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DEGRADATION AND DAMAGES FROM UTILIZING ECOSYSTEM SERVICES IN A RIVER BASIN

Travis Warziniack*

We examine the tradeoffs between utilizing multiple ecosystem services in an economic model of the Lower Mississippi-Atchafalaya River Basin. We show how economic development in the basin degraded the ecosystem, but diversified the economy. A degraded ecosystem and more employment opportunities elsewhere reduced the region's reliance on agriculture and other resource-related industries such as fishing. We compare the size of actual economic damages from reduced water quality associated with agricultural runoff in the upper basin with those that would have occurred without economic-ecosystem feedbacks and general equilibrium adjustments in the economy. We find increases in crop prices and subsidies to agriculture can increase risk of damages to the ecosystem in three ways: 1) by increasing total agricultural area, 2) by encouraging farmers to use more intensive agricultural methods, and 3) by competing for labor and capital with other types of economic activity that are less likely to degrade the environment.

Keywords: Ecosystem services, general equilibrium, impact analysis

INTRODUCTION

The ecosystem provides multiple services to multiple stakeholders, with benefits accruing at various spatial scales (Hein et al., 2006), temporal scales (Howarth and Norgaard, 1993), and with competing economic interests (Jones, 1965). Management of a given ecosystem requires acknowledgement of links between resources within the biological system, the impact of economic activity on the natural resources, and feedbacks between biological and economic systems (Settle et al., 2002). While gains have been made in understanding the complexity of the biological system, economic valuation and impact studies have largely focused on a single ecosystem service (Hein et al., 2006).

We expand the literature by considering the multiple factors and industries that make up a resource dependent economy, and the competing use of the ecosystem between provision of inputs to productive activities and use for disposal of waste. In this paper, ecosystem services affect local economies in two ways. They directly affect the productivity of factors, and they mitigate damages should a severe event, such as a flood, occur.

We frame our model around a story of nonpoint-source pollutants in the Mississippi-Atchafalaya River Basin (MARB). The Mississippi River once meandered through the country. Its shifts and flooding created rich agricultural lands and encouraged development along its banks. Risk of damages to the environment arises because the river basin produces two types of ecosystem services - those that rely on a healthy ecosystem to provide benefits (e.g., protection of storm surges, fish habitat) and those that degrade the ecosystem in order to provide benefits (e.g., flood control, crop production). We show how economic development in the basin degraded the ecosystem, but diversified the economy. A degraded ecosystem and more employment opportunities elsewhere reduced the region's reliance on resource-related industries such as fishing. We compare the size of economic damages from reduced water quality associated with agricultural runoff in the upper basin with those that would have occurred without economic-ecosystem feedbacks and general equilibrium adjustments. We find increases in crop prices can increase risk of damages to the ecosystem in three ways: 1) by increasing total agricultural area, 2) by encouraging farmers to use more intensive agricultural methods, and 3) by competing for labor and capital with other types of economic activity that are less likely to degrade the environment.

BACKGROUND

The MARB drains 40 percent of the land area of the United States, but to make the analysis clearer, our prototypical economy is only an agglomeration of the Louisiana and Iowa economies. These two states represent stark contrasts in the use of the MARB and Gulf of Mexico (GOM). At the southern end, a large shrimp industry exists in the coastal region of Louisiana. The GOM accounts for 85 percent of landings and 87 percent of dockside value of all shrimp harvested in the United States. Louisiana ranks first among all states in volume of catch, with annual average catch of 51,000 metric tons valued at \$138 million (NMFS Commercial Landings data, 2001-2010).

* Rocky Mountain Research Station, USFS; Fort Collins, CO 80526; twwarziniack@fs.fed.us; (970) 295-2960

In terms of contribution to the national economy, Louisiana shrimping is dwarfed by the size of Iowa corn production. In 2010, there were over 55 thousand km² of corn planted in Iowa with a productive value of over \$11.7 billion. Over the last half century virtually all of Iowa's rangeland and forests have been replaced by row crops, with about 60 percent of the state's land covered by row crops in 1992 (Iowa Geological Survey Landsat data, 1992).

Despite being 1200 km downstream, the primary habitat for GOM shrimp is directly affected by agricultural production in Iowa. A large amount of nitrogen fertilizer applied to Iowa farmlands ends up in MARB streams and flows into the GOM. Nitrogen runoff makes Iowa farmers the largest contributor to the largest hypoxic zone in the coastal United States (Goolsby et al., 1999). The hypoxic zone in the GOM has increased in size from an average 6900 square km² from 1985-1992 to 13,600 km² from 1993-2004 to 17,300 km² between 2005-2010 (mid-summer bottom water cruises, data source: Rabalais, Louisiana Universities Marine Consortium, and Turner, Louisiana State University).

Goolsby et al. (1999) estimate that about 13.4 percent of nitrogen used for farming in the basin eventually ends up in the GOM and that an additional 11.9 kg/km²/yr N is delivered from soil leaching and other unspecified sources for every 1 cm of runoff in the basin. For corn planted after a corn harvest, Iowa State University Extension (1997) recommends 16,800 - 22,400 kg/km² (150-200 lb/acre) N when applied before crop emergence; it recommends 11,000 - 16,800 kg/km² (100-150 lbs/acre) N for corn after soybean when applied before crop emergence.

We limit the focus of this analysis to the effect of the size of the hypoxic zone on catch of brown shrimp (*Farfantepenaeus aztecus*) because it is the species for which the effects of the Gulf hypoxic zone are clearest. Subadult brown shrimp avoid hypoxic waters, clustering on the edges of the hypoxic zone and dispersing to inshore and offshore waters (Craig et al., 2005; Craig and Crowder, 2005; Zimmerman and Nance, 2001). It is estimated that about 25% of brown shrimp habitat has been lost to the hypoxic zone, and displacement to suboptimal water temperatures reduces their weight and size enough to affect dockside value (Craig et al., 2005). Both Zimmerman and Nance (2001) and O'Connor and Whitall (2007) find evidence of reduced catch due to increases in size of the hypoxic zone.

METHODS

The model follows the general equilibrium model of an open economy developed by Copeland and Taylor (2003), which we have adapted to include payments for the ecosystem inputs and damages to ecosystem services. The numerical application uses a computational model called the General Equilibrium Model of Ecosystem Services (GEMES). GEMES is part of an ongoing effort to model ecosystem services with a computational general equilibrium (CGE) model to value the contribution of ecosystem services to regional economies and study the tradeoff between using ecosystem services as a factor of production and other more traditional factors of production such as capital and labor. Complete computer code can be provided upon request.

The model includes six producing sectors, $J = \{\text{corn and other grains, other agriculture, commercial fishing, power, oil and gas production, miscellaneous}\}$. Most of the grain production occurs in Iowa; most of the commercial fishing and oil and gas production occurs in Louisiana. There are nine representative households differentiated by income and two government agents (state and local, and federal). Government agents tax output and income, purchase goods at fixed proportions of government revenues, and supply a fixed portion of regional output. The model includes domestic trade with other areas of the United States and foreign trade according to the usual Armington assumptions (Armington, 1969). The economy is calibrated to a benchmark social accounting matrix using 2010 IMPLAN data (Minnesota IMPLAN Group). These methods are described in detail in Warziniack (2009) and Warziniack et al. (2011).

Theoretical Foundations of Model

Firms produce output Q_j by employing capital, labor, and ecosystem services in amounts K_j , L_j , and E_j . The production function for each firm $F_j(K_j, L_j, E_j)$ exhibits constant returns to scale. Capital and labor are supplied inelastically in competitive factor markets, with market prices r and w . Damages are defined simply as activities that raise the unit cost of utilizing ecosystem services. Firms vary in their susceptibility to damages and face a unique cost of utilization λ_j .

We distinguish between environmental damages and environmental degradation. Degradation occurs when firms deposit pollutants directly into the environment or adversely change the structure of the environment. Pollutants do not cause direct damages if they remain where deposited. However, natural and manmade events, such as runoff and storms, transport the pollutants through the ecosystem, at which time damage occurs.

Total degradation by firm j is given by $Z_j = \psi_j(\theta_j)Q_j$, where $\psi_j(\theta_j)$ is degradation per unit of output and θ_j is a control technology that reduces degradation. The aggregate amount of degradation determines the probability of an event occurring and the size of damages should an event occur. Define $Z = \sum_j Z_j$ as the aggregate amount of degradation in the economy.

The number of events that occur in a given period is a random variable S with Poisson distribution and mean $\mu(Z)$; $\mu'(Z) > 0$. Damage to firm j from event s is a random variable D_s^j with Normal distribution and mean $\Omega_j(Z)$; $\Omega_j'(Z) > 0$. Events are

i.i.d. Total damage to firm j if S events occur is $TD_j = \sum S D_s^j$. TD_j is a compound Poisson random variable with expected value

$$E[TD_j] = E[S] E[D_s^j] = \mu(Z) \Omega_j(Z).$$

We assume ecosystem services are purchased from a risk neutral, price discriminating firm that earns zero expected profits and charges expected marginal costs. This approach captures the effect of risk on firm decisions in the long run. Let c_j^E be the marginal cost of providing ecosystem services without risk of disaster. The total expected cost is $c_j^E E_j + E[TD_j]$, which gives an equilibrium price of

$$\lambda_j = c_j^E + (\mu(Z) \Omega_j(Z)) / E_j.$$

The affect of risk is similar to that of a risk premium paid on ecosystem services. If ecosystem services are freely provided by the environment, λ_j is a shadow price faced by the firms.

Investment in control θ_j is at the expense of output and normalized so one unit of control requires one unit of output. Define Y_j as net output in the presence of control; $Y_j = (1 - \theta_j) Q_j$. Net output Y_j is determined by the full employment of factors and relative returns in the economy from production of goods. The relative returns of goods is found by looking at the profit maximization problem for firms. Profits in industry j are

$$\pi_j = p_j Y_j - w L_j - r K_j - \lambda_j E_j - \tau_j Z_j,$$

where τ_j is the firm-specific price for damages that could be a direct fee by the government or represent a shadow price internalized by the firm for environmental degradation.

The level of ecosystem services affects the productivity of other factors employed by a firm, but firms do not compete for ecosystem services. Thus, for a given E_j tradeoffs in the economy are entirely with regard to allocating capital and labor between sectors to maximize the value of production. Factors of production are employed such that the marginal revenue products are equal between all firms and equal to the ratio of marginal returns from production. In our economy, there are two types of production possibility frontiers (PPFs), a potential PPF expressed in total production Q_j and a net PPF expressed in net production Y_j . Because $Y_j = (1 - \theta_j) Q_j$, the two are interchangeable. Equilibrium along the potential PPF occurs where the ratio of world prices p_j / p_j equals the slope of the potential PPF. Because resources are devoted toward control and cost of ecosystem services have a risk premium, firms do not earn the full world price. Equilibrium along the net PPF occurs where the ratio of returns to firms equals the marginal rate of transformation.

Calibration of per unit damages and cost of ecosystem services

Given this theoretical setup, we calibrate our numerical model to economic data and results from the literature. We begin by assuming a linear relationship between hypoxic zone size and nitrogen levels from Iowa such that *Size of Hypoxic Zone* = $\rho \times$ *Nitrogen Yield*. In line with Iowa State University Extension recommendations, we assume all planted corn in the basin receives 11,000 kg/km² N. Given 52,600 km² of planted corn in Iowa, this translates to 590 million kg N added to Iowa soils. Following Goolsby et al. (1999), 79 million kg of this nitrogen reaches the GOM. Calibrating to baseline values gives $\rho = 17,300 \text{ km}^2 / 79 \text{ million kg N} = 0.00022$.

We use estimates from O'Connor and Whitall study that shows brown shrimp catch decreases by 648 kg per km² of hypoxic GOM waters. Regressions in O'Connor and Whitall utilize the usual *ceteris paribus* assumption. Our goal, however, is to model the impact in general equilibrium where prices and quantities can change. We seek to map percentage increase in costs of utilizing ecosystem services in the shrimp industry to a percentage increase in fertilizer application on Iowa farmlands. Assuming a constant ratio between corn production and acreage planted, a 1% increase in Iowa corn production will lead to a 5.9 million kg increase in N on Iowa fields, of which 0.79 million kg are added to the GOM. The hypoxic zone increases by $1\% \times 79 \text{ million} \times \rho = 174 \text{ km}^2$. Shrimp catch will decrease by $1\% \times 174 \times 0.648 = 113 \text{ metric tons}$. With an average harvest of brown shrimp of 17,000 metric tons (2006 - 2009, NMFS), a one percent increase in Iowa corn causes a 0.66 percent reduction in brown shrimp catch, all else equal.

The effect of runoff and soil leaching is smaller. The average annual runoff of the Upper Mississippi River Basin is 23 cm/yr. This represents an additional $11.9 \times 23 = 273.7 \text{ kg / km}^2$ N added to the GOM, which increases the size of the hypoxic zone by 0.06 km² and decreases shrimp catch by 40 kg.

RESULTS

We consider five impact scenarios. The first three relate to an increase in the world price of corn; the last two relate to an increase in nitrogen intensity and runoff due to increased precipitation related to climate change. Results are summarized in table 1. Each scenario will have an impact from economic adjustments and from changes in nitrogen delivered to the GOM, which we try to decompose across scenarios. This section is meant to demonstrate the importance of modeling multiple ecosystem services within a river basin, highlighting how interactions and general equilibrium adjustments affect impact measures. The intent is not to measure the impacts of a particular event or policy. Such activities are more complicated than the scope of this paper allows and are highly dependent on calibration, elasticities, and parameter values (Whalley, 1975).

Table 1. Numerical Results

Scenario	(a)	(b)	(c)	(d)	(e)
GDP (% change)	.6	.6	0.5	3.6 E-6	0.-28
Corn output (% change)	98.5	98.5	1.1	1.2 E-5	0.2
Corn domestic price (% change)	.4	.4	.6	0	0
Corn labor employment (% change)	02.6	02.6	.3	1.7 E-5	0.3
Shrimp output (% change)	2.2	1.8	1.3	1.6 E-2	55
Shrimp domestic price (% change)	.7	.1	.7	0.03	0.03
Shrimp labor employment (% change)	0.7	1.6	.1	8 E-2	.9
Change in N applied of fields (mill kg)	578	0	6.5	-2 E-5	-1.7
Change in size of hypoxic zone (km ²)	16,900	0	0.1	0	3.6 E-4

Impacts of an Increase in Price of Corn

The price of corn on the world market doubled between June 2010 and June 2011. The increase in corn's world price makes MARB corn more competitive, causing the domestic market to expand. In our model, a doubling in the world price of corn (scenario a) causes domestic corn production to increase by 198 percent. As corn production increases, so does the use of nitrogen in the basin. Nitrogen increases by 578 million kg, of which 77 million kg eventually ends up in the GOM. The hypoxic zone increases by 16,900 km² (almost doubling). The increased size of the hypoxic zone increases the cost of ecosystem services to GOM shrimpers, reducing shrimping effort and harvest. Output in the shrimp sector falls by 2.2 percent. Shrimp represents a smaller portion of the MARB economy than corn, so basin-wide GDP increases 7.6 percent despite the extra nitrogen load.

The increase in the world price increases the value of benchmark output, increasing the scale of the economy. As corn expands, it draws factors of production from other areas of the economy. In this example, labor employed in the grain sector increases by 203 percent, and capital employed in the grain sector increases by 194 percent.

We re-run the analysis with a price increase but without an increase in the hypoxic zone (scenario b) and with an increase in the size of the hypoxic zone but without an increase in the price (scenario c). There is no noticeable difference in changes in GDP between the scenarios (a) and (b), though the loss to fishing is smaller in scenario (b). In scenario (b) fishing decreases by 1.8 percent. In scenario (c), the increased cost of shrimping causes both shrimp and corn production to fall. The result is a smaller hypoxic zone than would have been estimated ignoring general equilibrium adjustments in the economy. Comparing scenarios (a) - (c) shows the effects are not additive. There is a 1.8 percent decrease in shrimp output due to an increase in competition for factors (scenario b), a 1.3 percent decrease in shrimp output due to a increase in nitrogen (scenario c), and a 2.2 percent decrease in shrimp output when both occur (scenario a).

Impacts of Increased Precipitation and Runoff

A 2010 report on the effects of climate change in Iowa shows an 8% increase in precipitation statewide between 1873-2008 (Takle, 2011). Cedar Rapids saw a 32% increase in precipitation over the same period. The state also saw an increase in extreme precipitation events, leading to more annual flooding. Such changes are expected to cause denitrification of soils due

to saturation, increased soil erosion due to surface runoff, and increased nitrogen-nitrate runoff due to wider use of tile drainage.

We simulate the effect of increased precipitation by increasing per hectare use of nitrogen by 4 percent, which is equivalent to the per day loss of nitrogen due to soil saturation, and a doubling of runoff, which is a conservative estimate for flood years. These two changes make up scenario (d). In this scenario, the cost of utilizing ecosystem services in the shrimping industry increases, but the total impact is almost negligible. MARB GDP falls by 3.6×10^{-6} %. The impact is small because it does not affect any of the upstream resources that represent larger shares of the economy.

Because increased precipitation raises the cost of shrimping, other sectors expand, including corn production. Nitrogen in the GOM increases more than it would without general equilibrium adjustments. In scenario (e) we hold domestic prices fixed at equilibrium levels found in scenario (d) and set damages from nitrogen to zero. Increased costs to shrimping in scenario (d) leads to a relatively higher equilibrium price for shrimp than for corn. This leads to a large expansion of the shrimping sector and larger decline in corn production than occurred when shrimping was adversely affected.

CONCLUSION

We have considered impacts from environmental degradation when multiple sectors use ecosystem inputs as factors of production. Following degradation of the environmental input, industries substitute toward other factors like labor and capital, and the output mix changes to favor industries less dependent on the environmental input. These substitution possibilities keep economic losses lower than would have otherwise.

We applied our model to the Mississippi-Atchafalaya River Basin. We showed how increases in the price of corn in Iowa can affect shrimp harvest in Louisiana. In this example, the cost of utilizing ecosystem services in the shrimp industry caused factors to move out of the fishing industry, reducing the size of damages that would have otherwise occurred. We also considered scenarios where per hectare nitrogen runoff increased in corn farming due to increased precipitation. In these scenarios, the increased costs to shrimpers represented a loss of real economic resources. Corn output fell enough to decrease the total nitrogen runoff even though nitrogen intensity increased. The size of the hypoxic zone shrank, highlighting once again the importance of general equilibrium feedbacks.

Our results show how the level of ecosystem services available to an economy can determine its comparative advantage and its ability to adapt following loss of ecosystem services. This is why resource-rich economies are also generally resource-dependent economies. Adverse impacts to the environment will have larger impacts the more dependent the region is on its natural resources. A diversified economy is important to reducing the effects of negative shocks to ecosystem services.

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