward Gay apartments; (B) University High School; (C) LSU Systems office; (D) Fraternity and Sorority houses; (E) Child Care Center.

Several campus buildings rely only partially on on-campus provided utilities. Some buildings on the main campus are only partially accounted for in this study. These buildings (and the extent that they are included in the study) are University High School (electricity usage included), LSU Systems office (natural gas usage included), fraternity and sorority houses (33% of natural gas usage included), and the campus child care center (electricity usage included). GHG emissions resulting from utility consumption in these buildings is only accounted for the services supplied to them via the campus

powerhouse and co-generation facility (Figure 10). Emissions resulting from energy use at the Edward Gay apartment complex are not included in this study. Emissions from electricity, heating, and cooling of the apartments likely contribute a small amount to total overall campus emissions. The LSU AgCenter, which is a separate organizational unit from LSU A&M, makes use of a considerable amount of building space on the LSU A&M main campus in Baton Rouge. For the sake of convenience, energy use and resulting emissions attributed to AgCenter operations on the main campus are considered a part of the overall LSU-Baton Rouge main campus GHG inventory.

The LSU GHG inventory operational boundary includes Scope 1, 2, and 3 GHG emissions as described by the World Business Council for Sustainable Development (WBCSD) and the World Resources Institute (WRI) guidelines in the GHG Protocol. Scopes are an accounting concept developed to define levels of responsibility for emissions. This approach assumes that the University's responsibility for emissions is directly related to its control over, or ownership of, the sources of those emissions (CACP 2010). Scope 1 emissions consist of all direct emissions from sources that are owned and/or controlled by the University on the LSU-A&M main campus. Scope 1 emissions include the production of electricity and steam from the campus co-generation power plant, university vehicle fleet fuel consumption, and fugitive emissions which include intentional and unintentional emissions released from equipment leaks including refrigerants. The campus co-generation power plant generates electricity and useful heat via a natural gas combustion turbine. Steam produced at the co-gen facility is used to maintain appropriate building temperatures throughout campus 24-hours per day 365 days per year. Agricultural emissions in the form of methane (CH_4) produced by

campus livestock and nitrous oxide (N_2O) emissions resulting from fertilizer application on campus grounds are also considered Scope 1 emissions.

Scope 2 emissions are from sources that are neither owned nor operated by the University but whose products are directly linked to on-campus energy consumption. Indirect emissions sources that occur from the use of purchased electricity, heat, or steam are considered Scope 2 emissions. Scope 2 emissions are the result of imported/purchased electricity from the local utility provider and occurred where the energy was generated and not at the user site.

Scope 3 emissions include indirect emissions that occur as the result of outsourced activities. Scope 3 emissions are considered “optional” by corporate inventories because they originate from sources that are neither owned nor operated by the University but are either directly financed or otherwise linked to the campus via influence or encouragement. Scope 3 emissions included in this study are the result of solid waste disposal; directly financed air travel; faculty, staff, and student commuting; transportation and distribution losses from purchased electricity; and emissions resulting from campus wastewater treatment.

Scope 3 emissions resulting from outsourced activities on the LSU campus include total air travel miles accumulated by students, faculty, and staff as the result of official University business. The commuting activities of students, faculty, and staff, to and from campus as well as on-campus solid waste production and emissions associated with campus wastewater are included as Scope 3 emissions. Additional Scope 3 factors added to version 6.1, not reported in this study, were the amount and type of paper product consumption and fuels associated with student study abroad travel. I assume that

the inclusion of these factors would have made little difference in total emissions. Scope 3 boundaries recognized by the ACUPCC and the CACP calculator were used in this study. The study is neither an attempt at a life cycle assessment nor an embodied energy analysis of LSU (Hannon 1973; Murphy and Hall 2010). Such studies would broaden the boundaries of the present study to include emissions produced from existing infrastructure construction, materials consumption, and include the emissions associated with the environmental impacts of these activities. Off campus energy consumption by campus community members was outside of the scope of this study. Emissions that occur during the production of materials consumed on campus (*i.e.*, production and transport costs of food and materials sold on campus) were also outside of the scope of this study. Others have recognized the importance of carefully specifying boundaries in studies of this type. For example, Murphy and Hall (2010) concluded the largest problem in performing energy return on investment analyses was boundary definition.

The temporal boundary of the study was Fiscal Year (FY) 2007–2008. Emissions produced were calculated based on the most up to date datasets available. Data collection was carried out from August 2008 through May 2009. The majority of the data was collected directly from campus personnel. Documentation of energy purchases made by campus personnel was the main source of data for the study. Information not obtained through campus personnel was gleaned from previous studies concerning campus consumption patterns and behavior. Several studies were consulted to estimate past and present campus energy consumption patterns. These studies included the Walker Parking Master Plan (Walker Parking Consultants 2005) and the Solstice Consulting Report (Solstice Transportation Group 2008) to the Easy Streets II working group. Specifically,

these two reports included detailed analysis of past and present campus commuter habits including average distance of commute, numbers of commuters using the various modes of transportation, and overall demand for transportation alternatives to the personal automobile. Campus personnel and outside agencies provided the data on energy consumption used as inputs in the emissions calculator.

Upon completion of data collection and entry into the calculator, the emissions factor module automatically converted energy consumption source units to common units using prescribed emissions based on previous studies. An emissions factor is a unique value for scaling emissions to activity data in terms of a standard rate of emissions per unit of activity (CACP 2010). For example, the combustion of one gallon of gasoline in an industry standard automobile as part of the University fleet in 2008 produced 8.7 kg CO_2, 0.002 kg CH_4, and 0.0006 kg N_2O. Emissions factors in the calculator are based on previous government studies of national GHG emissions conducted by the US Environmental Protection Agency (EPA), U.S. Dept. of Transportation Statistics, and other U.S. government documents. Adding data in common units (*i.e.*, MMBTU of natural gas, gallons of gasoline, pounds of nitrogen fertilizer, *etc.*) is an important step necessary for accurate results because the emissions factors are already written into the calculator worksheet. Unit conversion analysis was performed where necessary for raw data provided by campus personnel and in previously published reports. No emission factors were altered or "customized" in the calculator for this study. However, custom fuel mix data was entered into the Scope 2 data input module so as to accurately represent the emissions resulting from purchased electricity.

Emissions are reported in terms of metric tons CO_2 equivalents (MT CO_2e). MT CO_2e units allow for the comparison of emissions of various greenhouse gases based on their global warming potential (GWP). The CO_2 equivalent of a non-CO_2 gas is calculated by multiplying the mass of the emissions of the non-CO_2 gas by its GWP. Further conversion to carbon equivalents (CE) is achieved by multiplying CO_2e by 0.27, the ratio of the mass of carbon to the mass of CO_2. Global warming potentials and the estimated atmospheric lifetime for greenhouse gases included in this report are based on the 100-year time horizon established by the IPCC Second Assessment Report (SAR) (U.S. Environmental Protection Agency 2008; Association for the Advancement of Sustainability in Higher Education 2010).

Results

Total campus GHG emissions in FY 2007 were 162,742 MT CO_2e. The majority of emissions (57%) were the result of On-Campus Stationary source (Scope 1) electricity generation at the University Co-generation facility. Purchased electricity (Scope 2) emissions accounted for 18% of the total and Scope 3 emissions accounted for the remaining 25%. Carbon dioxide was the most common greenhouse gas emitted followed by methane and nitrous oxide. Campus emissions are directly related to fuel source and overall energy usage on campus.

The co-gen plant generated 138,979,388 kWh of electricity in FY 2007 while the total purchased electricity from Entergy Gulf States was 65,406,232 kWh. The difference between generating that electricity with natural gas on campus versus purchasing it from Entergy and its variable source generation was a net emissions savings of approximately 13,897 MT CO_2e.

Scope 1 Emissions: Direct Emissions

The majority of Scope 1 and overall campus emissions result from basic infrastructure energy requirements in the form of lighting, heating, and cooling buildings. Maintaining campus-building infrastructure is largely dependent on the campus co-generation plant and Scope 1 emissions. Co-gen steam production resulted in 47,811 MT CO_2e or 29% of total emissions. Electricity production at the campus co-gen facility was the next largest contributor to Scope 1 campus GHG emissions and the 138,979,388 kWh generated accounted for 32,959 MT CO_2e (20% of total emissions) in FY 2007 (Fig. 11). The University experiences a low number of Heating Degree Days (HDD) when compared to institutions in more northern latitudes. The energy required to heat a building is generally more than that required to cool a building due to the larger differentiation in degrees from the 68 degree mean used to determine HDD and cooling degree days.

The University fleet consumed more than 284,463 gallons of fuel during FY 2007. Estimated University fleet fuel consumption is based on purchased fuel from Fuelman, Inc. pumps located at University Stores on Skip Bertman Dr. and the 2008 LSU Vehicle Utilization and Maintenance Report. Because the University bus transportation service was outsourced to the Capitol Area Transit System (CATS), bus commuter fuel statistics are counted as part of Scope 3 emissions and not included as part of the University fleet. Another aspect of the University fleet is the amount of diesel consumed for landscape services (mowers and tractors). Diesel purchases for this sector of campus services are estimated at 400 gallons per week during peak season (March–September)

and 200

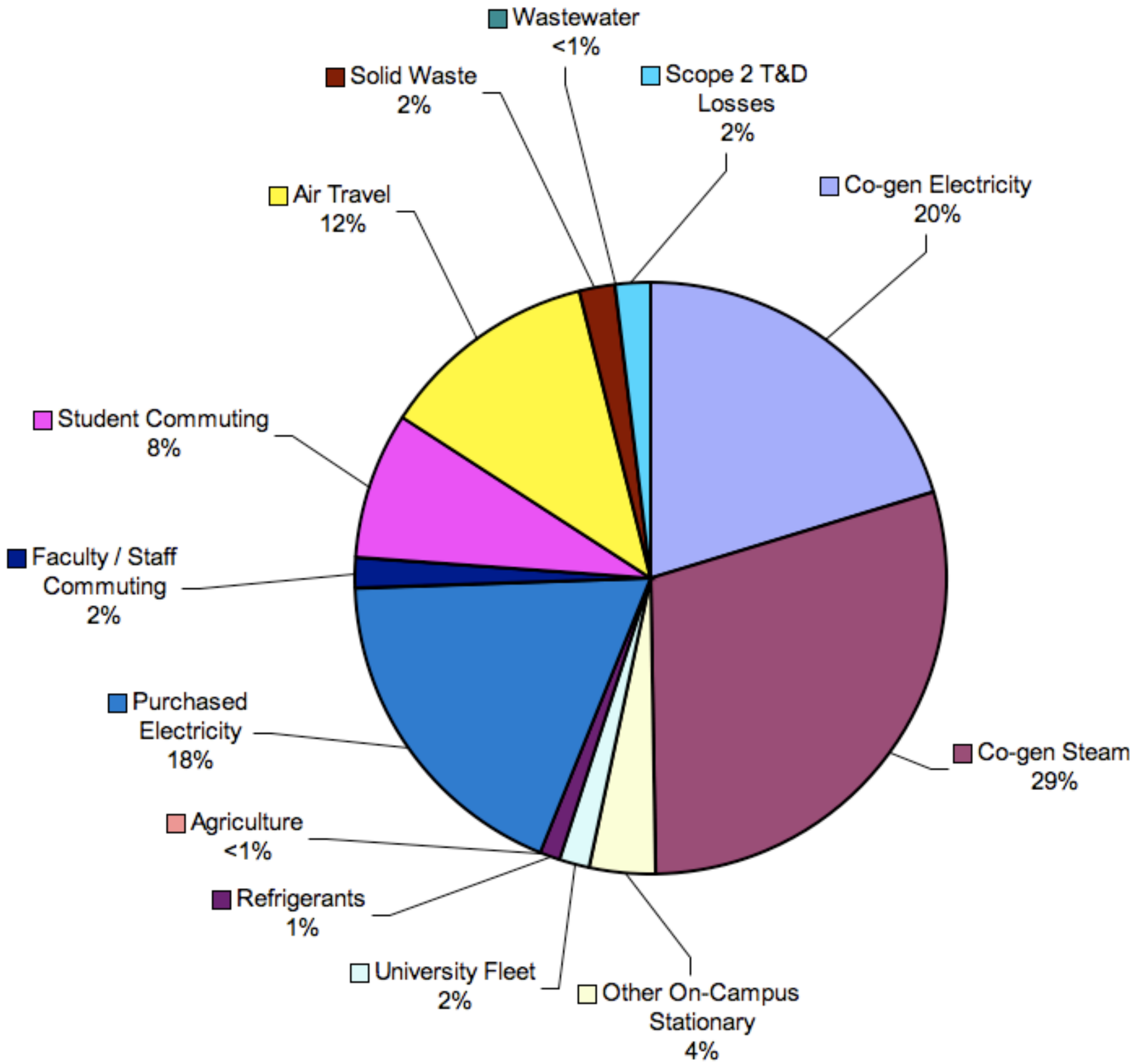

Figure 11. Percentage breakdown of LSU A&M GHG emissions by sector for FY 2007–2008.

gallons per week during off-peak months (October–February). It is estimated that landscape services uses 15,200 gallons of diesel fuel annually. The 284,463 gallons of gasoline and the 22,338 gallons of diesel consumed by the University fleet, resulted in 2,764 MT CO_2e or 1.6% of total emissions for FY '07–08'.

Fertilizers and livestock are the two sources of agricultural GHG emissions on campus. Personnel from several departments including University Recreation (UREC), Athletics, Landscape Services, and the campus golf course apply fertilizer. It is estimated that approximately 20 tons of synthetic fertilizer (33% N) is applied to campus grounds annually. A percentage of this fertilizer is released into the atmosphere as the greenhouse gas, nitrous oxide (N_2O), after application.

Campus GHG emissions resulting from livestock contained on the premises of the LSU Veterinary School are another agricultural source of emissions included as part of Scope 1 emissions. Livestock were present in variable quantities throughout the year but were estimated to include 122 horses, 24 goats, and 15 dairy cows, based on personal communication with Veterinary School personnel. The combined total of GHG emissions resulting from campus agricultural sources is 186 MT CO_2e.

The relative contribution of refrigerants to total campus greenhouse gas emissions was minor. In FY 2007, 2,300 pounds of R22 was released. This leak resulted in 1,774 MT CO_2e being released into the atmosphere.

Scope 2 Emissions: Off Campus Stationary Source Emissions

Purchased electricity was the only Scope 2 emission factor accounted for in this study. The University purchases electricity from Entergy Gulf States Louisiana LLC. Purchased electricity is produced using a variety of methods (coal, natural gas, nuclear, distillate oil, *etc.*) in varying proportions from year to year. In FY 2007, the University purchased 65,406,232 kWh of electricity. 62% of this electricity was purchased by Entergy through a third party, 19% was generated via natural gas, 11% was generated via

coal fired power plants, 8% was generated via nuclear energy, and <1% was generated via distillate oil. The emissions that resulted from the production of this electricity was 30,002 MT CO_2e or 18% of the annual total.

Scope 3 Emissions: Indirect Emissions

Emissions resulting from air travel by faculty, staff, and students on official University business were based on information obtained from Carson Wagonlit Travel, the state travel agency. The information provided includes departmental air travel miles from December 2007 through November 2008 for LSU (20,659,291), LSU Athletics (4,204,646), and the LSU Law Center (118,937). Air travel by campus personnel resulted in 19,395 MT CO_2e emissions in FY 2007.

Private automobiles are the primary mode of transportation on the LSU campus. Emissions resulting from commuter travel to and from the University are based on several previous studies conducted by private contractors and University personnel. The 2005 transportation and parking study estimated commuter students as the difference between the total number of enrolled students and resident students (Solstice Transportation Group 2008). The study estimated the student commuter population at 24,718 students in FY 2005–2006. A survey of students, faculty, and staff concerning campus transportation was conducted with a total of 8,738 respondents. 72% of the campus community responded that they commute alone via private automobile. 12.1% responded that they carpool with one or more people and 0.8% said they commute on a motorcycle. 7.1% ride the bus, 5.9% of respondents were pedestrian commuters, and 2.1% commuted on a bicycle. Approximately 80% of the University community lives within 4 miles of campus.

Annual GHG emission estimates for commuters are based on national statistics for average vehicle fuel mileage and percent total cars and light trucks (pickups, vans, and sport utility vehicles) in the fleet. Average commuting distance for students, faculty, and staff is estimated to be 4 miles (Walker Parking Consultants 2010). The majority of campus commuters make one round trip to and from campus each day for a total of 8 miles per trip.

It is estimated that student commuters drove or rode in private automobiles for a combined total of 30,671,424 miles and consumed 1,387,847 gallons of gasoline based on the industry standard average automobile fleet fuel efficiency of 22.4 miles per gallon. Student bus commuters rode approximately 2,385,555 miles consuming approximately 60,134 gallons of diesel. The operating expense for campus buses was $1.29 per passenger trip for 2005–2006 (Yasukochi 2007). During that same year, average fuel prices at the pump in Louisiana were $2.07 per gallon for gasoline and $2.15 for diesel. Assuming commuters were traveling a distance of four miles each way, they consumed a gallon of gas every 5.6 trips in a private automobile. Student commuters accounted for 12,991 MT CO_2e while faculty/staff commuters accounted for 2,582 MT CO_2e in FY 2007. The CACP calculator does not readily allow for the specification of commuter students versus resident students who presumably do not drive to and from campus daily. Therefore, an overestimation in commuter emissions may be assumed to be inherent in the reported results.

In FY 2007, LSU produced 11,432 tons of solid waste. Campus waste is transported and deposited in a landfill in Walker, LA. The landfill flares the methane produced during waste decomposition. Solid waste disposal emissions were 2,934 MT

CO_2e. The University produced approximately 612,000,000 gallons of wastewater in FY 2007. Campus wastewater is pumped to the East Baton Rouge Parish central wastewater treatment facility that uses aerobic methods for treatment. Wastewater treatment during FY 2007 resulted in approximately 295 MT CO_2e in emissions.

Discussion

Previous research has shown purchased electricity and co-gen production facilities are the major emission sources from University campuses (Association for the Advancement of Sustainability in Higher Education 2010). A large percentage (57%) of LSU A&M campus emissions are directly controlled by the University as Scope 1 emissions. The University may influence the future of campus emissions through policy measures that reduce campus energy consumption. Efforts towards reducing energy consumption often require increased management aided by technology. One such effort is the Metasys and Building Automation System that currently aid energy conservation efforts on campus. This computer-based system allows for personnel to alter heating, air conditioning, and lighting in buildings campus-wide with the touch of a button from any computer equipped with the proper system software. The system is enhanced further when campus personnel are aware of present outside temperature conditions and future forecasts. Being prepared (*i.e.*, switching on/off HVAC units) before forecasted drops or rises in outside temperatures is an energy conservation measure currently being utilized by campus personnel. Public education through dorm energy competitions like the one carried out in the spring of 2009 raise the level of awareness on campus regarding the increased need for energy conservation.

One major factor of interest is how campus emissions are affected as a result of

campus co-gen produced electricity. Electricity produced with natural gas at the cogeneration facility results in less GHG emissions than electricity purchased from the local utility with variable source production including natural gas, coal, nuclear, and distillate oil.

Since natural gas is a cleaner source fuel when it comes to GHG emissions, the University has effectively reduced emissions by shifting away from "dirtier" source fuels such as coal and distillate oil. Entergy Gulf States Louisiana decreased the percentage of natural gas used as a source fuel to produce electricity between 2001 (45.4%) and 2007 (19.4%). The 25% decrease in natural gas usage has probably come due to a rise in the wellhead price of natural gas during this same time period. There have been periods in which the campus co-gen facility was shut down and electricity was purchased directly from Entergy Gulf States due to the prohibitively expensive price of natural gas (July 12, 2008–August 26, 2008). However, recent additional natural gas discoveries (Dizard 2010) may lead to cheaper gas prices, at least in the short run.

Utilities are the single largest contributor to the GHG emissions of the university, as is the case for most universities (American College and University Presidents Climate Commitment 2009). The costs of utilities are important since energy costs are directly related to the institution's most basic operating costs. These operating costs are the required energy and financial costs of keeping the lights on and buildings heated and cooled. It is assumed that the most effective lowest cost fuel is the preferred source fuel. Recent price volatility in energy markets and policies that impose carbon taxes on fossil fuels may increase the attractiveness of alternative energy sources. Many of the externalities associated with fossil fuels may be internalized in the cost of future fossil

fuel production. Also, a single energy source fuel makes the institution more vulnerable to an individual fuel price increase as opposed to an institution that has a diverse energy portfolio. As the cost of fossil fuel energy increases, these costs will be born by the consumer, University students in this case. Education will become more expensive. In the long run, the costs of converting to renewable energy sources are likely to become more attractive as fossil fuel prices rise due to scarcity and the environmental costs associated with their production and consumption. Increases in the price of fossil fuels may also lead to increased energy conservation efforts.

Presumably, some institutions have no choice but to rely on the cheapest most convenient energy source available due to budgetary constraints. Institutions that rely heavily on fossil fuels and “dirty” energy sources may willingly accept a change to cleaner source fuels if subsidies are taken away from fossil fuels and directed towards renewable energy. Wealthy, pro-active institutions will likely lead the way in this transition. Increasing fossil energy scarcity is likely to lead to higher costs and greater interest in alternatives. Increased diversity of the campus energy portfolio will likely become a more sustainable way to decrease emissions.

The next largest contributor to campus emissions is often student, faculty, and staff commuter populations. LSU benefits from a commuter population that lives closer to campus (average of approximately 4 miles) than many similar sized universities like the University of Maryland where commuters travel an average of 16 miles each way to campus (Yasukochi 2007). However, parking permits on the LSU campus are extremely cheap when compared to other universities. The lowest annual parking permit price at LSU was $61 in 2007 (Yasukochi 2007). This falls short as a revenue stream when

compared to the \$384 charged at the University of Minnesota or the \$170 charged at North Carolina State University during the same year (Yasukochi 2007). Revenues gained from parking and transportation are an obvious tool that can be used to influence commuter behavior and raise revenues in the form of green fees to help facilitate campus sustainability projects. Commuter options should be expanded and planned with this in mind. Developing safe, accessible bicycle transportation corridors and more convenient public transportation would help relieve campus traffic congestion while also decreasing commuter emissions.

Recent national policy discussions regarding increasing fuel efficiency standards for automobiles may also decrease commuter emissions. Hypothetically, if all private automobile commuters drove the 2009 Toyota Prius the resulting emissions would be 9,781 $MTCO_2e$. If all students who drove personal automobiles instead rode the bus, student commuter emissions would decline to 8,703 $MTCO_2e$. On the other end of the fuel efficiency spectrum, if these commuters had been driving the 2009 Hummer H3, the result would be 27,877 $MTCO_2e$ in total emissions.

Air travel miles are another large contributor to campus emissions and may be the leading contributor of GHG emissions on many campuses after purchased electricity and co-generated power (Association for the Advancement of Sustainability in Higher Education 2010). Decreasing air travel can be accomplished by increasing the use of conference calls and telecommunications technology such as video-conferencing.

The potential for renewable energy production on LSU's main campus is large and the payback period may be made shorter as a result of scale and recent legislation offering tax breaks to investors in the technology. In particular, solar is a viable way to generate

renewable energy on campus (National Renewable Energy Laboratory 2010). The potential for wind energy to provide electricity in Louisiana is only feasible offshore (French 1981; National Renewable Energy Laboratory 2010) but an interconnected grid may make this a viable alternative.

Electricity generated from solar panels would be required to produce upwards of 15,000,000 kWh per month or 500,000 kWh per day at current peak consumption levels. On average, the system should provide 5,450,519 kW/month or 181,684 kW/day. Purchasing renewable energy from Entergy via their Geaux Green program is also an option although often times the money contributed to such a fund does little in the way of spurring renewable energy production (Press 2009).

A photovoltaic array suitable to generate average campus electricity consumption of 5,450,519 per month would require a 36,336 kW solar electric array. The cost of such a massive electricity production plant at $12,000 per kW would be $436,032,000, which is slightly less than the entire FY 2007 University operating budget. Clearly, this price should be seen as an overestimate since an economy of scale suggests a considerable decrease in price per kW when purchasing large amounts of solar photovoltaic panels. However, based on the 20,000,000 kWh energy budget of FY 2007–2008, the payback period at the $12,000/kW price range would be 22 years. A solar option is to install a smaller system designed to meet peak needs reducing the capacity necessary from the University co-gen facility.

Another alternative to decrease campus energy consumption and emissions is to transition from a five day to a four-day workweek. Daily campus energy consumption for the year 2008 suggests that electricity consumption decreases by about 63,000 kWh per

day on weekends as compared to weekdays. This sums to a 52-day annual electricity savings of 3,276,000 kWh. Associated emissions reductions from co-gen electrical production would be 455 MT CO_2e or 1503 MT CO_2e for purchased electricity. This savings does not include indirect emissions that would also be avoided by the campus commuter population.

A comparative analysis between LSU and several other universities was conducted in order to gauge emissions as they relate to other institutions. The analysis used published accounts of institutional data obtained from the ACUPCC website (American College and University Presidents Climate Commitment 2009). It is important to keep in mind that no one standard method for reporting GHG emissions has been set forth (Mascarelli 2009). Institutions are of variable size, use different sources for energy production, are in different climates, and contain different operational boundaries. However, all institutions cited below have posted GHG inventory reports containing Scope 1, 2, and 3 emissions (Table 6).

Results show that LSU is on the lower end of the emissions spectrum when compared to similar sized regional universities. The relatively low GHG emissions of the University are due in part to the mild climate of southern Louisiana. Also, Universities including LSU experience a decrease in building occupancy during the summer months and are able to save on energy expenditures compared to buildings occupied during the traditional academic year (Fall and Spring semesters). Strategic planning can replace capital-intensive projects as a means to cut down campus emissions. Consolidating classes and offices to increase building occupancy in the more modern energy efficient buildings on campus is one way to avoid excess energy costs especially during summer

semesters. Shutting down the campus on Fridays and moving to a four day workweek would also significantly decrease energy demand.

Table 6. Comparison of select higher education institutions and their GHG emissions as reported for FY 2007−2008 unless other year specified (American College and University Presidents Climate Commitment 2009).

University	**Total Student Enrollment**	**Gross Emissions ($MT\ CO_2e$)**	**Emissions per 1000 ft2 ($MT\ CO_2e$)**	**Emissions per Student ($MT\ CO_2e$)**
U. Illinois Urbana-Champaign	42,102	522,757	26	12.4
U. North Carolina	25,895	518,469	29.6	20
U. Florida	47,178	432,136	24.8	9.2
U. Maryland-College Park (FY2006–2007)	32,467	351,144	27.7	10.8
U. Tennessee	26,803	268,449	20	10
U. Arizona (FY2008–2009)	38,057	226,839	21.1	6
U. Colorado-Boulder	29,988	170,240	17.6	5.7
Louisiana State U.	28,019	162,742	14.5	6.1
U. Arkansas	14,939	158,468	29.8	10.6
Clemson U.	17,585	139,080	20.8	7.9
U. Vermont	11,497	67,705	13.7	5.9

Greenhouse gas reductions on campus may be strategically planned or be required as a result of budget shortfalls. The cost of sustaining and maintaining present infrastructure is likely to rise in the future. LSU currently has over $235 million in deferred maintenance costs with an additional $20 million added to this total annually (Monroe 2010). Campus planning and management for sustainability may only be as good as our understanding of energy requirements and energy affordability in the future.

The comprehensive GHG inventory of the University, including all indirect emissions, is greater than the emissions presented in this study. Emissions resulting from campus land use change and emissions incurred by third party contractors hired by the University to carry out projects are not included.. Materials consumption on campus such as paper, food, and bookstore merchandise are not included in this study. Materials consumption accounting would undoubtedly increase overall campus GHG emissions. Paper products may have a smaller impact on emissions than computers because the majority of paper used on the LSU campus is produced at a nearby Georgia-Pacific paper mill that predominantly mills Louisiana harvested timber. Campus computers and the associated emissions from mining and production of their components would likely increase emissions significantly. Food consumed on campus would likely have a considerable emissions price tag since food services are outsourced to a national food service provider. Also campus bookstore apparel and the associated manufacturing emissions would increase emissions.

A life-cycle assessment and/or embodied energy analysis would allow for a greater understanding of more of the indirect emissions not accounted for in Scope 3 of this emissions inventory. A life cycle assessment would also expand our understanding of the environmental impacts associated with energy and materials consumption. The GHG protocol is currently developing a standard, similar to a life cycle assessment, in order to more clearly define Scope 3 emissions. Meanwhile, direct campus energy usage and emissions will need to be curtailed on the path towards sustainability.

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CHAPTER 4

ESTIMATING CARBON STOCKS IN FOUR UNEVEN-AGED BOTTOMLAND HARDWOOD FOREST STANDS IN SOUTH LOUISIANA

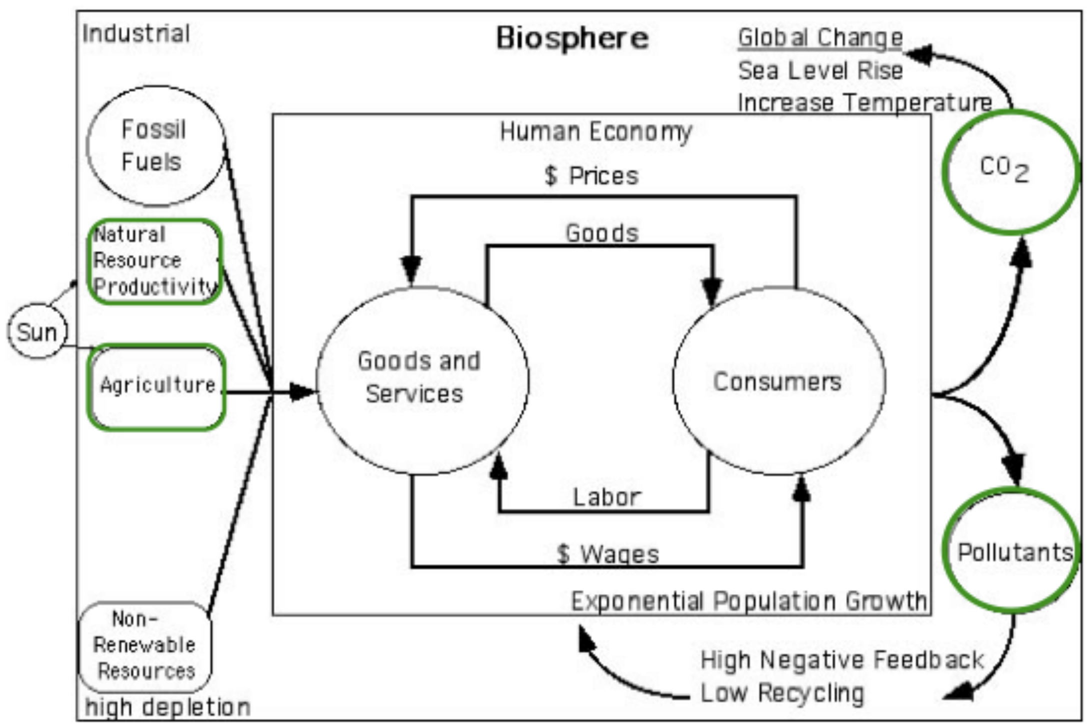

Figure 12. Conceptual diagram of the economic system and the biosphere for the full world scenario. The green highlighting designates aspects (renewable natural resources and waste products) of the economy that are discussed in Chapter 4.

Introduction

Bottomland hardwood (BLH) wetlands are riparian wetland forests present in river floodplains and other seasonally wet areas throughout the southeastern U.S. (Mitsch and Gosselink 1993). The location of BLH forests along river floodplains results in seasonal flooding by surface water and sediment deposition events that contribute to the formation of highly productive soils. The largest expanse of BLH forests in the southeast exists in the Mississippi River floodplain. Historically, the Mississippi River valley contained 21 million hectares of BLH forests although only 4.9 million hectares were estimated to remain in 1991 (Mitsch and Gosselink 1993). The loss of BLH forests results in the loss of ecosystem service function values including carbon storage, water quality, wildlife habitat, and flood control (Jenkins et al. 2010).

In the past, seasonal overbank flooding of the Mississippi River deposited large amounts of sediments into wetlands of the Lower Mississippi Alluvial Valley (LMAV). Not only did these floods provide an allochthonous source of mineral sediments, which contributed directly to vertical accretion, but also the nutrients associated with these sediments promoted vertical accretion through increased autochthonous organic matter production and deposition, and the formation of soil through increased root growth. This sediment and nutrient source has been eliminated since the 1930's with the completion of levees along the entire course of the lower Mississippi (Day et al. 2007). Presently, the most prevalent form of BLH forest restoration is through afforestation of former agricultural lands as a result of federal and state conservation programs (Gardiner and

Oliver 2005) as well as for carbon sequestration (Shoch et al. 2009). Afforestation is the establishment of a forest on previously unforested land.

Historic stream meandering across the broad LMAV floodplain has resulted in the characteristic formation of the floodplain's ridge, swale, and flat topography (Taylor et al. 1990; Saucier 1994; Hodges 1997;Mitsch and Gosselink 2000). Bottomland hardwood species distribution at these sites is largely the result of microtopographic variation within the forest (Fig. 13). Minor topographic variation has a large effect on site hydrology. Hydrology is the major autogenic force determining species presence and natural patterns of ecological succession (Hodges and Switzer 1979; Hodges 1994; Gardiner and Oliver 2005). Small changes in elevation and flooding frequency parallel shifts in community composition in mature bottomland hardwood forests (Wharton et al. 1982, Huenneke and Sharitz 1986, Titus 1990, Sharitz and Mitsch 1993, Jones et al. 1994, Allen and Sharitz 1999, Battaglia et al. 1999). Frequency and duration of flooding and forest productivity within microtopographic zones also affects the biogeochemical function of these wetlands (Mitsch and Gosselink 1993). In addition, retention, restoration, or enhancement of microtopographic variation in the LMAV may play an important role in the success of restoration and afforestation efforts in the region (Battaglia 2002).

The southern region of the U.S. contains the greatest amount of forestland area in the country (Heath et al. 2011). Publicly owned forests in the southern region contain a mean carbon density (162 Mg C/ha) equal to the overall average carbon density of all U.S. forests (Heath et al. 2011). Forest lands contain several carbon pools including:

above- and belowground live tree biomass, understory vegetation, standing dead trees, down dead wood, litter, and soil organic carbon (Smith et al. 2006).

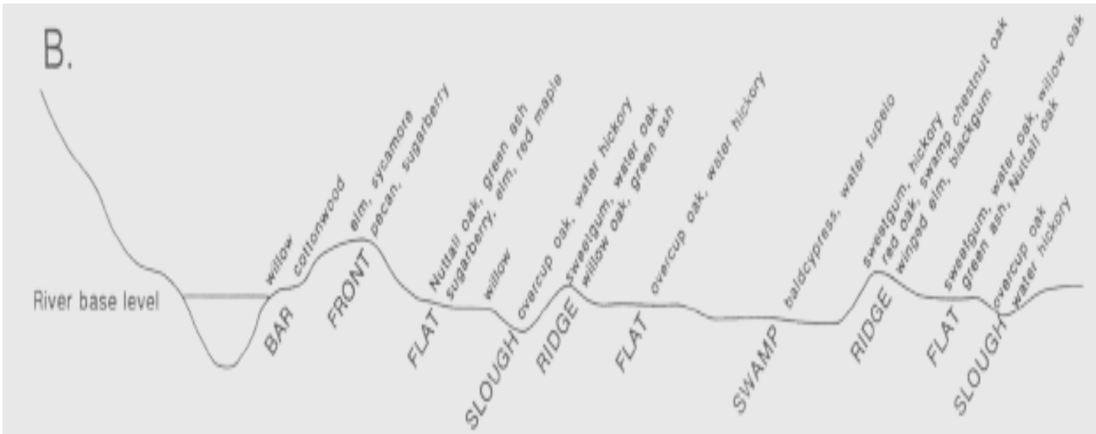

Figure 13. Bottomland hardwood forest species associated with topographic variations within a major stream valley (Hodges 1997).

Forest ecosystems contain different percentages of carbon in each of these pools. The greatest percentage (47%) of aboveground live biomass carbon is found in the southern region. As a result, southern forests have high average annual net carbon sequestration potential (Zheng et al. 2011).

The United States agreed to provide an annual inventory of carbon stocks and carbon change when government officials signed the United Nations Signatory Framework Convention on Climate Change (UNFCCC 1994). Since then, the methods and protocols for developing accurate estimates of national forest carbon stocks have evolved through the work of scientists, evolving policy interests, and new technology (Heath et al. 2011).

Birdsey (1996) developed tables for projecting forest carbon stocks and carbon in harvested wood to provide basic information on average carbon change per year for regional forests in the U.S. These tables were subsequently updated by Smith et al.

(2006). The tables allow users to look up average regional carbon values for forest types of a given region and project future carbon stocks in 5-year increments. Carbon stocks in the tables are dependent on two variables: age and growing stock volume. However, the tables are large-scale averages and may be inadequate for estimating the carbon stocks of uneven aged multi-cohort forest stands that exist across different microtopographic environments in the LMAV.

The results of annual forest carbon storage estimates are published by the U.S. Environmental Protection Agency as part of the U.S. Greenhouse Gas Inventory (USEPA 2011). Over time, estimates are becoming more spatially and temporally explicit so as to include the various compositional differences of ecosystems that affect the carbon storage capacity of specific forest types.

Although bottomland hardwood forests have been shown to be highly productive forest ecosystems with a high capacity to sequester carbon (Brinson 1990), there remains a scarcity of published growth and yield studies (Shoch et al. 2009). Much of the published work with regard to the sequestration capacity of these forests has focused on afforested stands and plantation forests. However, remnant cutover forests and naturally regenerating forests make up the majority of bottomland hardwood forests in the LMAV. Few studies have focused on bottomland hardwood carbon storage along the Mississippi floodplain in south Louisiana. Several studies document carbon storage of even aged stands, forest plantations, and naturally regenerated stands of known age (Smith et al. 2006, Heath et al. 2011) throughout the U.S. and Shoch et al. (2009) examined carbon storage rates in BLH forests of more northern reaches of the LMAV. They concluded that the U.S. Department of Energy look-up table for the south-central U.S. region

underestimates carbon storage in live tree biomass of bottomland hardwood stands in the lower Mississippi Valley aged 20-90 years. There remains a need for a better understanding of the variability in carbon storage rates of bottomland hardwood forests in the southeast. The majority of remaining bottomland hardwood stands in the region have been selectively harvested and are uneven aged stands. These stands are not amenable to simple modeling by age due to their structural diversity (Smith et al. 2006; Shoch et al. 2009).

The carbon storage capacity of bottomland hardwood forests is assessed by the forest service during the Forest Inventory Analysis every 5 years (USFS 2011). No studies, to our knowledge, have been conducted which examine the carbon storage capacity of these systems in relation to microtopography. Topographic variation across major river floodplains includes several different zones that contain associated species adapted to particular elevation, soils, and hydrologic conditions (Hodges 1997). At the same time, forest productivity is more variable on sites with hydroperiods that change annually as compared to stands located on ridge topography that are inundated less frequently (Megonigal 1997). Therefore, grouping these forests together as a single type ignores the differing contribution to storage capacity that results from stands in the different microtopographic zones of the floodplain.

Large differences in site quality and species suitability occur in BLH forests of the LMAV due to small changes in topography (Stanturf et al. 2001). Fine scale studies of forest carbon stocks and the microtopographic differences that result in the diverse forest types and carbon storage rates of the LMAV have not been intensively studied.

This study examines the carbon storage capacity of four LMAV floodplain forests with emphasis on microtopographic variability.

BLH forests in Louisiana can have high productivity rates (Messina and Conner 1998). Productivity rates are impacted by factors including hydrology and microtopography. Some research suggests increased productivity in transitional BLH forests that exist between cypress-tupelo swamps and upland forests (Conner and Day 1976; Taylor et al. 1990) while other studies have shown benefits from flooding events being diminished by the physiological stresses of anaerobic soils and drought (Mitsch and Rust 1984; Megonigal 1997). In addition to hydroperiod, the nutrient concentrations associated with water inputs to the system can impact forest growth (Hunter 2000).

Nutrient retention and transformation are two important functions floodplain forests provide to society (Walbridge 1993; Messina and Conner 1998). The biogeochemical function of BLH wetlands is based on the quantity, quality, and timing of water introduced to the system (Faulkner and Patrick 1992; Corstanje and Reddy 2004). Forest productivity influences soil microbial populations that affect rates of decomposition along with nutrient uptake. Local hydrology combined with the quality and quantity of organic material in a wetland system impacts the nitrate removal capacity of the wetland (Hill 1996, Martin 1999, Schnabel 1996).

Many wetlands in the deltaic region have been hydrologically isolated from surrounding marshes, swamps and bayous due to the construction of canals and spoil banks during the past century (Turner and Cordes 1987). In addition to impeding drainage and, in many cases, physically impounding wetlands, these spoil banks also

prevent the overland flow of sediments and nutrients into coastal wetlands, creating essentially ombrotrophic systems from what were naturally eutrophic or mesotrophic. A number of man-made spoil banks and canals exist at the St. Gabriel site. It is assumed that their presence is affecting the present hydrology and overall ecosystem function of the forest.

In addition to hydrologic variability, tree species, age, size, and soil type are determinants of whether or not species will survive altered hydrology resulting from land use change (Hook and Scholtens 1978; Conner and Brody 1989). Smaller trees (<13cm) are more affected by increased water levels than are larger (>38cm) more mature trees. Excessive water levels may increase tree mortality. This highlights the fact that a mature forest is much more likely to withstand flooding pressures than is a younger forest (Harms et al. 1980). Also, bottomland hardwoods are replaced by cypress tupelo species as elevation decreases and flooding increases (Pearlstine 1985). The variable hydrology due to elevation differences at the site is hypothesized as the main cause for present species composition. This study did not take into account tree mortality at the sites.

Objectives and Hypotheses

The purpose of this study is to sample across a range of microtopographically different uneven aged bottomland hardwood stands in the LMAV in south Louisiana. I then compare the amount of carbon stored in live aboveground woody biomass at the stands using two sets of allometric equations. Baseline water quality conditions were measured to assess nutrient loading rates at the sites. Leaf litterfall measurements were made in order to compare litterfall productivity among sites and to previous studies conducted in forested wetlands.

I hypothesized that forest stands across varying microtopographical environments store carbon at different rates based on stand age, local climate, and site hydrology. Understanding if these differences exist and how they impact forest growth, can help forest managers to more accurately account for the carbon storage variability of these forests.

Site Description

This research was carried out at two bottomland hardwood sites owned by the LSU AgCenter. One site is approximately 300 acres of bottomland hardwood forests at the Ben Hur Agricultural and Forest research station (Figure 14) located in East Baton Rouge Parish. The forest is located approximately 3 km south of the LSU main campus and is bordered by agricultural fields and private residential home developments. Tree species present at the site are heavily influenced by local hydrology. Two general forest habitat types, ridge and swale, exist at the site. The ridge habitat (BHR) is dominated by oaks, hickories, and sugarberry while the swale habitat (BHS) is dominated by cypress and tupelo. The sites are composed of mixed species stands in the understory reinitiation stage of stand development (Oliver and Larson 1996). Ridges and swales at the site are well defined and occur successively approximately every 25-30 meters to give the appearance that the swales are functional drainages while the ridges serve as natural levees rarely breached by floodwaters. Water enters the site in the form of precipitation and from the overflow of a drainage ditch that runs along the western edge of the forest adjacent to a suburban housing development. Both the ridge and swale sites are composed of multi-cohort uneven-aged forest stands. The dominant soil series at the Ben Hur sites are gently undulating Schriever-Thibaut clays. The swale site is composed of

poorly drained Schriever clay typical of meander scar landforms. Parent material is clayey alluvium down to 152cm and the reported depth to water table is 0-61 cm (NRCS 2011). The ridge site is composed of Thibaut clays that are the dominant soil type of natural levee ridges formed from clayey over loamy alluvium parent material. Reported depth to water table is 46cm -91cm.

Figure 14. Map of the proposed study sites at the Ben Hur experimental research forest.

The second site is located at the St. Gabriel forest (Figure 15) approximately 18 km southeast of LSU main campus on the land located east of the LSU AgCenter Reproductive Biology Center. The approximately 700 acre forest is composed of mixed bottomland hardwood species as well, but has not been managed as an experimental research forest in recent years. The area was heavily logged in the middle part of last century and the study sites are composed of naturally regenerating multi-cohort stands in the stem exclusion stage of stand development (Oliver and Larson 1996). A well-defined ridge lined with live oak trees runs along the eastern side of the forest and acts as the

main site access route. The site hydrology differs from the forest at Ben Hur due to the increased number of spoil banks present at the site. The spoil banks were erected as part of a film production in the late 1960s. Spoil banks act to impede and enhance water flow between different sections of the forest. As is the case at the Ben Hur site, species composition of the forest results from the frequency and duration of inundation. Impounded areas that are drier for longer periods, the St. Gabriel flat (SGF), are composed of mixed bottomland hardwoods oaks, American elms, and sugarberries while the wetter areas, the St. Gabriel swale (SGS), are dominated by cypress and tupelo. The impounded areas at the St. Gabriel site are much broader than the well-defined ridge and swale habitats at the Ben Hur site. The St. Gabriel sites are both classified as backswamp landforms composed of Schriever clay. The swale site is reported to flood more frequently than the flat site (NRCS 2011). Water inputs to the site occur in the form of precipitation and through runoff from the agricultural fields located southwest of the study site. The main canal that drains the forest watershed flows from the northeast corner of the site towards the Spanish Lake Basin.

Materials and Methods

Initial site assessments were carried out to determine representative forest sample sites. Two pairs of 100m x 20m sites were established at the bottomland hardwood forests on LSU AgCenter property. Sites were marked at all four corners with PVC pipes and flagging. Soils were characterized using the Natural Resources Conservation Service web soil survey (NRCS 2011).

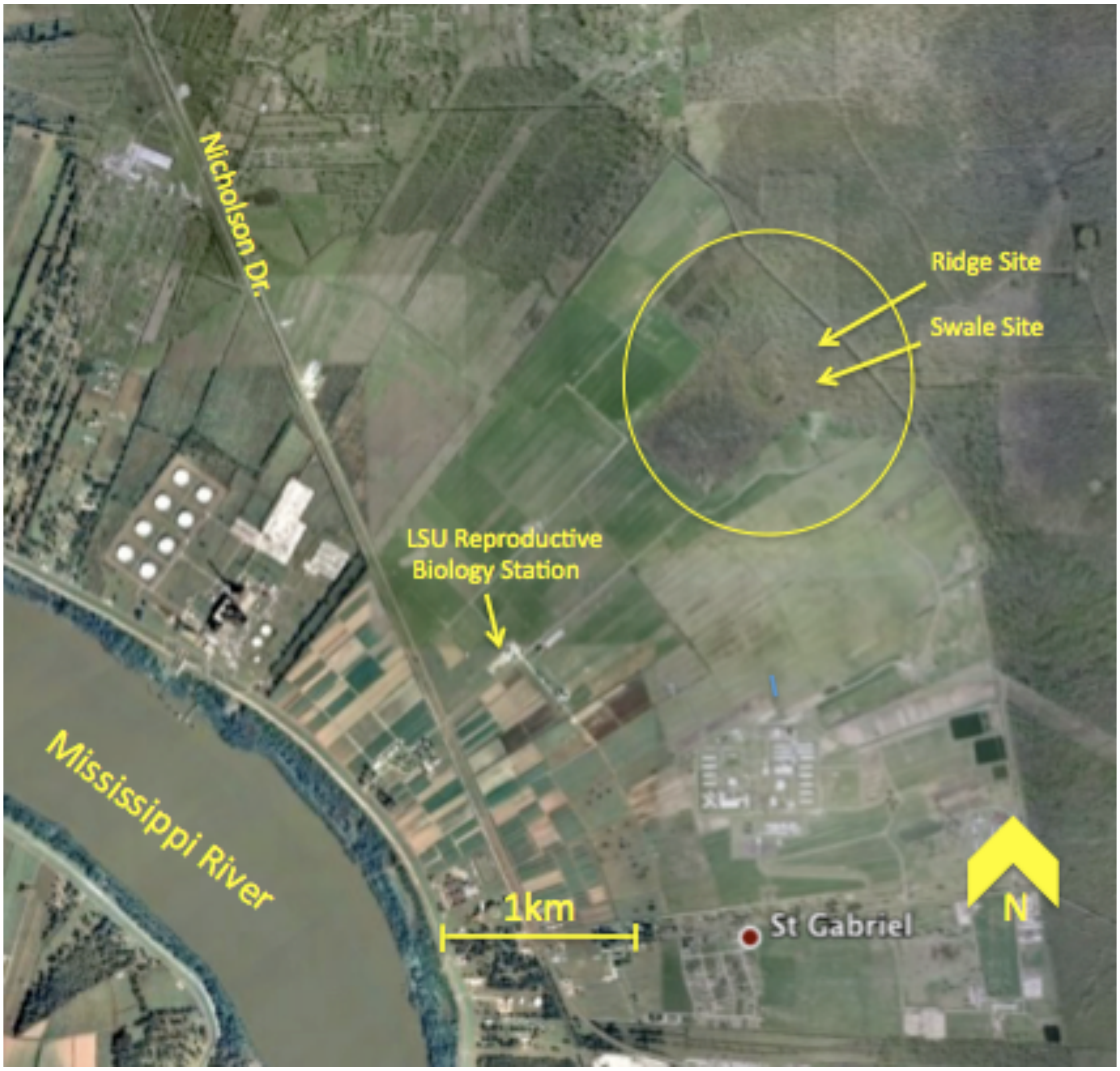

Figure 15. Map of the proposed study sites at the St. Gabriel forest.

Four water wells (2.5 meter deep) were set up at each site to monitor ground water levels. One well was installed in each of the study sites. The wells consist of a 3m x 7cm PVC pipe with holes located along the lower two thirds of the pipe. The pipe was wrapped in several layers of nylon and inserted into a 2.5-meter deep hole. Odyssey capacitance water level recorders were inserted into the pipe and programmed to record water levels every 30 minutes for the period of one year from November 2009-November

2010. Water level data were downloaded from the recorders on a bi-monthly basis. The well tubes were capped to prevent rainwater from filling the tube.

Water quality was measured from inflow and outflow drainage ditches at the sites. Three samples were taken during each sampling trip along the hydrologic flow gradient at the Ben Hur swale, St. Gabriel swale, and St. Gabriel flat site. Samples were not taken at the Ben Hur ridge site because the site remained dry throughout the study period. Water quality sampling trips occurred in December 2009, February 2010, and June 2010. Sampling locations are presented in Fig. 16. Discrete water samples were carefully taken 5 to 10 cm below the water surface so that bottom sediments were not disturbed and that no surface film was sampled. The samples were immediately stored at 4˚C, on ice, for preservation. The samples were transported to the laboratory, and within 24 hours filtered and sub sampled. Samples analyzed for nitrate+nitrite were filtered in the laboratory using 0.45um Whatman GF/F glass fiber filters, and unfiltered samples were subsampled into 125ml bottles. Both filtered and unfiltered samples were frozen prior to analysis. The samples were analyzed by the School of the Coast & Environment Analytical Services Laboratory at Louisiana State University for nitrate+nitrite (NO_3^- $+NO_2^-$-N), total Kjeldahl nitrogen (TKN), and total phosphorus (TP) using EPA methods 353.2, 351.2, and 365.1. Total nitrogen (TN) was calculated by adding NO_2+NO_3-N and TKN values.

Figure 16. Water quality sampling sites at the Ben Hur and St. Gabriel study sites. Blue arrows represent the general flow of water into and out of the study sites. Red and blue dots represent the discrete site where each sample was taken during December 2009, February 2010, and June 2010.Tree species composition was visually surveyed and recorded at each study site. Stand characteristics to determine relative density and relative dominance were measured using methods from Barbour et al. (1987).

Relative density is the density of one species as a percent of total stand density. Stand density was determined as the number of individuals of a species in a stand, divided by the total number of all individuals in the stand. Relative dominance is the basal area of each species as a percent total of the basal area of the stand. Relative dominance was calculated as the total basal area of a species divided by the total basal area of all species.

Trees greater than 3cm in diameter were tagged and measured to determine the diameter at breast height (DBH) for each individual tree in the 100m x 20m sample plots. Tree cores were taken from a random subsample of trees at each site to determine the relative age of the stand. The number of tree cores taken at each site are listed in Table 7. Stem production was estimated for 2009 and 2010 from annual changes in woody biomass calculated based on field measurements of stem diameter at breast height (dbh,

≅1.3 m). Diameter was measured above the butt swell on large cypress and tupelo trees. Measurements of diameter at breast height (DBH) can be converted to estimates of forest carbon stocks using allometric relationships (Gibbs et al. 2007). Allometric equations statistically relate measured forest attributes to destructive harvest measurements, and exist for most forests (e.g. Brown 1997, Chave et al. 2005, Keller et al. 2001, Gibbs et al. 2007). Tree biomass was calculated using allometric equations derived from Megonigal (1997) and Jenkins et al. (2003). Carbon was calculated as 50% of tree biomass (Swift et al. 1979). Two different sets of allometric equations were used because previous work has shown that differences in equation forms and species groupings may cause differences at small scales depending on tree size and forest species composition (Jenkins et al. 2003). The equations derived from Megonigal (1997) contain several species-specific equations while the Jenkins et al. (2003) equations are generalized estimates for species groups. The applicable equations used from Jenkins et al. (2003) were for the mixed hardwoods species group and the oak/hickory species group. Allometric equations applied to derive estimates of individual tree biomass are presented in Appendix 1.

Stand basal area was calculated as the sum of individual tree basal areas at each site for a given year. Stand density index was calculated for each of the study sites. Stand density indices are a measure of resource exploitation and competition among trees and are useful for developing quantitative management tools for forest types that have not been extensively studied (Keim et al. 2010). Stand density index (SDI) was calculated at each site using the equation (Keim et al 2010):

$$SDI = n(d/25)^{1.6}$$

where n = number of trees per ha and d = quadratic mean diameter (cm), or diameter of

the tree of average basal area.

Table 7. Listing of tree cores taken at each site by species and total number of cores by site.

Site	# cores by species	Total cores
Ben Hur ridge	*Carya caroliniana* 2	14
	Carya glabra 2	
	Celtis laevigata 4	
	Quercus michauxii 3	
	Liquidambar styraciflua 1	
	Ligustrum japonicum 2	
Ben Hur swale	*Acer rubrum* 2	18
	Celtis laevigata 4	
	Fraxinus pennsylvanica 3	

(Table 7 continued)

	Nyssa aquatica 5	
	Taxodium distichum 4	
St. Gabriel flat	*Acer rubrum* 1	16
	Carya aquatica 1	
	Celtis laevigata 3	
	Fraxinus pennsylvanica 2	
	Quercus texana 2	
	Ulmus americana 7	
St. Gabriel swale	*Acer rubrum* 5	14
	Carya aquatica 4	
	Fraxinus pennsylvanica 5	

Measurements of tree biomass were extrapolated to the stand level on a per hectare basis based on forest composition and field measurements taken from the 20x100m forest stand plots.

Leaf litterfall productivity was measured at each of the sites. Leaf litterfall consisted of all non-woody litter including flowers, fruits, and seeds that typically account for less than 10% of the non-woody litterfall total (Megonigal and Day 1988). Six 1-m^2 litter-fall baskets were randomly placed along a 100m x 20m transect within each of the study sites. Litter-fall was collected once monthly at each site over the course of one year. After collection, leaves were brought back to the lab and dried for 24 hours at 60° C and weighed. Annual leaf litterfall measurements were tested for statistical significance using a one-way ANOVA with a Tukey-Kramer adjustment for honest significant difference using SAS JMP statistical software (Sall et al. 2005).

Trees were cored with a clean, Teflon-coated 5.15 mm diameter increment borer. Tree cores were taken from a proportion of trees of each DBH class at each of the sites. Cores were taken at breast height with care taken to avoid ring malformations in the buttressed base (Parresol and Hotvedt 1990) and included the pith of the tree. Tree cores were stored in labeled plastic straws with ends sealed and placed within a hard-shell sample holder. Cores were taken back to the lab where they were dried in a mechanical convection oven at 60°C for two weeks before being mounted on wooden frames. Mounted cores were sanded with a series of increasingly finer sandpaper grit (200-600) to expose tree rings. Ring width was measured and recorded to the nearest 0.01 mm on a Velmex sliding stage (model A60, Bloomfield, New York). Ring widths were compiled into a basal area increment series in order to estimate historic forest growth. Using tree

core diameters, annual basal area increments (BAI) were calculated for each tree from 2003 to 2009.

Trees at each site were divided into classification groups based on dbh and the proportion of representative tree cores from each size class. Site-specific size classification groups at Ben Hur ridge were <20cm and >20cm. Ben Hur swale dbh classification groups were <20cm, 20-30cm, 30-50cm, and >50cm. Classification groups at St. Gabriel flat were <20cm, 20-30cm, 30-40cm, and >40cm. St. Gabriel swale dbh classification groups were <20cm, 20-40cm, and >40cm.

Annual ring width measurements from tree cores obtained at each site were then averaged for each class at each site for the years 2003-2008. I limited the time series to 5 years to minimize possible confounding factors such as changing tree age, forest condition, and canopy position (Anderson and Mitsch 2008). Mortality of individual trees within stands increases with time. This can lead to increasing the potential error of estimates with increasing time. I calculated the dbh for individual trees in each size class based on mean ring width measurements for each site-specific size class for the years 2003-2008. Basal area increment (BAI) is used in forest growth studies to quantify wood production from measurements of the ever-increasing diameter of a growing tree (Rubino and McCarthy 2000). Changes in basal area increment were calculated for each tree in each size class at each site for the years 2003-2009. Total stand BAI was calculated as the sum of BAI for each tree in each class per year.

Carbon storage for individual trees at each site during the years 2003-2008 were estimated based on changes in dbh. Carbon storage estimates were summed for each site

to provide an estimate of total carbon stored in live woody biomass at each site during each year. Annual rates of storage on a per hectare basis were calculated as the difference in carbon storage between years (i.e. Mg/C/ha 2008 – Mg/C/ha 2007). The study does not account for tree mortality and does not estimate forest carbon stored in other forest carbon pools such as litter, dead wood, non-woody vegetation, and soils.

Results

Tree Species Composition

Study sites were composed of mixed bottomland hardwood communities typical of the LMAV. The overstory of the Ben Hur ridge site was composed of several large *Quercus michauxii* (swamp chestnut oak) , *Liquidambar styraciflua* (sweet gum), and a few large *Carya glabra* (pignut hickory) and *Celtis laevigata* (sugarberry) (Fig. 17). The Ben Hur ridge site understory was dominated by *Carpinus caroliniana* (American hornbeam) and *Acer negundo* (boxelder). *Ligustrum japonicum* (Japaneses privet), *Carya glabra* (pignut hickory), *Ulmus Americana* (American elm), and *Symplocos tinctoria* (common sweetleaf) were also found in the understory. The dominant overstory species at the Ben Hur swale site were *Taxodium distichum* (bald cypress) and *Nyssa aquatica* (water tupelo) and the understory was composed of *Acer rubrum* (red maple), *Celtis laevigata* (sugarberry), *Ulmus americana* (American elm), and *Fraxinus pennsylvanica* (green ash) (Fig.18).

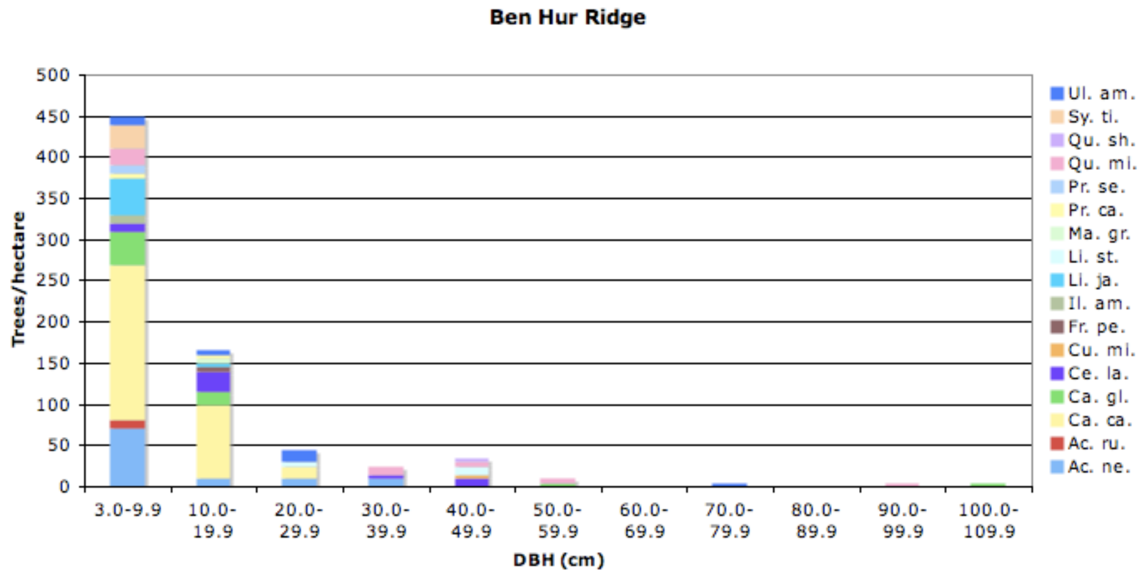

Figure 17. Graph of the number of trees per hectare by species and DBH at the Ben Hur Ridge site in 2009.

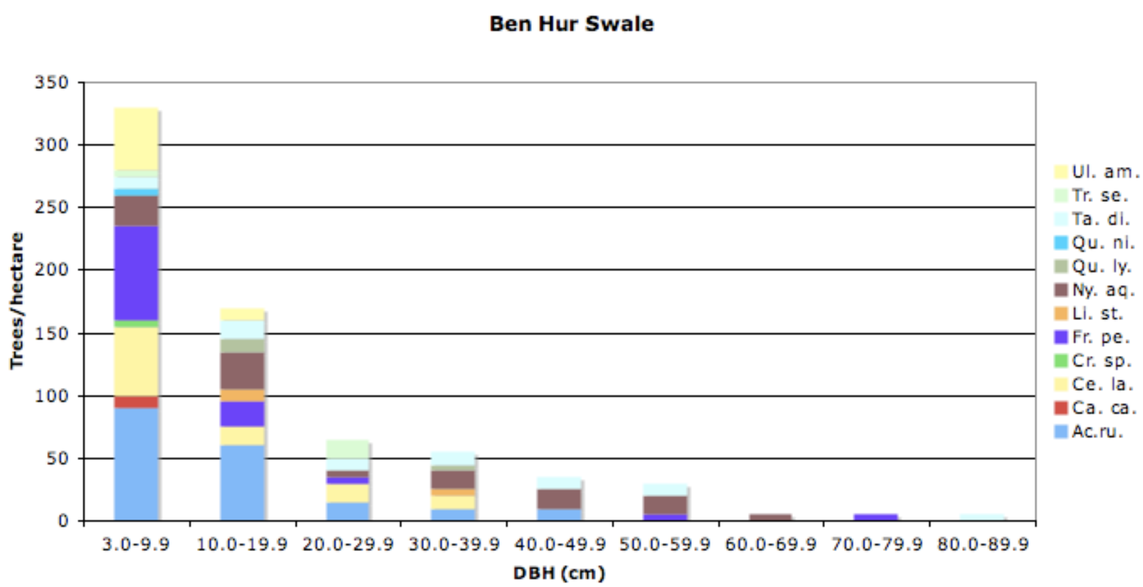

Figure 18. Graph of the number of trees per hectare by species and DBH at the Ben Hur Swale site in 2009.

The St. Gabriel flat site was composed predominantly of *Ulmus americana* (American elm), *Celtis laevigata* (sugarberry), and *Fraxinus pennsylvanica* (green ash) . *Acer rubrum* (red maple) was present in the understory. Several large *Quercus lyrata*

(overcup oak) were also present on this site (Fig. 19). The St Gabriel swale site was composed of *Acer rubrum* (red maple), *Ulmus americana* (American elm), *Celtis laevigata* (sugarberry), and *Fraxinus pennsylvanica* (green ash). *Taxodium distchum* (bald cypress) and *Nyssa aquatica* (water tupelo) were present in lesser abundance on the site along with *Quercus lyrata* (overcup oak) and *Carya aquatica* (water hickory) (Fig. 20).

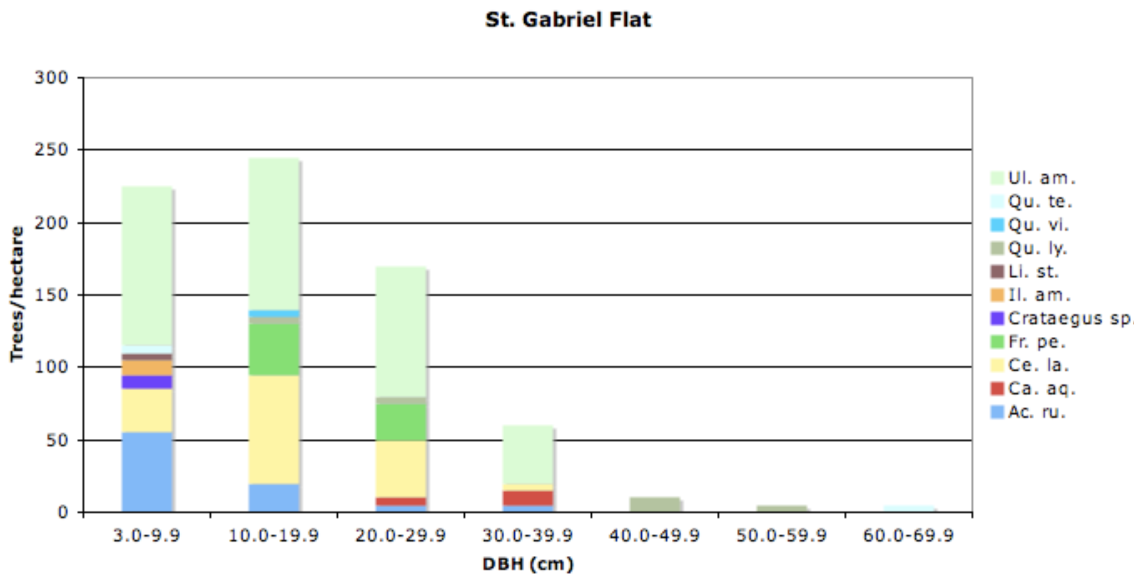

Figure 19. Graph of the number of trees per hectare by species and DBH at the St. Gabriel Flat site in 2009.

Stand Characteristics

The relative density of the three most abundant species based on number of individual trees is presented in Table 8. Relative density is the density of one species as a percent of total plant density. Relative dominance is the total basal area of species in the

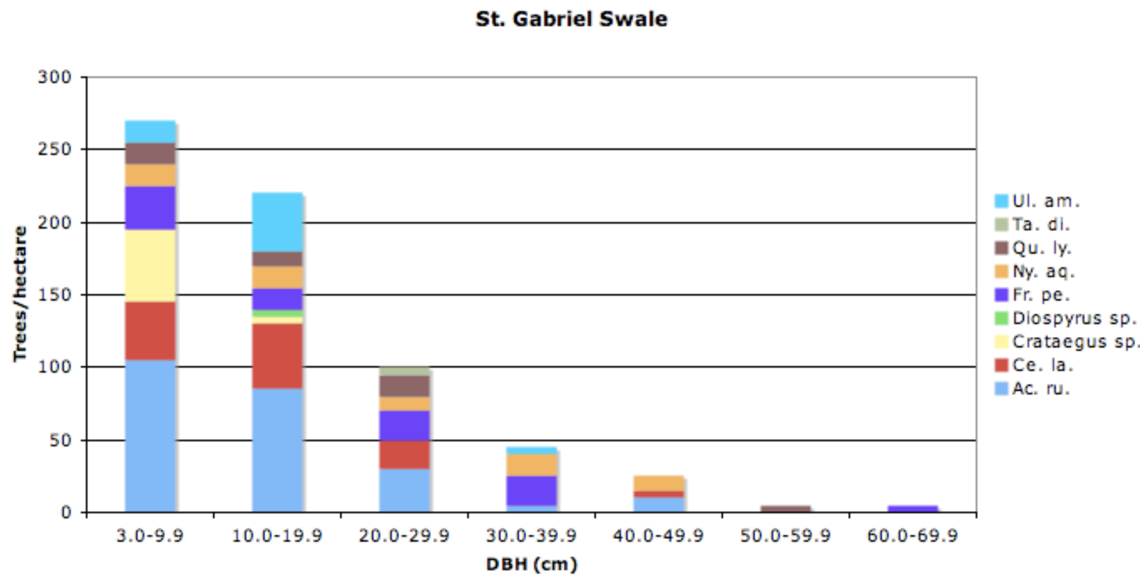

Figure 20. Graph of the number of trees per hectare by species and DBH at the St. Gabriel Swale site 2009.

site compared to the total basal area of all tree species in the site. *Acer rubrum* had the highest species density at both of the swale sites and was the dominant species found at the St. Gabriel swale site. *Nyssa aquatica* was the dominant species found at the Ben Hur swale site. The Ben Hur ridge site had *Carpinus caroliniana* in the highest density with *Carya glabra* as the dominant. *Ulmus americana* had the highest species density and was the dominant species found at the St. Gabriel flat site.

Stand Density Index

Stand density was greater at the Ben Hur sites than at the St. Gabriel sites. Stand density at the Ben Hur ridge (661) and swale (651) was comparable. SDI was 528 at St. Gabriel flat site and 480 at St. Gabriel swale site.

Table 8. Species composition analysis at the study sites based on the relative density and relative dominance of the three most abundant species at each site.

Site	Species	Relative Density	Relative Dominance
Ben Hur Ridge	*Acer negundo*	0.13	0.05
	Carpinus caroliniana	0.34	0.09
	Carya glabra	0.08	0.17
Ben Hur Swale	*Acer rubrum*	0.27	0.15
	Fraxinus pennsylvanica	0.16	0.13
	Nyssa aquatica	0.16	0.31
St. Gabriel Flat	*Acer rubrum*	0.12	0.05
	Celtis laevigata	0.21	0.16
	Ulmus americana	0.48	0.43
St. Gabriel Swale	*Acer rubrum*	0.35	0.24
	Celtis laevigata	0.16	0.12
	Fraxinus pennsylvanica	0.13	0.22

<u>Stand Basal Area</u>

Stand basal area was greater in 2009 and 2010 at the Ben Hur swale site. Stand basal area at the Ben Hur Ridge site was approximately equivalent to basal area at the Ben Hur swale site. Stand basal area at the St. Gabriel flat site was greater than at the St. Gabriel swale site Table 8. Stand basal area at the Ben Hur sites increased from 2009 to

2010 at an equal rate (1.3 m^2/ ha) while basal area increased at approximately half this rate (Table 9).

Table 9. Stand basal area at the study sites measured in 2009 and 2010.

Site	2009 basal area (m^2/ha)	2010 basal area (m^2/ha)	Change in basal area (m^2/ha)
BHR	31.1	32.4	1.3
BHS	31.2	32.5	1.3
SGF	23.6	24.3	0.7
SGS	21.2	21.8	0.6

Carbon Storage

Total carbon storage in tree biomass increased from 2009 to 2010 at all sites (Table 10). A greater increase in carbon storage was measured at the Ben Hur sites than at the St. Gabriel sites. Carbon storage in woody biomass was greater at the Ben Hur site than at the St. Gabriel site. The Ben Hur ridge site contained more carbon than the Ben Hur swale site. The St. Gabriel flat site contained more carbon stored in woody biomass than the St. Gabriel swale site. The application of the different allometric equations led to slightly higher carbon storage values for the swale sites based on Jenkins et al. (2003) equations while values at the Ben Hur ridge site and St. Gabriel flat site were higher when equations from Megonigal (1997) were applied.

Table 10. Carbon storage in Mg C/ha at each of the study sites for 2009 and 2010 based on field measurements and allometric equations by Megonigal (1997) and Jenkins et al. (2003). YoY=year on year.

Site	2009 (Megonigal)	2010 (Megonigal)	YoY change in carbon storage	2009 (Jenkins)	2010 (Jenkins)	YoY change in carbon storage
BHR	133	140	7	131	136	5
BHS	91	96	5	104	109	5
SGF	74	76	2	72	73	1
SGS	63	63	<1	64	65	1

Tree cores from each of the sites provided an estimate of the relative stand ages. The percentage of carbon stored in the ten largest trees was greater than 50% of all live woody biomass carbon stored at all sites Fig. 21. The Ben Hur ridge site contained older trees compared to the other sites, several of which dated back to the early 20th century from 1899-1926. One tree at the Ben Hur swale dated to 1876 and another to 1927 but the majority dated from the 1960's. The St. Gabriel flat site is composed of younger trees dating back to the 1970s with several older oaks dating back to the early 1960s. The St. Gabriel swale site consists of overstory trees that date back to the 1940's and 1950's. The higher percentages of carbon in the ten largest trees at the Ben Hur ridge site and St. Gabriel flat site are a result of remnant mature trees present in the multi-cohort stands.

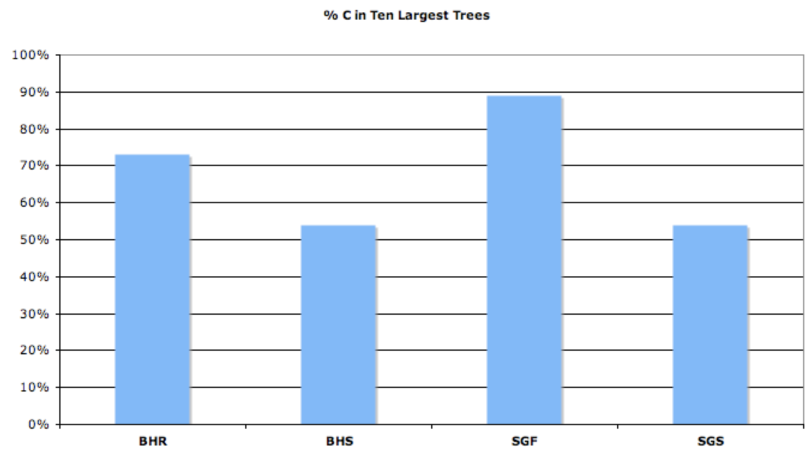

Figure 21. Percent of carbon in each stand stored in the ten largest trees by DBH at each site.

Change in BAI, by tree class at each site, for the years 2003-2009 are presented in Fig. 22-25. Trends in BAI were highly variable across sites. However, similar patterns in tree growth size classes within sites occurred. In general, BAI was higher at BHR for all tree size classes than at any other site. The BHR site saw BAI increases in trees >20 cm during period where BAI decreased in trees <20 cm dbh. The only exception to this was in 2005-2006 when BAI increased in both stands. Similar trends in BAI for trees >30cm were measured at the BHS site. This suggests that the larger trees in the stand may be growing at a faster rate than the smaller trees and are storing carbon in larger quantities and at a greater rate. BAI for trees <20cm showed an overall increase in BAI throughout the study period at all study sites except SGF. The highest BAI (0.23 m^2/ha) occurred at SGF in the 20-30 cm size class while the slowest growing size class was for trees 30-40 cm dbh from 2005-2008 at SGF. This suggests that the medium sized trees are growing at a faster rate at the SGF site and competing with the larger, taller trees for light in the stand where the canopy is more open than at the Ben Hur sites. The variable growth dynamics within stands require active management for carbon storage to be site

specific. These BAI results suggest different uneven-aged stands and tree size classes store carbon at different rates in stand development. BAI was slightly higher at SGS than at SGF. Trends in BAI followed a roughly similar trajectory for trees greater than 20 cm from 2006-2009. BAI was greatest at SGS in 2007 for trees >20 cm. The greatest increase in BAI for trees <20 cm occurred from 2007-2008.

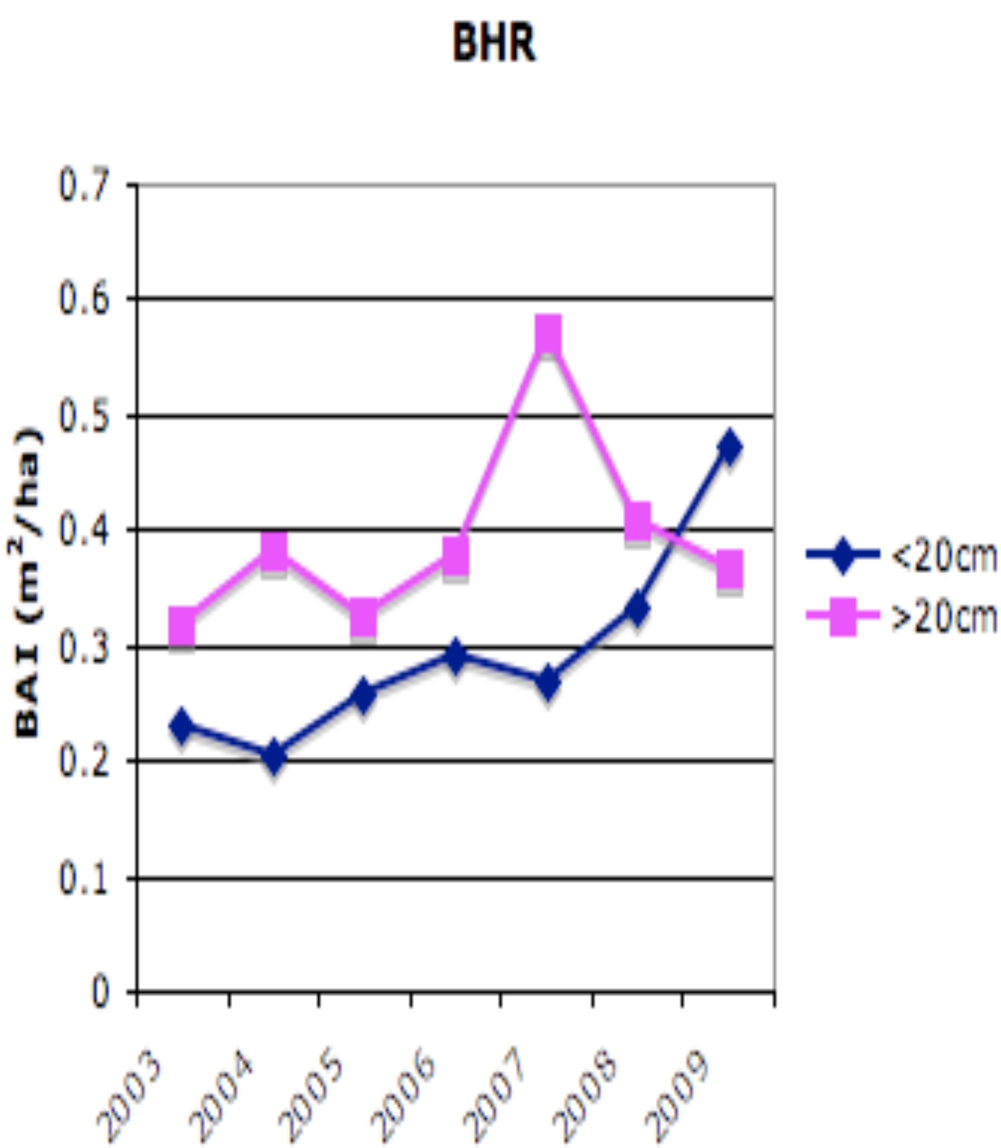

Figure 22. Mean BAI (m^2/ha) at the Ben Hur ridge site from 2003-2009.

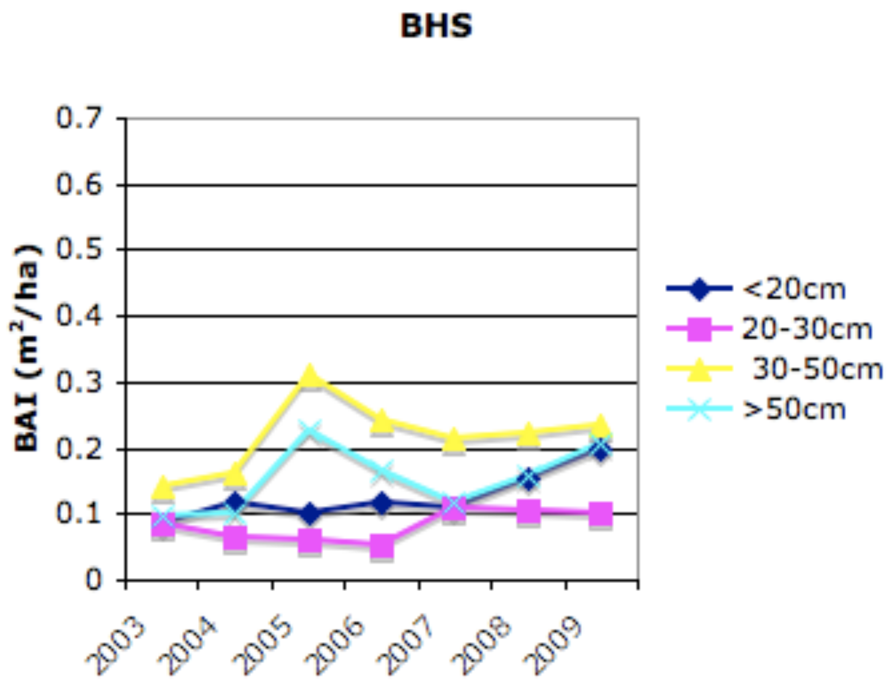

Figure 23. Mean BAI (m^2/ha) at the Ben Hur swale site from 2003-2009.

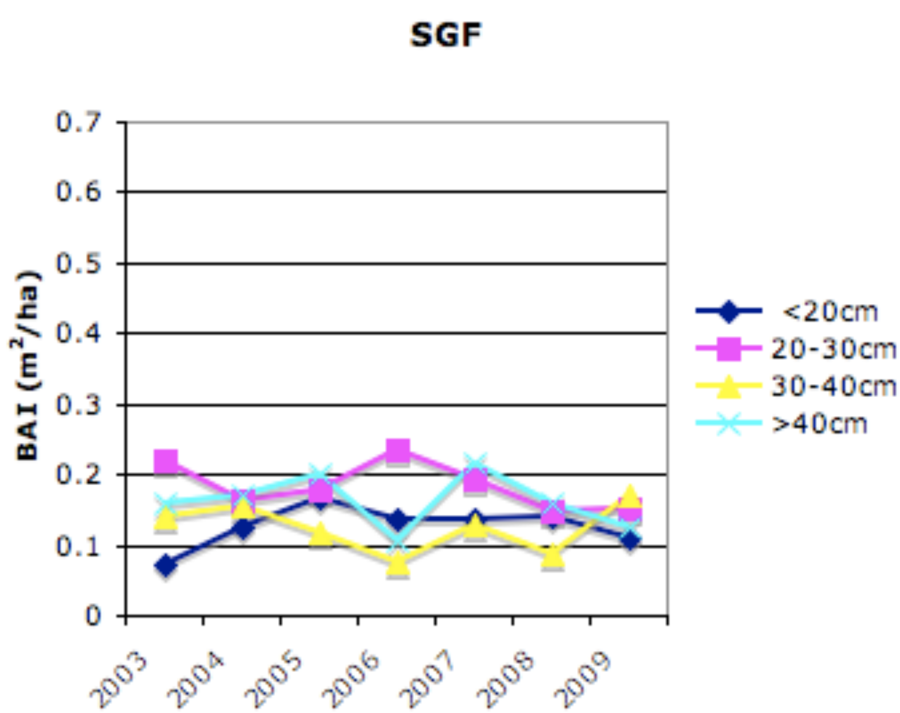

Figure 24. Mean BAI (m^2/ha) at the St. Gabriel flat site from 2003-2009.

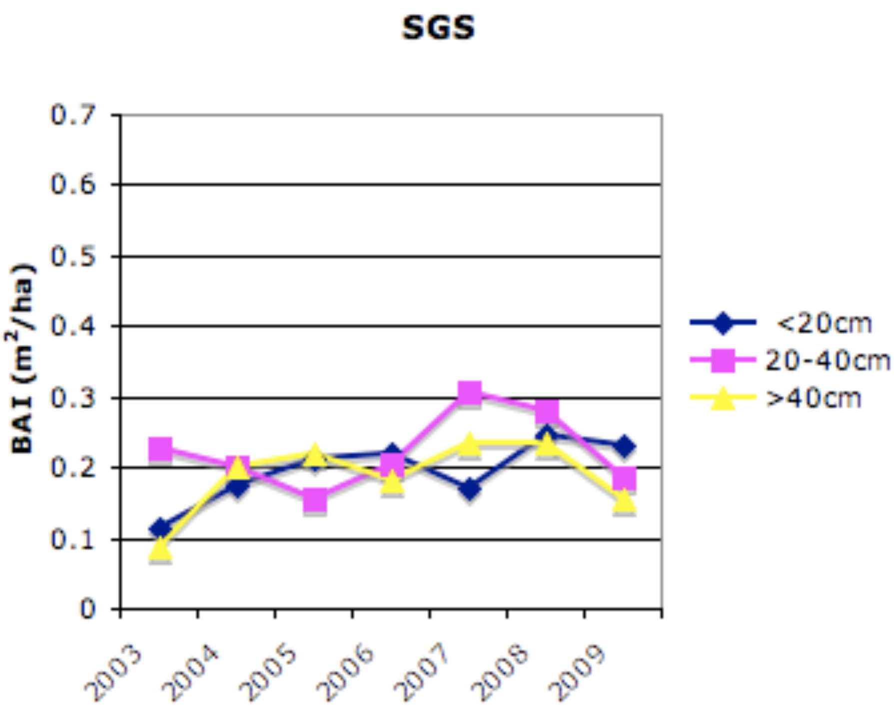

Figure 25. Mean BAI (m^2/ha) at the St. Gabriel swale site from 2003-2009.

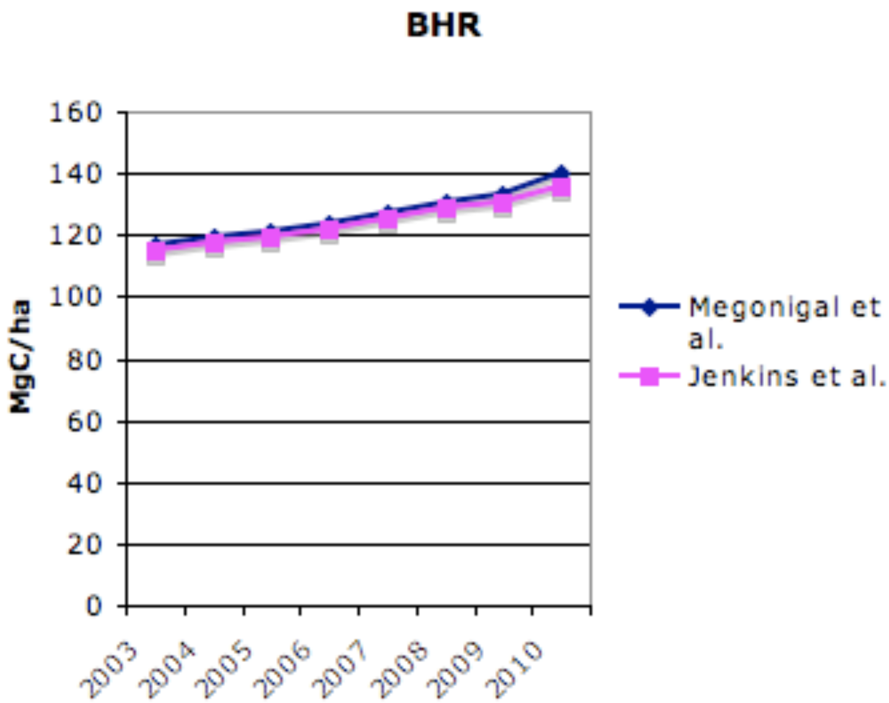

Figure 26. Carbon storage in live woody biomass at the Ben Hur ridge (BHR) site from 2003-2010 using allometric equations from Megonigal et al. 1997 and Jenkins et al. 2003.

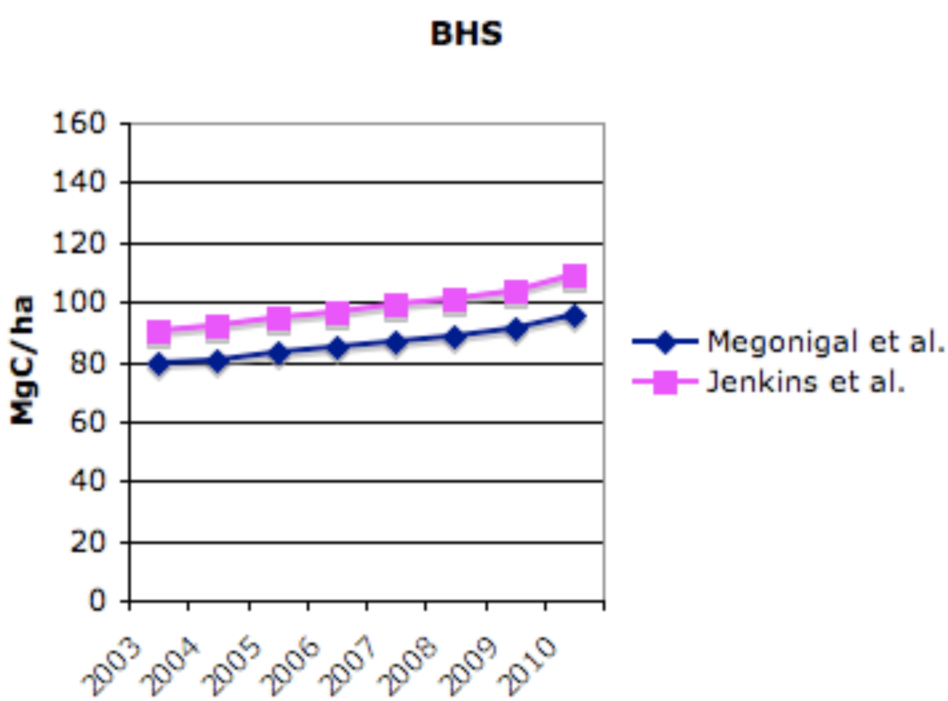

Figure 27. Carbon storage in live woody biomass at the Ben Hur swale (BHS) site from 2003-2010 using allometric equations from Megonigal et al. 1997 and Jenkins et al. 2003.

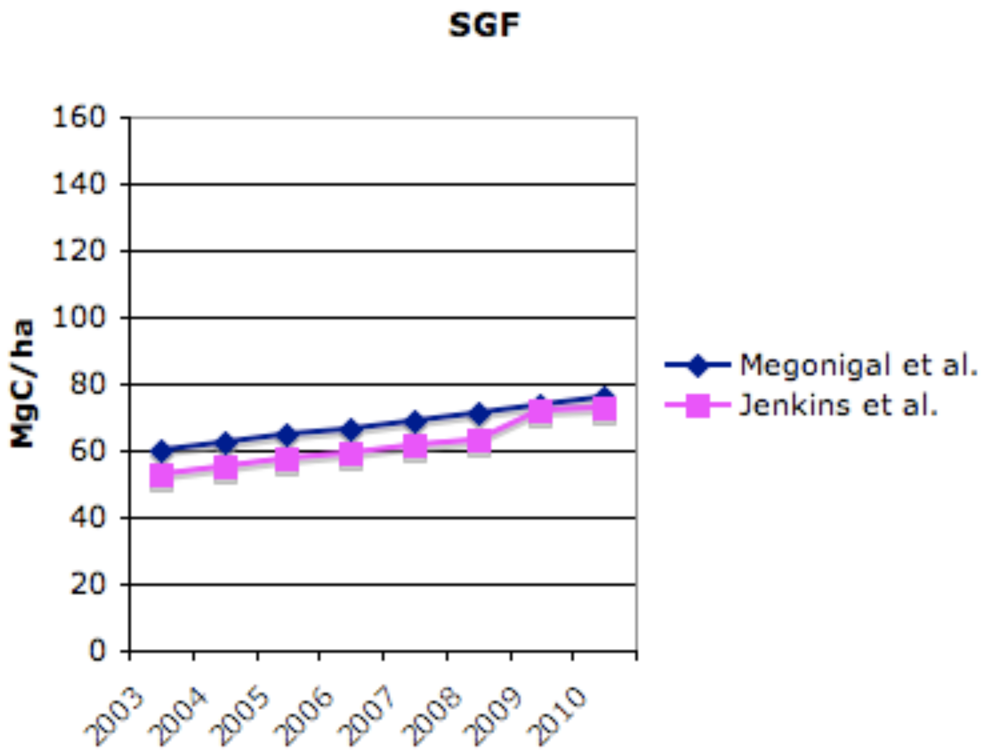

Figure 28. Carbon storage in live woody biomass at the St. Gabriel flat (SGF) site from 2003-2010 using allometric equations from Megonigal et al. 1997 and Jenkins et al. 2003.

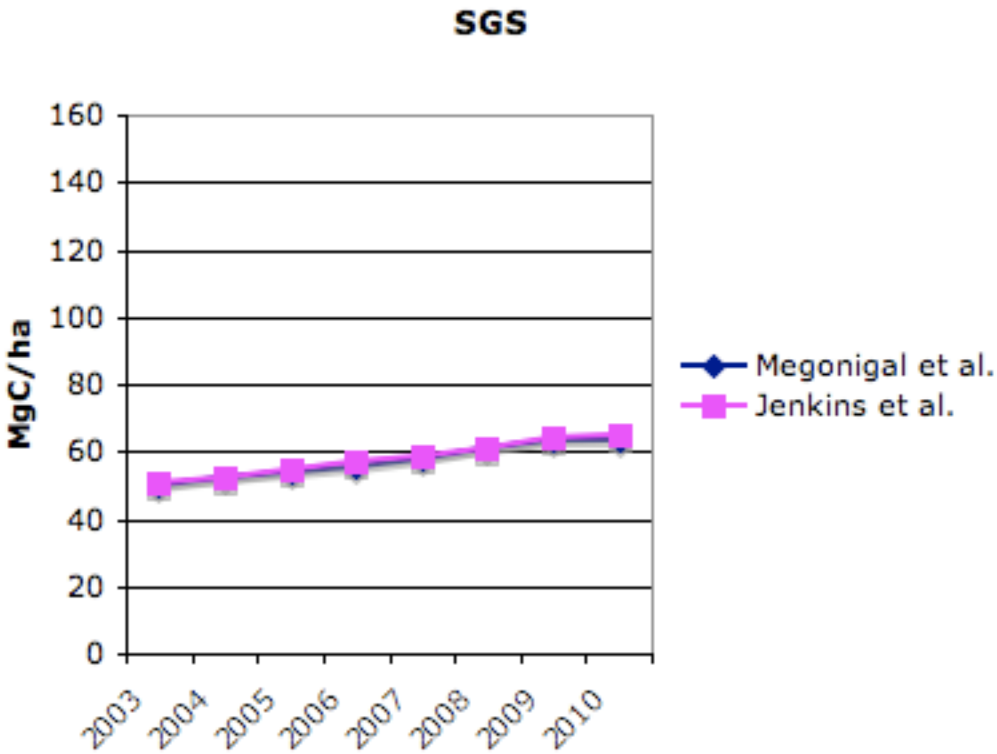

Figure 29. Carbon storage in live woody biomass at the St. Gabriel swale (SGS) site from 2003-2010 using allometric equations from Megonigal et al. 1997 and Jenkins et al. 2003.

Figures 26-29 contain the compiled carbon storage data as measured from tree cores (2003-2008) and the field measurement data for the years 2009 and 2010. The graphs of carbon storage over time show that carbon storage rate in live woody biomass was greater using the Megonigal equations at the BHR and SGF site while the Jenkins et al. equations produced greater carbon storage values at BHS and SGS. The differences in these calculations were the result of species composition and the various size classes of individual trees at the study sites. The Megonigal equations produced greater results for most species with the exceptions of *Taxodium distichum* (bald cypress), Nyssa aquatica (water tupelo), *Quercus* species (oaks) and *Carya* species (hickories). The presence of *Taxodium distichum* and *Quercus lyrata* (overcup oak) at the SGS site accounted for

slightly higher biomass estimates when using the Jenkins equations. The presence of a larger number of *Taxodium distichum* and *Nyssa aquatica* species in larger size classes at BHS, led to higher estimates using the equations from Jenkins et al. BHR had several younger hickory species present that were estimated to store more carbon using equations from Jenkins et. al. (2003). This led to approximately equal estimates of carbon storage using both methods at the BHR site.

Table 11. Estimated mean annual rate of carbon storage per site from 2003-2010 and total carbon stored in live woody biomass during the same time period. MgC=Megagrams Carbon

Site	Mean annual rate of carbon storage MgC/ha/yr (2003-2010) Megonigal et al.	Mean annual rate of carbon storage MgC/ha/yr (2003-2010) Jenkins et al.	Total change in carbon storage MgC/ha (2003-2010) Megonigal et al.	Total change in carbon storage MgC/ha (2003-2010) Jenkins et al.
BHR	3.4	3.0	23.4	20.8
BHS	2.4	2.7	16.7	18.5
SGF	2.3	2.9	16.4	20.1
SGS	1.9	2.1	13.0	14.5

Changes in carbon storage occurred at different rates across each of the sites (Table 11). The mean annual rate of carbon storage was greatest at BHR, as was total change in carbon storage from 2003-2010. BHR was the only site where equations for Megonigal produced greater rates of change and total change in carbon storage over time.

The allometric equations used to measure carbon led to different estimated quantities of carbon stored at each site in a given year. However, estimated average annual rates of carbon storage at each site using the two separate sets of allometric equations, were within 0.5 MgC/ha at all sites. Total carbon storage across the 7-year period at the Ben Hur site was higher (23.4 MgC/ha) using the Megonigal et al. equations as opposed to the Jenkins et al. equations (20.8 MgC/ha).

Forest Litterfall

Mean monthly leaf litterfall data is presented in Figure 30. Monthly leaf litterfall was greatest at all sites in November 2009. Litterfall at Ben Hur was greater at the ridge site for each month besides November and December when litterfall at the swale site was 69.4 g/m^2 and 47.7g/m^2 respectively. Mean annual total litterfall production was significantly higher at the Ben Hur sites. Mean annual total litterfall was 187.5 $g/m^2/yr$ at BHS, 182.4 $g/m^2/yr$ at BHR, 118.1 $g/m^2/yr$ at SGS and 96.6 $g/m^2/yr$ SGF.

Water Level

Site hydrologic characteristics were a result of local rain events and depth to the water table at each site (Fig. 31-32). Water levels at the St. Gabriel swale site were above the soil surface for approximately 210 days from late November 2009 through late November 2010. Water levels at the St. Gabriel flat site were above surface level for approximately 84 days during the same time period. The Ben Hur swale site was inundated for 124 days during the study period from late November 2009 through late November 2010. The greatest period of inundation occurred at each of the sites from December 2009 until April 2010. The water level at the Ben Hur Ridge site monitoring well remained below surface level during the entire study period.

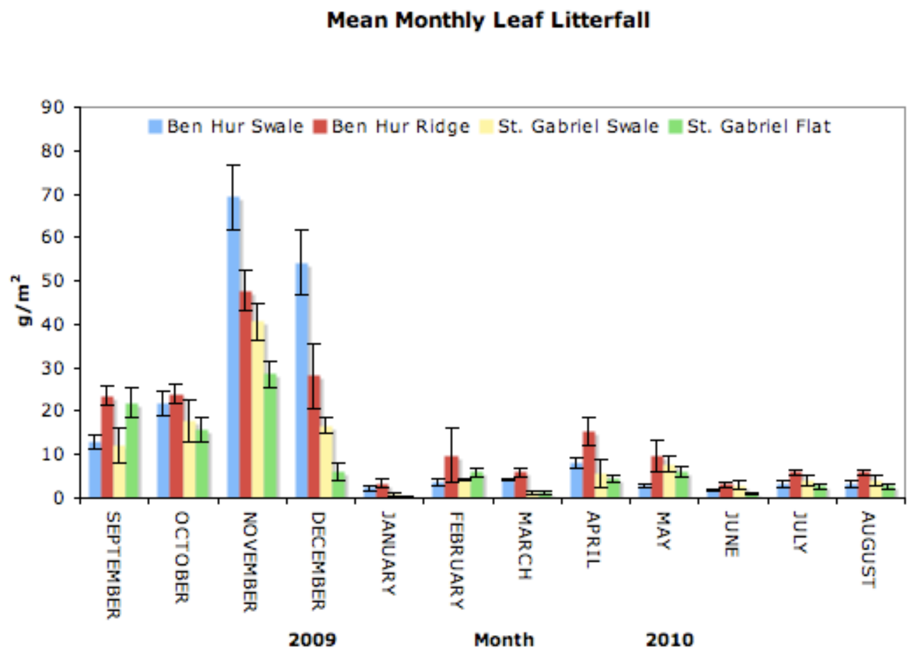

Figure 30. Monthly litterfall values at the study sites from September 2009-August 2010. Error bars designate standard errors (n=6).

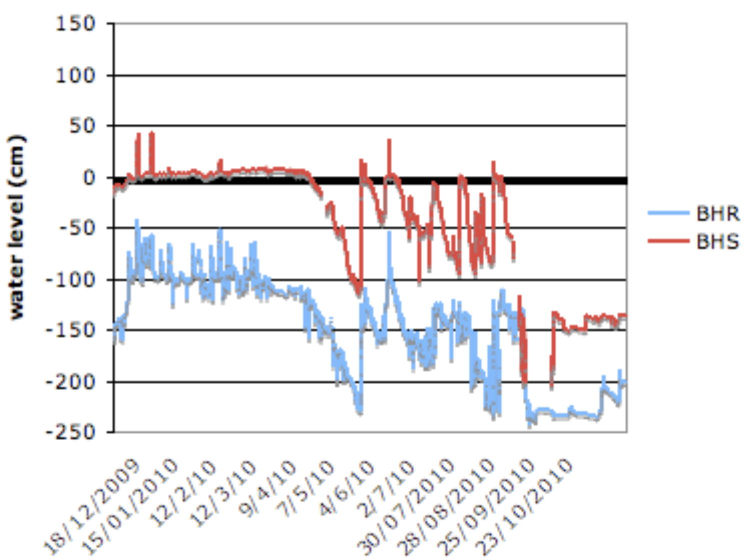

Figure 31.Water level at the Ben Hur study sites from November 2009-November 2010.

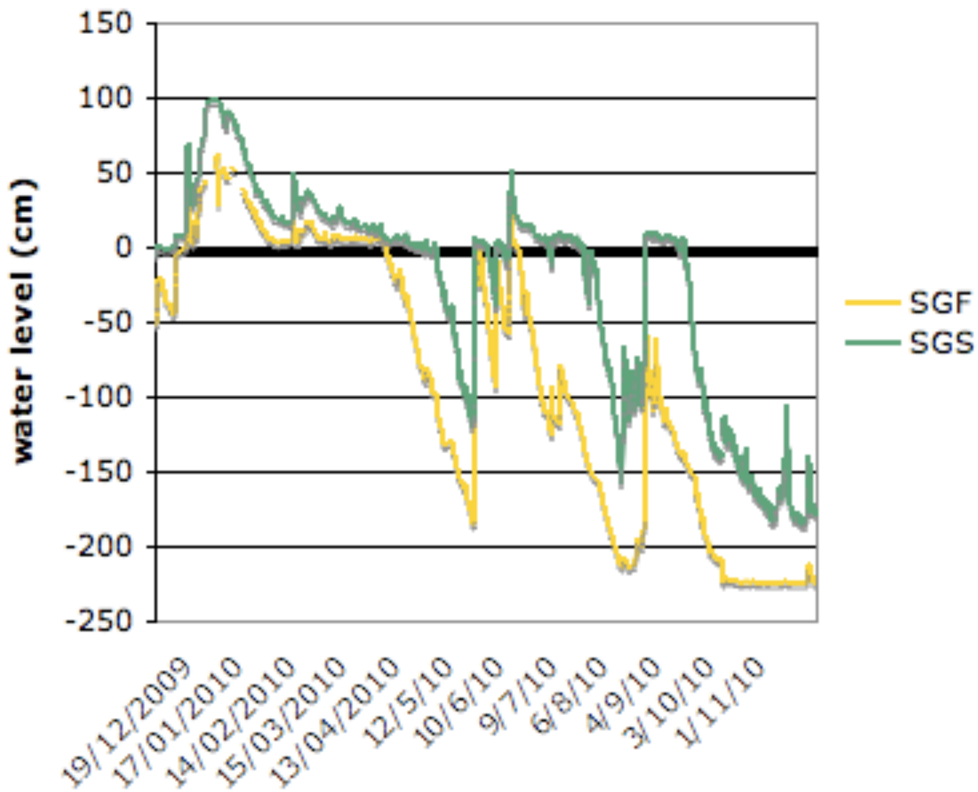

Figure 32. Water level at the St. Gabriel study sites from November 2009- November 2010.

Water Quality Nutrient Analysis

Nutrient data is provided in Figure 33. Surface-water NO_x concentrations ranged from below detection limit (<0.01 mg/L) to 0.07 mg/L at the Ben Hur swale site compared to from below detection limit (<0.01mg/L) to 0.18 mg/L for the St. Gabriel site. NO_x concentrations at the St. Gabriel flat site ranged from 0.01 mg/L to 0.06 mg/L. Surface water NH_4^+ concentrations ranged from 0.04 mg/L to 0.31 mg/L at BHS, from 0.04 mg/L to 3.04 mg/L at SGS, and from below detection limit (<0.01 mg/L) to 0.71 mg/L at SGF. NO_2 levels were <0.01 mg/l at all sites during all sampling periods. NO_x levels were less than <0.5 mg/l at all sites during all sampling periods except for at the St.

Gabriel swale site in Dec. 2009 when they reached 0.8mg/l at SGS1. NH_4 levels were below 1 mg/l at each sample site besides the St. Gabriel swale site. There was a slight increase in NH_4^+ levels at the St. Gabriel site and BHS2 in June 2010. PO_4^{3-} levels were highest >1.5 mg/l at most of the St. Gabriel sites in December 2009, highest at BHS1 and BHS3 in Dec. 2009, and highest at BHS2 in June 2010.

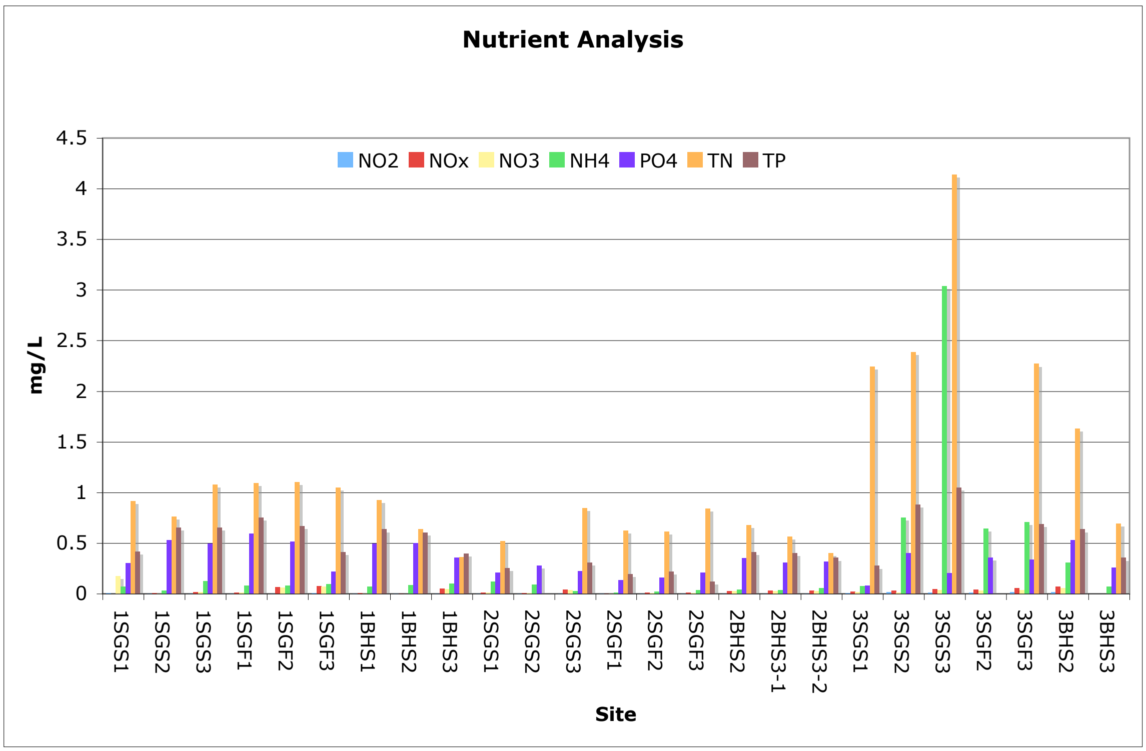

Figure 33. Nutrient concentrations in water samples taken at each sampling site during the three water sampling trips.

Discussion

Estimates of carbon stored in live woody biomass at the study sites ranged from 63 Mg/C/ha to 133 Mg/C/ha. Annual rates of carbon storage from 2009-2010 ranged from <1Mg/C/ha to 7 Mg/C/ha. These numbers varied as a result of the different methodologies applied in the calculation of woody biomass at each of the sites. The

methodologies did not produce consistently high or low estimates but varied with respect to species composition at each of the sites.

Species compositions at the sites were typical of the microtopograhic environments of the LMAV (Hodges 1997). Results of this study suggest consistency with previous studies where changing elevation by a few inches at the study sites had a marked difference on site quality, species occurrence and stand development (Hodges & Switzer 1979; Wharton et al. 1982; Hodges 1997, 1998; Stanturf et al. 2001). The variability within forest carbon storage rates is likely a result of several factors including stand age and hydrology (Megonigal 1997; Ryan et al. 2010). Soils at the study sites were typical of those associated with the LMAV (Stanturf and Schoenholtz 1998). Hydrologic data collected during this study demonstrates the high amount of variability in hydroperiod experienced by bottomland hardwood trees in differing microtopographic environments. These differences in hydroperiod, soil drainage and aeration, and soil redox potential are the result of minor elevation changes within the study sites (Stanturf et al. 2001). Although it is not possible to determine effects on forest growth from one year's hydrologic data, the SGS site with the longest duration of flooding (210 days) had the lowest amount of carbon storage in the standing crop of woody biomass. There were a large amount of downed trees and trees that were topped off at this site, which suggests that the site is in a transition to more water tolerant species. However, forest community response to environmental change often occurs over a number of years (Conner et al. 2011) thus more comprehensive, longer term monitoring of the sites would be needed to accurately describe the relationship between hydrology and productivity at each of the sites.

There are few published estimates of carbon in dead wood (i.e. standing dead, understory snags, and forest floor litter) in LMAV bottomland-hardwood forests. The USFS FORCARB2 regional model (Smith et al. 2006) tables and research conducted by Cochran (2008) provide the best estimates for dead wood in forest stands in the LMAV. In general, the volume of coarse woody debris differed between stands and ranged from 7-23 m^3/ha while fine woody debris ranged from 2-5 m^3/ha, across 9 sites in the LMAV (Cochran 2008). Dry sites had less woody debris present than wet sites (Cochran 2008).

Differences in carbon storage at the sites may also be attributed to stand age (Ryan et al. 2010) and the presence of remnant mature trees. The number of remnant mature trees that exist within each plot influences the carbon storage capacity of the stand. More than 50% of the carbon stored in live woody biomass occurred in the ten largest trees. The St. Gabriel flat site had nearly 90% of the total carbon stored on site resulting from the 10 largest trees.

The uneven aged stands examined in this study stored carbon at variable rates ranging from 1.9 MgC/ha to 3.4 Mg/C/ha. The ridge site stored carbon at the highest mean annual rate (3.4 MgC/ha) for the years 2003-2010. Carbon storage rates at all the sites were within 1 MgC/ha of each other, on average, during the study period. Carbon storage rate variability within sites ranged from 0.2 – 0.6 MgC/ha per year. These differences were largely the result of the variable species composition within sites and the different allometric equations used to measure biomass at each study site.

Group specific allometric equations from the Jenkins equations led to higher estimates of biomass in oak and hickory species than did the Megonigal equations. The

Megonigal species specific equations for *Taxodium distichum* and *Nyssa aquatica* led to smaller values than the equations applied to the same species from Jenkins. The Megonigal equations led to higher biomass estimates for all trees <10 cm dbh. The variability that results from the application of these different equations is magnified when the species differ between sites. Large diameter trees tend to account for a large proportion of the aboveground biomass in mature forests (Ryan et al. 2010). This was also the case with regard to uneven-aged cutover forests with remnant mature trees as has been demonstrated in this study. The BHS site is an example where several large cypress and tupelo trees were present and carbon estimates were greater using the Jenkins equations because these trees were grouped as mixed hardwoods rather than measured on a species specific basis using the equations from Megonigal.

The carbon storage rates reported in this study are low in comparison to previous research conducted to assess the carbon storage capacity of bottomland hardwood forests in the LMAV. Previous research focused on even aged stands that followed a sigmoid growth curve in regards to age. Carbon storage variability within trees at each of the uneven-aged stands in this study are placed in the context of the carbon storage curve developed by Shoch et al. (2009) in Figure 34. Carbon storage at the uneven-aged stand study sites are low, and may be better represented by the estimates of predicted carbon storage rates of oak-gum-cypress stands in the south-central U.S. according to Smith et al. (2006). Future investigations into carbon storage across microtopographic environments in the LMAV should consider both models in order to arrive at accurate estimates for carbon storage in uneven aged stands of the floodplain.

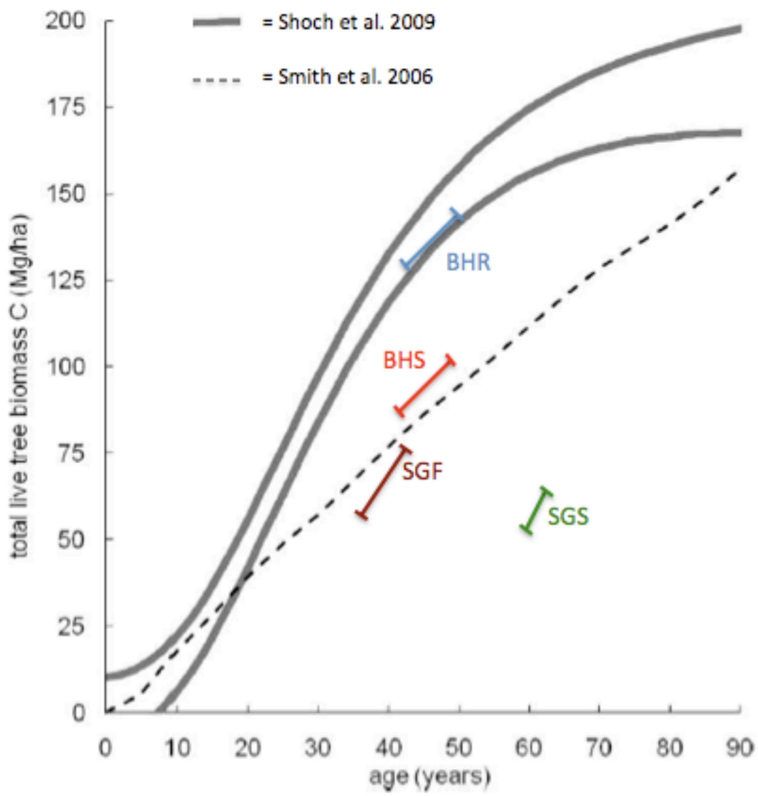

Figure 34. Comparison of live tree biomass carbon growth models for bottomland hardwoods in the Lower Mississippi Valley. Solid bounds represent 95% confidence interval of model for even-aged planted and naturally regenerated bottomland hardwood stands (Shoch et al. 2009). Dashed line represents regional estimate of live tree above- and below-ground biomass yields for oak-gum-cypress stands with afforestation of land in the South Central U.S. (Smith et al. 2006). Carbon storage in uneven-aged, naturally regenerated stands from this study are superimposed in color.

Ranges of leaf litterfall biomass and average annual stem biomass production from this study are compared to other studies carried out in bottomland hardwood forests in Louisiana in Table 12 (Messina and Conner 1998). Higher litterfall and stem growth rates at the ridge site are consistent with previous studies that examined microtopographic productivity variations within major river floodplains (Kellison et al. 1998; Stanturf et al. 2001). However, leaf litterfall estimates in this study are low compared to litterfall estimates made in other bottomland hardwood forest systems in Louisiana and

throughout the southeast. This could be due to the low nutrient concentrations measured at the sites. Stand density index values suggest that the sites are well below the maximum potential stand density indexes for similar bald cypress and water tupelo forests in south Louisiana (Keim 2010). These lower stand densities likely play a role in decreased annual leaf litterfall production numbers when compared to other site production numbers. Maximum stem density in cypress tupelo stands is approximately 1200 and approximately 1100 for bottomland hardwoods (Keim 2010). An SDI value >30% of this maximum suggests that the site contains a closed canopy and >55% of this total suggests self-thinning through biotic competition amongst trees. The Ben Hur sites are at the self-thinning stage while the St. Gabriel sites have lower stem densities and are likely not experiencing such strong competition amongst the standing stock of trees. Low litterfall production at the study sites may be to the amount of damage sustained by the forests during recent hurricane events, altered hydrologic characteristics at the sites , and low nutrient concentrations that may be related to the lack of sediment deposition events accompanying flood events that were highly influential with regard to historic vegetation development (Stanturf et al. 2001). In particular, hurricane Gustav in 2008 appears to have negatively impacted the trees at the St. Gabriel study site more than the trees at the Ben Hur sites.

Table 12. Comparison of aboveground biomass production in forested wetlands of the southern United States.

Location/Forest type	Leaf litterfall t/ha/yr	Stem growth t/ha/yr	Reference
Louisiana/bald cypress-water tupelo	6.20	5.00	Conner and Day 1976
Louisiana/bald cypress-water tupelo	4.17	7.49	Conner et al. 1981
Louisiana/bald cypress-water tupelo	3.30	5.60	Conner et al. 1981
Louisiana/bald cypress-water tupelo	4.88	3.38	Megonigal et al. 1997
Louisiana/bald cypress-water tupelo	7.25	4.30	Megonigal et al. 1997
Louisiana/bald cypress	3.33	3.30	Megonigal et al. 1997
Louisiana/mixed bottomland hardwoods	1-1.93	4.19-7.50	This study
Kentucky/green ash-bald cypress	1.36	4.98	Mitsch et al. 1991
Virginia/Atlantic white-cedar	5.69	N/A	Gomez and Day 1982
Virginia/Atlantic white-cedar	5.06	1.68*	Day 1984
Virginia/bald cypress-red maple-blackgum	5.68	N/A	Day 1984
Virginia/green ash-blackgum-bluebeech-red maple	2.52	4.92	Fowler & Hershner 1989

* = 57 year average

Understanding the ecosystem service of carbon storage provided by bottomland hardwood ecosystems is an important component of accurately assessing the price valuation of the services bottomland hardwood forests provide to society (Batker et al.

2010, Costanza et al. 1997). Live and dead trees contain about 60% of the carbon in a mature forest, and soil and forest litter contain about 40% (Ryan et al. 2010). Based on this study, one hectare stores between 63-140 MgC in live aboveground woody biomass. This must be multiplied by 3.7 to arrive at CO_2 equivalents because 1 MgC=3.7 metric tons CO_2. CO_2 equivalents (CO_2e) are a common unit for measuring the carbon emissions of work processes and the storage potential of forests. Between 233 and 518 metric tons of CO_2 e/ha are stored in these forests.

Bottomland hardwood forests store carbon at different rates during different stages of stand age and development. The amount of bottomland hardwood forest area required to mitigate against emissions (162,742 MT CO_2e, Moerschbaecher and Day 2010) from the LSU main campus for the FY 2007 is estimated to be the standing stock of carbon in an uneven aged BLH forest ranging from 314 to 698 hectares. The amount of annual carbon storage in one of these forests occurs at a rate of 1MgC/ha/yr up to 7 MgC/ha/yr (3.7 MT CO_2/ha/yr-25.9 MT CO_2/ha/yr) depending on stand age and growth stage. This would require the annual carbon storage capacity of between 6,284 hectares of fast storing forest or 43,984 hectares of slow storing forests to offset FY 2007 emissions. These ranges quantify the wide difference in carbon storage capacities of naturally regenerating bottomland hardwood forests during different growth stages in different microtopographic environments of the LMAV.

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CHAPTER 5

SUMMARY AND CONCLUSIONS

The cost and availability of energy influences the consumptive patterns of society. These patterns are shaped by energy availability and the capacity of ecosystems to provide inputs to and assimilate wastes produced by society. The relationships and limitations of these industrial, human, and natural systems should be clearly defined to develop policies that allow for the long-term sustainability of the systems. The previous three chapters examined some of the issues with regard to long-term system sustainability in south Louisiana.

Our values for EROFI at the wellhead ranged from $45/barrel to $141/barrel. By comparison, production costs for Mideast and North Africa oil ranges from $6 to $28/barrel (International Energy Agency 2008) and for the United States overall, roughly $55 to $70/barrel. These values for the ultra-deepwater GoM indicate that the price of oil would have to be in the range of current prices, >$70 barrel, to maintain profitable production in the ultra-deepwater GoM. These prices may be too high to sustain economic growth (King and Hall 2011; Hall et al. 2009, Murphy and Hall 2011). A decline in economic growth would come at great socio-economic expense to the country.

The analysis yielded EROI values ranging from 4–22:1. The lower end of this range of EROI is probably more accurate because these values were derived using energy intensity ratios for the oil and gas industry. EROI for domestic oil and gas has declined from 100:1 for discoveries in the 1930s and about 30:1 for production in the 1950s–1970s to about 10:1 in 2005–7 (Cleveland et al. 1984; Cleveland 2005). EROI values presented in this study are in the lower range of previously published estimates for domestic oil production, especially if high-energy intensity values are used. The EROI for oil and gas at the wellhead in ultra-deepwater in 2009 ranged from 7–22:1, while the EROI for oil

alone in ultra-deepwater was 4–14:1. These values fit the trend of decreasing EROI over time as oil was produced from increasingly expensive fields (Murphy and Hall 2011). A factor contributing to the increased drilling in the deep and ultra-deepwater of the GoM are federal government subsidies to drilling companies. This increases financial profitability for oil companies but does not affect EROI. In effect, the government is subsidizing the most profitable corporations in the world at the expense of public taxpayers. These subsidies provide false market signals to continue energy supply processes that otherwise would not be competitive, thereby reducing economic efficiency (Freudenburg et al. 2008). This encourages oil companies to go after low EROI oil reserves that would likely not be produced without subsidies. Such subsidies further obscure reality by causing alternative energy markets to be less cost competitive (Environmental Law Institute 2009).

Air and water pollution by the oil and gas industry are market externalities that in reality are costs borne by society. Ecosystem degradation in the form of wetland loss, partly as a result of oil and gas industry infrastructure, has increased the risk of natural disasters to coastal communities (Costanza et al. 2008). Batker et al. (2010) carried out a partial assessment of the value of ecosystem services of the Mississippi River delta. One of the major market externalities inherent in the energy production sector is externalizing the cost to society from the pollution produced through fossil fuel extraction and combustion. The decreasing returns on energy invested in fossil fuels are unlikely to be able to pay for the costs of global climatic change that is occurring as a result of fossil fuel consumption (Mastrandrea and Schneider 2010). Neither are the energy returns adequate to bring CO_2 concentrations in the atmosphere down to a level similar to those

that existed when our species evolved. It is more likely that industry and society will change as climate changes. As industry continues to pursue diminishing returns from low net energy resources, the pollution risks will increase as will the percentage of GDP that must go directly into the energy extraction sector thereby leading to a decline in the discretionary income available to society. The decline in net energy of the resource base will have impacts on how institutions within society, that were created and became dependent upon cheap, abundant fossil fuel energy, will function in the future.

Previous research has shown purchased electricity and co-gen production facilities are the major emission sources from university campuses (Association for the Advancement of Sustainability in Higher Education 2010). A large percentage (57%) of LSU A&M campus emissions are directly controlled by the University as Scope 1 emissions. The University may influence the future of campus emissions through policy measures that reduce campus energy consumption.

The University has effectively reduced emissions by shifting away from “dirtier” source fuels such as coal and distillate oil because natural gas is a cleaner source fuel when it comes to GHG emissions. Entergy Gulf States Louisiana decreased the percentage of natural gas used as a source fuel to produce electricity between 2001 (45%) and 2007 (19%). Natural gas usage decreased probably because of a rise in the price of natural gas at the time. There have been periods in which the campus co-gen facility was shut down and electricity was purchased directly from Entergy Gulf States because of the price of natural gas (July 12, 2008–August 26, 2008). However, recent additional natural gas discoveries in shale formations (Dizard 2010) may reduce natural gas prices, temporarily. A controversy with shale gas is that hydraulic fracturing results in more

greenhouse gas emissions at the wellhead than conventional oil, natural gas, and coal production processes (Howarth 2011). Again, such studies provide further evidence of the importance of boundary designation when conducting GHG emissions analyses of alternatives to conventional fossil fuels.

Greenhouse gas reductions on campus may be strategically planned or be required as a result of budget shortfalls. The cost of sustaining and maintaining present infrastructure is likely to rise in the future. LSU currently has over $235 million in deferred maintenance costs with an additional $20 million added to this total annually (Monroe 2010). Campus planning and management for sustainability may only be as good as the understanding of energy requirements and energy affordability in the future. The total GHG emissions of the University, including all indirect emissions, is greater than the sum of emissions presented in this study. Emissions resulting from campus land use change and emissions incurred by third party contractors hired by the University to carry out projects are not included. The materials demand generated by the University is also largely unaccounted for in this study. A life-cycle assessment and/or embodied energy analysis would allow for a greater understanding of more of the indirect emissions not accounted for in Scope 3 of this emissions inventory. A life cycle assessment would also expand the understanding of the environmental impacts associated with energy and materials consumption. Meanwhile, direct campus energy usage and emissions will need to be curtailed on the path towards sustainability.

Excess carbon dioxide in the atmosphere is the result of anthropogenic emissions from land use change and the combustion of fossil fuels at a rate greater than the storage capacity of the natural environment. A collective responsibility of humanity is to

understand and adapt policies to the safe operating space available to the species within the biosphere (Rockstrom 2009). Neglecting such understanding and responsibility leads to patterns of behavior that are sustainable in the short term, but may have long-term deleterious effects on the biophysical life support systems of the planet. Understanding the carbon storage capacity of forests in Louisiana helps to further define the safe operating space of humanity. To categorize the forests as one type, oak-gum-cypress, dismisses the different rates of storage in micro-topographically distinct environments. This difference can be substantial when averaged over large spatial areas. The study presented in Chapter 4 explains some of the variability within the carbon storage capacity of micro-topographically dissimilar environments in naturally regenerating un-even aged forest stands in south Louisiana. Results of the study show that forest ridges store carbon at similar rates than forest flats and swales and may aid in the management of these forests when forest carbon storage is recognized as a viable means for offsetting greenhouse gas emissions. Stand age and forest structure are more important factors to consider when examining carbon storage across uneven aged stands in micro-topographically dissimilar environments in the LMAV. There are considerable tradeoffs between maintaining a forest as a carbon sink and harvesting it to produce fuel. These tradeoffs should be properly understood before policy decisions are made so as to ensure the continued functioning of bottomland hardwood ecosystems.

Approximately 48%, or 13.8 million acres, of land area in Louisiana is forested (LA Dept. of Ag and Forestry 2011). Preliminary estimates suggest 268 million metric tons of carbon is stored in all biomass components of Louisiana's forests (Xu and Wang unpublished). Thus, Louisiana forests currently function as a carbon sink. The potential

to increase forest growth and manage forests to enhance carbon storage capacity depends on an accurate assessment of the present rates of growth and carbon storage capacity of forests as well as the factors that affect forest growth. The majority of the work currently being conducted on forests with regard to carbon storage is the calculation of the carbon storage capacity of even-aged afforested and plantation forests (Smith et al. 2006; Shoch et al 2009). Little consideration is being given to the carbon storage capacity of the remnant cutover forests that make up a large proportion of the bottomland hardwood forests in south Louisiana.

Live and dead trees contain about 60% of the carbon in a mature forest, and soil and forest litter contain about 40% (Ryan et al. 2010). Based on the study in Chapter 4, one hectare of standing stock biomass stores between 63-140 Megagrams Carbon (MgC) in live woody biomass. This must be multiplied by 3.7 to arrive at CO_2 since 1 MgC=3.7 metric tons C. So between 233 and 518 metric tons of CO_2e/ha are stored in the live woody biomass of these forests.

Bottomland hardwood forests store carbon at different rates during different stages of stand age and development (Smith et al. 2006; Shoch et al. 2009). The amount of bottomland hardwood forest area required to mitigate against emissions (162,742 MT CO_2e per year, Moerschbaecher and Day 2010) from the LSU main campus for the FY 2007 is estimated to be the live biomass standing stock of 314 - 698 hectares of forest. The amount of annual carbon storage in one of these forests occurs at a rate of 1 to 7 MgC/ha/yr (3.7 MT CO_2/ha/yr - 25.9 MT CO_2/ha/yr) depending on stand age and growth stage. Between 6,284 hectares of fast storing (Ben Hur ridge) forest or 43,984 hectares of slow storing (St. Gabriel swale) forest could offset FY 2007 emissions in one year.

These results demonstrate the wide difference in carbon storage capacities of naturally regenerating bottomland hardwood forests during different growth stages. Therefore, there is a need to accurately account for these differences in order to properly assess the differences in the rate of emissions and the rate of storage from the natural environment that may be selected to provide offsets against those emissions.

A clearer understanding of the costs at which fossil energy resources are produced, consumed, and stored in the environment may help to maintain the earth's climate system at a level that permits for the long-term habitability of the planet by the current human population. One step in this process is identifying the limits at which the marginal energy costs of maintaining the financial profitability of present fossil fuel extraction outweigh the marginal benefits to society. The point at which costs outweigh benefits can be a threat to the long-term sustainability of system functioning. The rates and manner in which energy is consumed is important to understanding the long-term sustainability of the system that depends on the energy for system functioning. Fossil energy resources can be consumed in a way that enhances the quality of life of the species over the long term or it may be squandered over the short term. Regardless, there exist limits both to the amount of fossil energy available to society and to the waste storage capacity of the natural environment to process the resulting emissions from the combustion of these finite resources. An accurate understanding of these limits may help to determine policy considerations that could affect the long-term sustainability of the society.

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APPENDIX A: LIST OF ALLOMETRIC EQUATIONS

Allometric equations used for calculating aboveground woody biomass production at the study sites.

Species	y	= f(DBH)	DBH range	Reference
1Fraxinus spp.	Biomass(kg)	= ((2.669*((DBHcm*0.394)^2)^1.16332))*0.454	>10 cm	Megonigal et al. '97
2Taxodium distichum	Biomass(kg)	= 10^(-.97+2.34*LOG10(DBHcm))	>10 cm	Megonigal et al. '97
3Nyssa aquatica	Biomass(kg)	= 10^(-.919+2.291*LOG10(DBHcm))	>10 cm	Megonigal et al. '97
4Acer rubrum	Biomass(kg)	= ((2.39959*((DBHcm*0.394)^2)^1.2003))*0.454	10-28 cm	Megonigal et al. '97
8 Other Species	Biomass(kg)	= ((2.54671*((DBHcm*0.394)^2)^1.20138))*0.45	10-28 cm	Megonigal et al. '97
9	Biomass(kg)	= ((1.80526*((DBHcm*0.394)^2)^1.27313))*0.45	>28	Megonigal et al. '97
10 All species <10cm)	Biomass(kg)	= ((2.50008*((DBHcm*0.394)^2)^1.19572))*0.45	<10cm	Phillips 1981

from Megonigal et al. 1997

Species Group	Parameters β_0	β_1
Mixed hardwood	-2.4800	2.4835
Oak/hickory	-2.0127	2.4342

Biomass equation: $bm = \text{Exp}(\beta_0+\beta_1 \ln dbh)$

where

bm= total aboveground biomass (kg) for trees 2.5cm dbh and larger

dbh= diameter at breast height (cm)

Exp= exponential function

ln= natural log base “e” (2.718282)   from Jenkins et al. 2003

APPENDIX B: GLOSSARY OF TERMS

barrel of oil equivalent (BOE) – 42 gallons of crude oil or 5800 cubic feet of natural gas

carbon credit- tradable certificate or permit that represents the right of the holder to emit one ton of carbon dioxide equivalent; carbon credits can also be sold to polluters to offset greenhouse gas emissions

carbon dioxide equivalent (CO_2e)- concentration of a greenhouse gas that would cause the same radiative forcing as a given volume of CO_2, usually measured in tons; methane, nitrous oxide, and other GHGs have different global warming potentials than CO_2 and this measure establishes a functional equivalent so quantities can be compared easily

carbon finance- branch of environmental finance that refers generally to the buying, selling, and trading of carbon credits

carbon stock- refers to the standing stock of live woody biomass carbon at a study site

conventional reserves- crude oil produced using the well drill method; does not include oil produced through enhanced recovery methods, tar sands, oil shale, biofuels, or other alternative liquid fuels

ecosystem services- services provided by natural ecosystems including resources such as clean drinking water and processes such as the storage of carbon by trees during photosynthesis

energy intensity ratio-the ratio of the amount of energy, measured in megajoules (MJ), required to produce $1 of GDP in a given year; ratio differs across sectors based on the energy intensity of the sector

externality- a positive or negative consequence of an economic activity experienced by a third party; the costs of externalities are not accounted for in the market transaction that produces them

federal outer-continental shelf (OCS)- consists of the submerged lands, subsoil, and seabed in a specified zone (between 3 and 9 miles from shore in the Gulf of Mexico depending o the state) up to 200 nautical miles or more offshore from U.S. coasts

greenhouse gas (GHG)- a gas that traps infrared radiation heat in the atmosphere: a buildup of concentrations of these gases in the atmosphere causes climatic change

Hubbert approach- refers to the Hubbert linearization method of determining extractable reserves of energy from a given region where the sum of a large number of asymmetrical distributions becomes symmetrical (normal) under the Central Limit Theorem of statistics; model of cumulative oil production in a region developed by M. King Hubbert

Macondo Prospect- Mississippi Canyon block 252 (MC252), oil and gas prospect located in the northern Gulf of Mexico; site of Deepwater Horizon rig explosion and subsequent oil leak

neo-classical economics- present, mainstream economic thought that focuses primarily on the allocation of resources and goods in the economy through the operation of markets

net energy- the amount of energy delivered to society by a technology to the total energy required to find, extract, process, deliver, and otherwise upgrade that energy to a socially useful form

peak oil-the point in time of the maximum rate of oil output production; oil, like any finite resource extraction process will eventually reach a point in time when further increases in the rate of production will not be possible and extraction rates will then begin to decline

production profile curve- term for the quantity vs. time relationship that occurs as a resource is extracted from a reservoir; oil well extraction usually follows a bell-shaped production profile curve

shale oil-unconventional synthetic crude oil produced from marlstone, also known as kerogen oil; large deposits are thought to exist in the western united States although it is uncertain if they are economically or energetically profitable to extract

shut-in volumes- products of delayed oil production; oil not extracted during the previous year or years due to a disturbance such as a hurricane

subsidies- an assistance payment paid to a business or economic sector

sustainability-meeting the needs of the present without compromising the ability of future generations to meet their own needs

tar sands-unconventional petroleum deposits, also known as bitumen, found in large quantities in Alberta, Canada

unconventional reserves-petroleum produced using non-traditional methods; petroleum produced through enhanced oil recovery techniques and from sources such as shale oil and tar sands

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Matthew Moerschbaecher was born in Washington, D.C., and moved to Jefferson Parish, Louisiana, at the age of two. He was raised in Metairie and completed his primary and secondary educational training in New Orleans. Upon graduation from high school, he attended Warren Wilson College in Swannanoa, North Carolina, where he completed a bachelor of science degree in environmental studies. He spent the next two years working at seasonal jobs from the Waffle House to guiding rafts on the rivers of western North Carolina and eastern Tennessee and vagabonding through South America and Africa in his spare time. He began attending graduate school LSU's Department of Environmental Sciences in Fall 2006, and completed his master's of science with a concentration in wetlands science before beginning his doctoral career in the School of Renewable Natural Resources in Fall 2008. Following completion of his dissertation, he will be moving to London to work with the Institute for Integrated Economic Research, in conjunction with the Imperial College, on a modeling project that focuses on the economy of England.