INTRODUCTION

Statement of the Problem

With increasing demand for lands by all types of development in support of growing human populations, there has been an increasing pressure to develop marginally developable lands. In Florida, where estimates suggest that approximately 30% of the landscape is wetlands (Frayer and Hefner 1991), this pressure translates into potentially significant impacts to wetland ecosystems.

In the past century much of Florida's developed landscape was constructed on the most usable land, leaving wetlands and poorly drained flatwoods. Now, with developable land becoming more and more scarce, especially near rapidly growing urban centers, attention is shifting toward more marginal land. This shift in the direction of development is resulting in an increased pressure on wetlands.

There are many state and federal regulations that limit direct impacts to wetlands. However, as a result of increased demand for developable lands, agencies responsible for protecting wetlands are under pressure to permit development in and around wetlands. To offset losses of wetlands, state and federal agencies have instituted systems of mitigation. Mitigation in this context generally means the act of offsetting losses that result from the elimination of wetlands through development actions. While at times mitigation has included such practices as restoration of impaired wetlands or preservation, in this thesis mitigation has been more narrowly defined as construction of wetlands as replacement for those destroyed.

Early regulations associated with mitigation required that it take place on the site where the impacts occurred. However, as agencies have gained more experience, there has been a shift away from onsite and type for type mitigation to off site and, most recently, toward the creation of regional mitigation banks. Today, compensatory mitigation and mitigation banking are relatively common practices, yet there is no clear understanding of the environmental benefits and losses to society that result from these practices. In addition, regulations pertaining to mitigation are hindered by the lack of a clear and objective means of quantitatively determining appropriate mitigation ratios. As a result of those concerns, several questions arise. (1) How might the various properties and functions of wetlands be evaluated? (2) What are the relative values of wetlands? (3) What functions of wetlands are the most valuable? (4) What are the costs and benefits of wetland mitigation? (5) What is the best scheme for determining appropriate mitigation ratios?

All in all, what is needed is an assessment method that can determine the environmental values of whole systems. With such an evaluation, society could judge the costs, benefits, and trade-offs associated with wetland impacts and mitigation. Furthermore, by using the relative values of ecosystems more appropriate mitigation ratios might be determined.

In this thesis, the structural properties and main processes of several wetland and upland ecosystems were evaluated using emergy analysis techniques. The goal of the research was to determine relative values of wetland and upland ecosystem components and processes, and then to develop insight by comparative analysis related to costs and benefits of mitigation.

Review of the Literature

Ecosystems Valuations

Ecosystems have been conventionally valued on the basis of their monetary contribution to human society. For instance, salt marshes may be given a monetary value dependent upon the perceived profit from fisheries production, tourism, and recreation use. Forested wetlands may be evaluated on the basis of their marketable timber. These types of evaluations focus on ecosystem functions and storages that have a marketable value and can thus be sold as commodities such as fish or timber (Bell 1997). However, other non-marketable attributes of ecosystems remain ignored by these types of evaluations, such as water purification or wildlife habitat. In the literature, there are several approaches to valuating wetlands. These methodologies can be grouped into two main categories: (1) economic valuations from perceived monetary gains, (2) energetic valuations from ecosystem processes and pathways.

The most common type of economic valuation of non-marketable ecosystems services and natural capital is to assess an individual's willingness-to-pay for those services. This approach relies on human preferences and perceived gains from ecosystems to establish a "price" for non-marketable attributes (Costanza et al. 1997). While it is a widely employed method of estimating value of non-marketable goods and services, its shortcomings are also widely recognized (Ludwig 2000, Starrett 2000, Odum and Odum 2000). In fact, the willingness-to-pay method fails to accurately quantify ecosystem value from a scientific perspective, since it is based solely on people's preferences, not on the ecosystems' structural and functional components (Brown and Ulgiati, 1999). Bell (1997) identifies other methodologies, including the "land-price" analysis method, which estimates wetland values on the basis of the highest economic use that can be derived from the land, and the “replacement or substitution model”, which assesses wetland values by calculating how much it costs to restore destroyed or developed wetlands to their original state. The latter simply adds up costs for machinery, products, and human labor to carry out the project, and again ignores other valuable natural services provided by wetlands. A somewhat more simplistic methodology is the “opportunity cost of preservation model,” in which preservation of natural resources that cannot be monetarily evaluated is favored unless the value of the forgone development is “unacceptably” large (Batie and Mabbs-Zeno 1985). However, this method fails to provide any quantitative guidelines for what is considered “unacceptably” large, and while it considers in depth the economic values of the possible development scenarios, it fails to account for the ecosystem values lost from wetland destruction. All of these economic valuations are only appropriate for recognizing services from ecosystems that have a market, (i.e. fish or timber sold on the market) and result in subjective estimations of the many other services ecosystems provide to society, such as infiltration, water storage, increased water quality, and wildlife value.

The importance of integrating ecological and economic values of ecosystems was recognized by Odum (Odum 1996). Energetic evaluations of ecosystem processes and pathways emphasize energy networks and processes within ecosystems. Gosselink et al. (1974) employed such a methodology in estimating the value of one acre of tidal marsh wetland. Their calculations involved estimating the economic value of the wetland products and services (fisheries, aquaculture potential, and waste treatment), as well as the life support value as a function of energy flow (gross primary production times energy/money conversion ratio). The Gosselink et al. (1974) study resulted in a value of $82,000/ acre of tidal marsh. This value can be compared to a more traditional economic value for a saltmarsh calculated by Bell (1997) that ranged between $981 and $6,471. The huge difference in the reported values is probably due to the fact that Bell (1997) attempted to place an economic value on the contribution of wetlands to recreational fishing alone, without taking into account other important services of saltmarshes, such as gross primary production.

Energetic valuations and emergy. Odum developed a method of valuation that was based on the total amount of energy of *one* kind used directly or indirectly (and through all pathways) to make a product or service (Odum and Odum 2000). The concept was later termed emergy, signifying “energy memory” (Odum, 1996). The emergy accumulated in an ecosystem increases as it matures and it is calculated by multiplying the energy storages by their transformity. Transformity, or the solar emergy required to make one joule of a service or product (Odum 1996), is calculated by dividing a product’s solar emergy by its energy. Transformity increases as processes become more refined, and it thus can be a measure of maturity and efficiency. For example, the biomass of a mature, old growth forest will have a higher transformity than the one of a younger forest, since its emergy has been accumulating for a longer time.

Compensatory Mitigation and Mitigation Banking

Wetland mitigation has become an indispensable tool in the implementation of the “no-net-loss” policy for wetlands, which stemmed from Section 404 of the Federal Clean Water Act. In its broadest definition, mitigation refers to the avoidance, minimization, and elimination of negative impacts to wetlands, or compensation by replacement or substitution of equivalent wetland value in order to achieve “no-net-loss” of wetland function. However, “equivalent wetland value” and “wetland function” are not explicitly defined and are thus subject to personal interpretation. Much of the literature on wetland mitigation reports on the success or failure of mitigation sites (Zedler 1996,Brown and Lant 1999, Brinson and Rheinhardt 1996), while there are very few studies that address the issue of how to quantify a wetland’s contribution to society (Bardi and Brown 2001).

Compensatory mitigation, which is the replacement of impacted wetlands by creating new ones, has had limited success due to difficulties in implementing regulations, monitoring, and assessing the long-term viability of the numerous and small-scale mitigation sites. To address this concern, there has been a move in recent years towards the use of mitigation banks as an alternative to the “postage-stamp” wetland creation. Mitigation banks are often large-scale projects that incorporate wetland creation, restoration, enhancement or preservation within regionally significant lands. Unlike compensatory mitigation, which occurs simultaneously or after wetland impacts have already taken place, mitigation banks are established in advance by a third party (mitigation banker), who then sells the wetland credits to future developers whose projects impact wetlands.

Wetland mitigation banks offer several advantages and disadvantages: first, they consolidate small-scale projects into larger tracts of land, thus reducing permitting and monitoring requirements by federal, state, and local agencies. Second, they create the wetland credits in advance of impacts, thus ensuring the achievement of no-net-loss, and are required to invest in long-term financially secured management plans, usually by donating the banks to nature preserves or state agencies once they sell out. Finally, such large-scale projects can be more economically cost effective, thus reducing overall waste of human and material resources. On the other hand, the money-making enterprise of mitigation banking has attracted a lot of skepticism as well, and critics of mitigation banks question whether it is ecologically sound to shape the landscape by concentrating wetlands in one location at the expense of smaller, isolated wetlands that dot the landscape.

Mitigation ratios. Whether compensation occurs through compensatory mitigation or mitigation banks, a mitigation ratio is used to calculate how many acres of compensation are required for a specific wetland impact. This mitigation ratio represents the value of acres compensated per acres converted of a particular ecosystem (Brown and Lant,1999). Because the current system lacks clearly defined functional methodologies for assessing wetland value, mitigation ratios are assessed qualitatively and are dependent on several criteria: the perceived value of the ecosystem to be impacted, the ease of replacement, and the perceived recovery time needed for the constructed ecosystem to reach predefined success criteria (Zedler, 1996). The acres compensated must not necessarily be in the form of newly constructed ecosystems, but can also extend to restoration, preservation and enhancement of already existing ecosystems. Typical mitigation ratios range between 2:1 for restoration, 3:1 for creation, 4:1 for enhancement, and 10:1 for preservation, that is, for 1 acre of wetland impacted, 2 acres have to be restored while if the new ecosystems are created, for each acre impacted 3 acres would have to be constructed. However, because each wetland is assessed on a case by case basis, there is much variability in their use.

Systems Modeling

Simulation models of ecosystems are useful tools to make predictions of ecosystem behavior from data collected in the field. Most models have focused on the dynamics of succession (Odum 1967, Burns 1970, Regan 1977), or prey-predator relationships and competition for scarce resources (Wiegert 1974).

Tilley (1999) explored new theories in computer simulation by modeling the energy, emergy, and transformity of forest biomass, organic matter, and saprolite in the Coweeta watershed. Until then, energy quality had been analyzed using emergy analysis at a particular point in time. Tilley's simulation showed that energy, emergy and transformity all increased over time, with the physical components (energy storages) reaching their maximum value at a faster rate than both emergy and transformity. Emergy accumulation and transformity, in other words, the quality of ecosystems, is not only a function of the energy storages, but also of the time it takes to accumulate value.

Plan of Study

This thesis focuses on quantifying ecosystem value and calculating mitigation ratios among different ecosystems. First, emergy evaluations were conducted for six major Florida ecosystems and their components: depressional cypress dome, shrub/scrub wetland, freshwater marsh, floodplain forest, mesic hardwood forest, and pine flatwoods. Comparisons between systems and their components were then made.

Second, the energy costs of constructing a forested wetland were evaluated. Third, a dynamic simulation model of an aggregated ecosystem was used to evaluate the energy, emergy, and transformity of biomass and organic matter in forested wetlands. Results from the simulation model were used to investigate the time needed to recover the initial investment of wetland construction/creation to explore the question of whether created wetlands are sound investments for the future of Florida. Finally, these analyses and the resulting data were used to study mitigation options and overall policy with recommendations for mitigation ratios and timing.

METHODS

The following methods are divided into several sections, beginning with a description of the ecosystem types that were evaluated. The second and third sections, “Emergy Evaluation of Ecosystems” and “Emergy Evaluation of a Constructed Forested Wetland,” provide details of methods used to evaluate data gathered from the literature on Florida ecosystems and a constructed wetland. The fourth section, “Simulation Modeling,” presents the methodology applied to the computer simulation models.

Descriptions of Ecosystem Types

Six Florida ecosystems were evaluated: four wetland ecosystems (cypress dome, shrub/scrub wetland, freshwater depressional marsh, and floodplain forest), and two upland ecosystems (a mesic hardwood forest and pine flatwoods). These ecosystems make up approximately 97% of the freshwater wetland area and 87% of the forested upland area in the current landscape of Florida (Florida Geographic Data Library 2000). Descriptions of each ecosystem, summarized from Brown et al. (1990) and Brown and Schaefer (1988), follow:

Cypress domes--Cypress domes are found throughout Florida as small depressions most often within pine flatwoods. These small depressions are called cypress domes due to the domed shape of the trees when viewed from the side. Cypress domes are one of the most common forested wetlands in north central Florida. Standing water occurs in cypress domes from 50%-90% of the time. Pond cypress (*Taxodium ascendens*) is the dominant canopy specie ther canopy species include black gum

(*Nyssa sylvatica*), pond pine (*Pinus serotina*), slash pine (*P. elliotti*i), red maple (*Acer rubrum*), and one or more of the bay species, such as red bay (*Persea borbonia*), sweet bay (*Magnolia virginiana*), and loblolly bay (*Gordonia lasianthus*). The understory of these ecosystems is often diverse. Dominant understory species in cypress domes include fetterbush (*Lyonia lucida*), wax myrtle (*Myrica cerifera*), dahoon holly (*Ilex cassine*), buttonbush (*Cephalanthus occidentalis*), Virginia willow (*Itea virginica*), and myrtle-leaf holly (*Ilex myrtifolia*). Vegetation at ground level is often sparse and is a function of the wetland hydroperiod. The most frequent herbaceous species are lemon bacopa (*Bacopa caroliniana*), Virginia chain fern (*Woodwardia virginiana*), coinwort (*Centella asiatica*), redroot (*Lachnanthes caroliniana*), and various graminoids (e.g. *Panicum* spp.). The ecotone consists of transitional species such as wax myrtle, gallberry (*Ilex glabra*), high-bush blueberry (*Vaccinium* spp), fetterbush (*Lyonia lucida*), greenbriar (*Smilax* spp.), blackberry (*Rubus spp.*), muscadine grape (V*itus rotundifolia*), and yellow jessamine (*Gelsemium semprevirens*).

Shrub- scrub wetland--The shrub-scrub wetland can be relatively diverse or dominated by only a few species depending on hydrology and fire regime. When diverse, these ecosystems are dominated by both woody shrubs and herbaceous wetland vegetation. Common woody shrub species include: Carolina willow (*Salix caroliana*), fetterbush, wax myrtle, dahoon holly, buttonbush, and Virginia willow, all occurring at varying dominance depending on the hydroperiod. Many of the same herbaceous species found in marshes are also found in the shrub-scrub wetland, but at much lower densities. Common herbaceous species include lemon bacopa, sawgrass (*Cladium jamaicense*), bullrush (*Scirpus* spp.), Virginia chain fern, coinwort, and panicum. In some instances, the scrub-shrub wetland is dominated by only one or two woody species and has higher densities of herbaceous vegetation. The ecotone consists of transitional species such as such as wax myrtle, stagger-bush (*Lyonia ferruginea*), gallberry, fetterbush, and vines such as greenbriar, blackberry, muscadine grape, and yellow jessamine (Brown and Schaefer, 1988; Brown et al. 1990).

Depressional herbaceous marsh--Shallow marshes occupy low topographical areas and are common throughout central Florida as interspersed ecosystems in pine flatwoods matrix. Shallow marshes are typically circular in shape and vary from small (less than one half acre) to large (tens of acres). Depth of standing water during the rainy season is typically 25 to 55 centimeters. Most flatwoods marshes are relatively oligotrophic, with the main source of nutrients being rainfall and surface drainage from surrounding watersheds. The ecotone of these systems often consists of mesic oak communities, pine flatwoods, or cypress domes. Shallow marshes are common where inundation is frequent and depths of inundation are less than 0.5 meters. Marsh vegetation consists of a diversity of species. In the grassy shallow marshes, species that consistently occur and are often dominant include panicum, St. John's Wort (*Hypericum spp.)*, yellow-eyed grass (*Xyris* spp), marsh fleabane (*Pluchea* spp), redroot, and pickerel-weed (*Pontedaria cordata*). Also common occurring species are sawgrass, spikerush (*Eleocharis spp.*), soft rushes (*Juncus spp.).* Broad-leaved marshes, often referred to as flag ponds, are marsh communities that exhibit deeper inundation, longer hydroperiods, and deep accumulations of organic matter. Dominant species include pickerelweed, arrowhead (*Sagittaria* spp.), fire flag (*Thalia geniculata*), bulrush (*Scirpus* spp.), and cattail (*Typha* spp.) (Brown and Schaefer, 1988; Brown et al. 1990).

Floodplain forests--Floodplain forests make up approximately one-third of Florida's swamps and are found predominantly in north Florida. They occur along creeks, rivers, and sloughs and are often referred to as bottomland hardwood forests. Although there are six types of river swamps in Florida, depending on the river's energy, water quality, and location in the landscape (Wharton et al. 1977), this analysis focuses on Blackwater floodplain forests. Blackwater rivers and creeks exhibit much slower flow rates than alluvial rivers and thus carry little alluvium to the surrounding floodplain. Occasionally an impermeable soil layer beneath the floodplain also contributes to standing water (Ewel 1990). Canopy species include white ash (*Fraxinus caroliniana*), bald cypress, red maple, swamp blackgum (*Nyssa sylvatica* var. *biflora*), water hickory (*Carya glabra*), and hornbean (*Carpinus caroliniana*), to name a few. Understory shrubs include dahoon holly, wax myrtle and buttonbush. The herbaceous layer is often diverse with cinnamon fern (*Osmunda cinnamomea*), Virginia chain fern, pickerelweed, lizard's tail (*Saururus cernuus*), and many others. Floodplain wetlands are often bordered by mesic hardwoods and flatwoods in slightly higher elevations.

Mesic hardwood forests--This community is found throughout most of the Southeastern Coastal Plain but coverage is restricted to areas shielded from fire. These forests therefore do not occur extensively, but rather as narrow bands of vegetation bounded by sandhills and flatwoods on upgradient slope and bottomland forests down gradient. This community is a diverse and complex ecosystem characterized by large evergreen trees such as live oak (*Quercus virginiana*), Southern magnolia (*Magnolia grandiflora*), loblolly bay (*Gordonia lasianthus*), intermixed with deciduous tree species such as sweet gum (*Liquidambar styraciflua*), red maple, water oak (*Quercus nigra*) and laurel oak (*Quercus laurifolia*) (Odum and Brown 1975). Pines such as slash (*Pinus elliottii*) and loblolly (*Pinus taeda*) are often present at low densities. A variety of factors influence the vegetation composition of mesic hardwood forests, such as organic matter, exchangeable cations, pH, and nutrient availability. For example, evergreen species occur more often on nutrient poor sites as they have a more closed nutrient cycle compared to deciduous species.

Mesic hardwood forests are characterized by greater diversity, vegetation layering, and greater accumulation of organic matter than the adjacent pinelands (Platt and Schwartz 1990).

Pine flatwoods--Pine Flatwoods cover as much as 50% of the Florida peninsula (Edmisten 1963). Flatwoods, as the name indicates, are generally located in areas of little relief in somewhat poorly drained to very poorly drained soils (Edmisten 1963). They are characterized by open canopies composed of one or more pine species such as pond pine (*Pinus palustris*), slash pine, and loblolly pine. Understory species include a variety of shrubs, graminoids, and herbaceous plants such as wax myrtle, saw palmetto (*Serenoa repens*), gallberry, staggerbush, fetterbush, blueberry, and wiregrass (*Aristida beyrichiana*). Vegetation composition is influenced by factors such as soils, drainage, and hydroperiod. Wet flatwoods are seasonally inundated, occur on sandy soils, and are composed of slash pine, pond pine, and cabbage palm with a hydrophytic understory that includes wax myrtle and fetterbush. Mesic flatwoods are prevalent in drier sites and have canopies of slash and longleaf pine, with an understory of gallberry, rusty lyonia, and wiregrass (Abrahmson and Hartnett 1990). Pine flatwoods have been described as the matrix tying together different types of vegetation, such as wet prairies, marshes, swamps, sandhills, and scrubs (Edmisten 1963). Pine flatwoods are fire maintained ecosystems.

Emergy Evaluation of Ecosystems

Emergy evaluations were conducted using emergy terminology and symbols as introduced by Odum (1996). Appendix A summarizes emergy terminology (Table 9) and symbols (Figure 31) used throughout the study.

System Boundaries and Evaluated Parameters

Figure 1 illustrates the system boundary for the depressional wetland evaluations and depicts the various parameters included in the evaluations. The underlying geologic structure was included within the system boundary. For illustrative purposes, half the wetland is shown as a forested wetland and the other half as a marsh. The evaluations were done for 1 hectare (approximately 2.5 acres) of typical wetland.

Figures 2, 3 and 4 are generalized systems diagrams of a depressional wetland, a riparian forest, and an upland ecosystem, respectively. Figures 2, 3 and 4 show the main driving energies, environmental services, and storages (natural capital) that were evaluated for each of the ecosystems. The dominant driving energies of the ecosystems are: sunlight, wind, rainfall, run-in (surface water runoff from the surrounding watershed), and the emergy contribution from geologic processes. Mesic hardwood forests and pine flatwoods are not net sinks of run-in (Sun 1995), and therefore it does not appear as an input in Figure 4. The main material storages of biomass, peat, water, and geomorphic structure were evaluated for the four wetland ecosystems, while only biomass, organic matter, and water were evaluated for the two upland ecosystems.

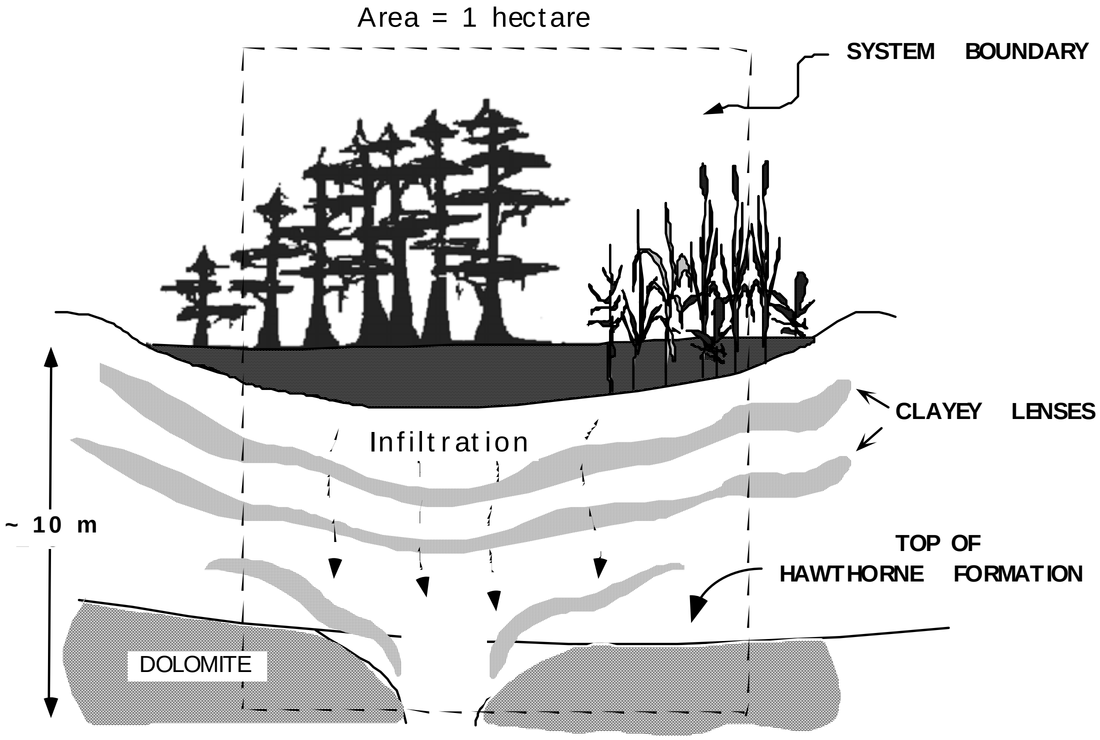


Figure 1. System boundary of a depressional wetland.

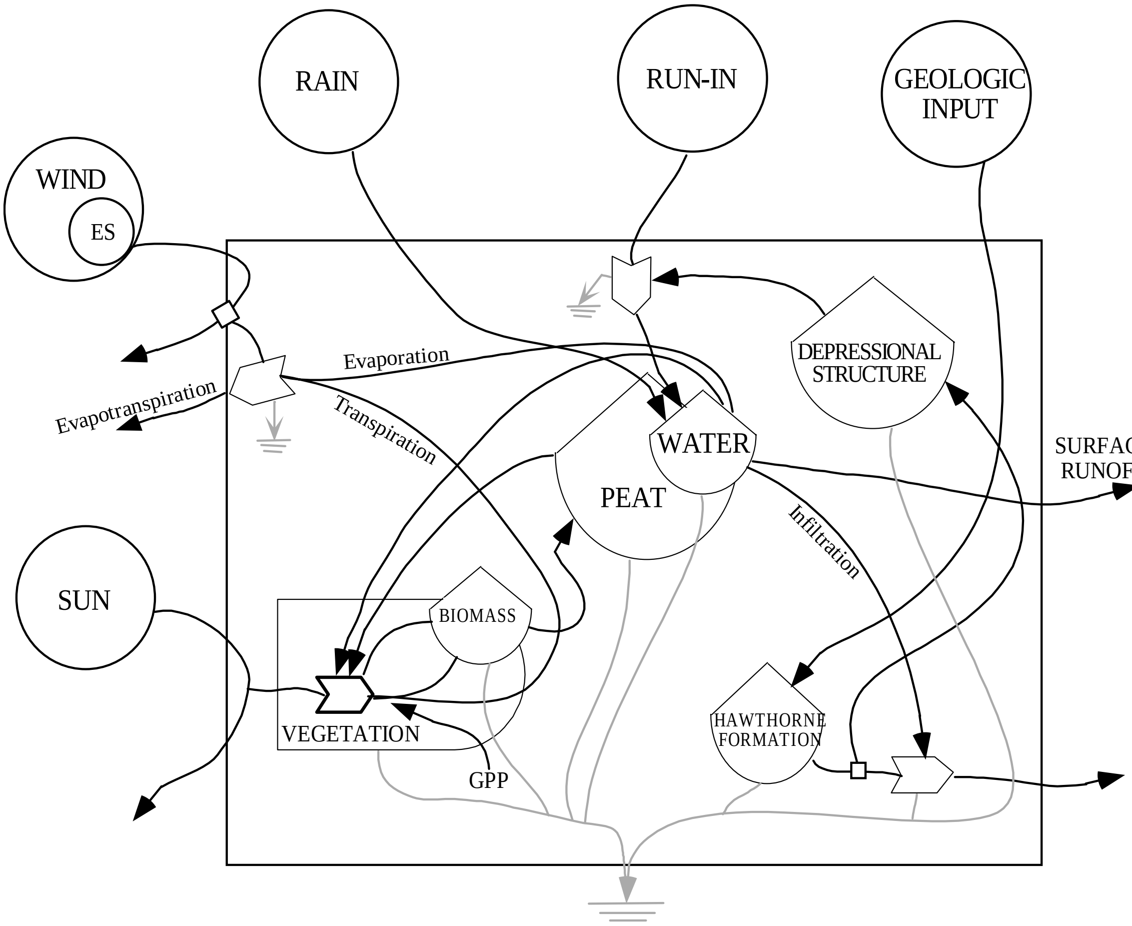


Figure 2. System diagram of a depressional wetland. GPP = gross primary production; ES = saturation deficit.

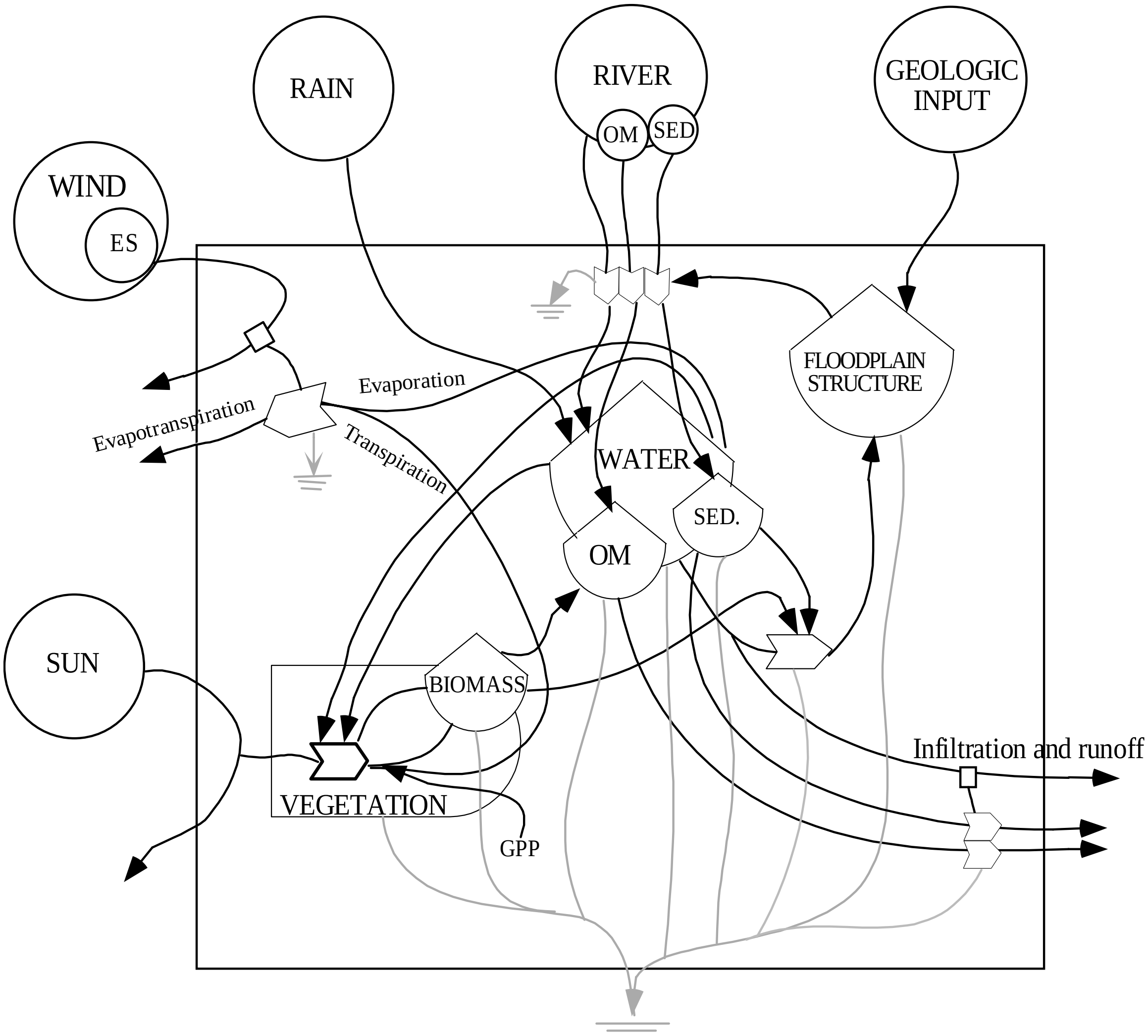


Figure 3. System diagram of a floodplain forest. GPP = gross primary production; O.M. = organic matter; SED = sediment; ES = saturation deficit.

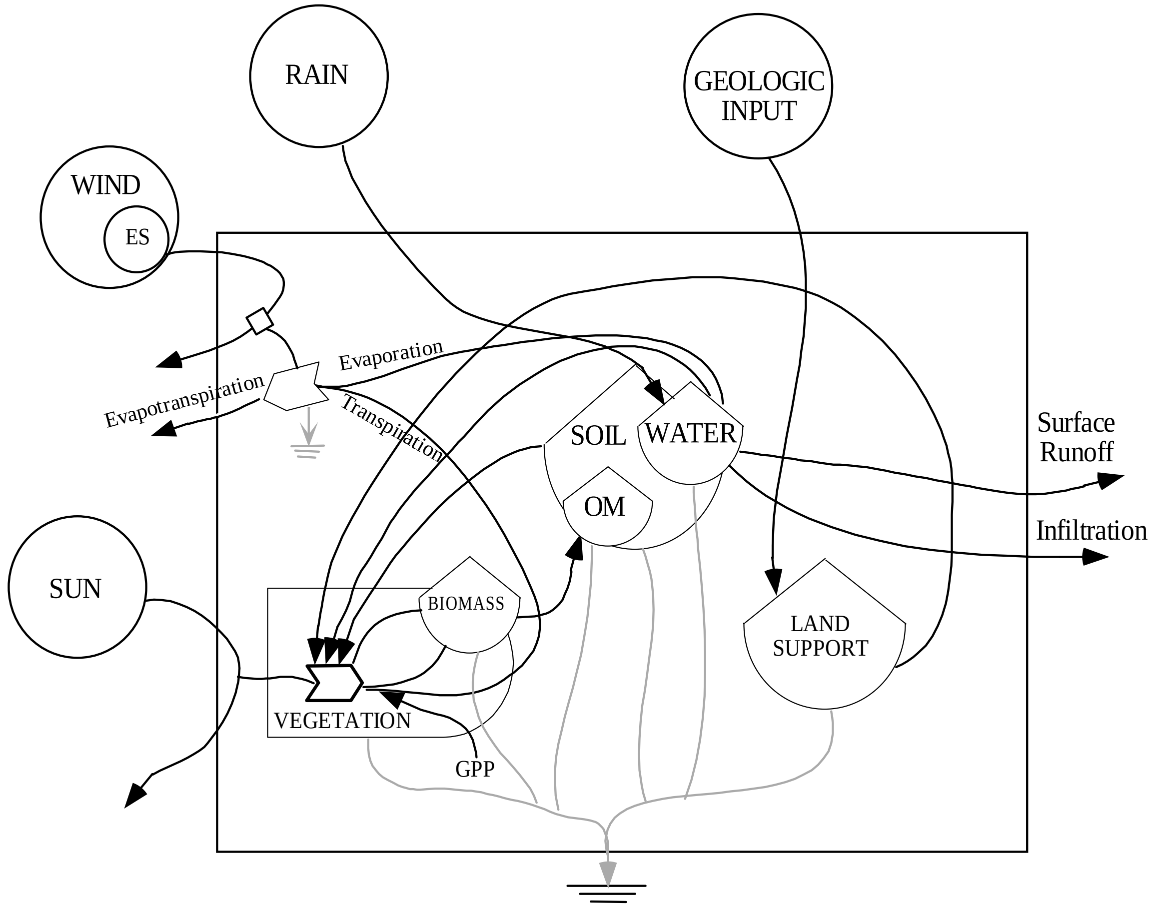


Figure 4. System diagram of an upland ecosystem. The upland ecosystems included mesic hardwood forests and pine flatwoods.

Driving energies and ecosystem storages interact in several processes that generate ecosystem services. Three services (ecosystem functions) of these ecosystems were evaluated: (1) transpiration of water, (2) gross primary production (GPP), and (3) water recharge (infiltration).

Mass and Energy Flows

Data from the literature were used to evaluate the mass and energy flows for each of the ecosystems. Sunlight, wind, and rainfall were taken as average conditions for the North Central Florida location. Run–in (surface runoff into the wetland) for forested and scrub/shrub wetlands was cited from Heimburg (1984) and Schwartz (1989) respectively. A runoff coefficient of 0.35 and a 1:1 watershed to wetland ratio was assumed for run-in to the marsh. Stream overbank flow, which represents the major portion of run-in water for the floodplain forest, was calculated from estimates of Brown (1978), and water budget equations. Mesic hardwood forests and pine flatwoods are not net sinks of run-in (Sun 1995).

The geologic input to the forested wetland was estimated as 0.275 mm of limestone erosion per year (Odum 1984). The amount of limestone eroded from the interaction of acidic waters leaching through the underlying limestone creates and maintains the wetland depression. The geologic input to shrub-scrub and marsh wetlands was assumed to be proportional to infiltration rates compared to the forested wetland: 78% and 9% less than the estimated value of the forested wetland for the shrub-scrub and marsh wetlands respectively. The geologic input to the floodplain ecosystem and the mesic hardwood forest and pine flatwoods ecosystems was assumed to be equal to the average limestone erosion of Florida, or 10 mm every 1000 years as estimated from

Odum (2000). The floodplain structure is also maintained by the constant work of the stream channel and overbank flow, and the shape of stream channels and their floodplains is related to stream power (Gordon et al. 1992). For this reason, the stream geopotential, which describes a stream's erosive capacity, was also used to quantify the geomorphic input to the floodplain ecosystem and was added to the geologic input necessary to maintain the land support.

While five driving energies were evaluated, (sun, wind, rain, run-in and geologic processes), these flows are all co-products of the world process. Therefore, globally the emergy required for each is the same (Odum 1996). Adding the five driving energies would erroneously result in double counting the emergy required to support the system. In order to determine the driving emergy of a particular system, Odum (1996) suggests using the largest of the geobiospheric inputs. Therefore, total driving emergy for the six ecosystems was calculated to be the sum of transpiration (water use, rather than water input) and geologic input, and river geopotential was also added to the floodplain forest.

Transpiration is the use of water for biological production while geologic inputs result from the erosion of limestone built historically. Similarly, for the floodplainforest, the work of stream geopotential over time contributes to the structure of the floodplain. Geologic input of emergy can be added to present day annual emergy use without double counting since the limestone that is eroded is geologic contribution from a geologic storage built long ago.

Ecosystem Services. GPP was estimated from the literature by summing net primary production (NPP) and community respiration. The annual emergy driving GPP was taken as the sum of transpiration and geologic input (and river geopotential for the floodplain forest). Rates of transpiration and infiltration were taken or estimated from the literature and transformities were calculated as the weighted average of the transformities of rainfall and run-in for all ecosystems.

Ecosystem Storages. Main storages evaluated included: biomass, peat or soil organic matter, water, and geomorphic structure. The emergy of ecosystem storages was calculated by multiplying the annual emergy required to make the storage by its turnover time. Energy and/or mass values for each storage were obtained from the literature.

Geomorphic structure, the basin structure found in depressional wetlands and the floodplain channels in riparian wetlands, is constantly maintained by the limestone erosion beneath the depressions or by the constant work of the stream. This structure is unique to the different types of wetlands, and indirectly supports wetland vegetation by concentrating run-off into the depressional wetlands or the floodplain landform.

Basin structure was calculated based on the amount of eroded material in the underlying limestone. Odum (1984) calculated that 1818 years are required to generate a 50 cm deep depression beneath cypress wetlands based on a 0.275 mm/year erosion rate of limestone. The emergy of the basin structure, then, is the annual driving emergy multiplied by 1818 years. Similarly, the emergy of shrub-scrub and marsh wetland basin structure was calculated based on the amount of material eroded and the number of years required.

Floodplain structure was calculated by estimating the mass of channel and levee displaced (Figure 5). This was calculated by multiplying the volume of displaced sediments by the bulk density of the sediments, or 1.2 g/cm^3. Turnover time of the floodplain was estimated as the time required for the stream channel to move across the floodplain (Figure 6). This was estimated to be approximately 1000 years. The emergy of this structure is therefore the annual driving emergy multiplied by the time required to create the structure.

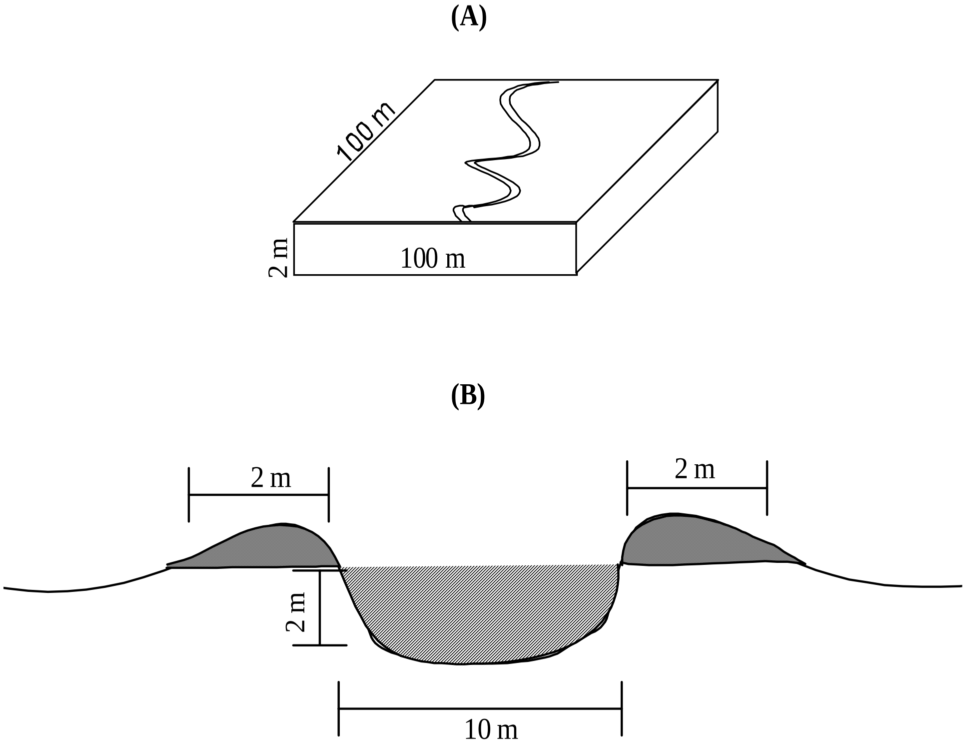
Mesic hardwood forests and pine flatwoods are not characterized by unique structures such as basins or floodplain channels. The land support (structure) beneath upland ecosystems is replenished yearly by equal rates of erosion and uplift. The same land support exists beneath depressional wetlands and floodplain ecosystems, however its contributions are negligible compared to the emergy needed to create wetland basin or floodplain morphology. Therefore, the storage of land support was not calculated for the upland ecosystems since the structure is not unique to those systems.

Calculation of Transformities

Transformities for driving energies of sunlight, wind, chemical potential energy of rain, and geologic input were taken from Odum (1996). The transformity of stream water (chemical potential) was taken from Buenfil (2000). The one remaining source, chemical potential of run-in, was calculated by multiplying the transformity of rain by the appropriate rain:run-in ratio for each ecosystem.

Transformities for ecosystems services of transpiration, infiltration, and gross primary production (GPP) were calculated from the annual driving emergies. A weighted average of rainfall and run-in was used to calculate the transformities for transpiration, infiltration, and water storage, using the rationale that these flows are a mixture of the two water inputs (Figure 7).

The emergy driving GPP was the sum of water used (transpiration) and geologic input (as well as stream geopotential for the floodplain forest). The rationale of using



(C)

Channel Mass = Width * Depth * Length * Sinuosity
= 10 m * 2 m * 100 m * 1.2
= 2400 m^3
Levee Mass = 2 levees * height *width * length * sinuosity
= 2 * 0.3 m * 2 m * 100 m * 1.2
= 144 m^3
Total Mass = 2544 m^3
Bulk Density = 1.2 g/cm^3
Mass = 3.05 E+9 g
Total driving emergy = Sum of transpiration, geologic input and river geopotential
= 3.97 E+15 sej/yr

$$\text{Emergy/gram} = \frac{(3.97\text{ E+15 sej/yr} * 1000)}{3.05\text{ E+9}}$$

= 1.29 E+09 sej/g

Figure 5. Boundary of Floodplain Ecosystem (A), with cross-sectional dimensions of channel and levees (B), and calculations of mass displacement (C).

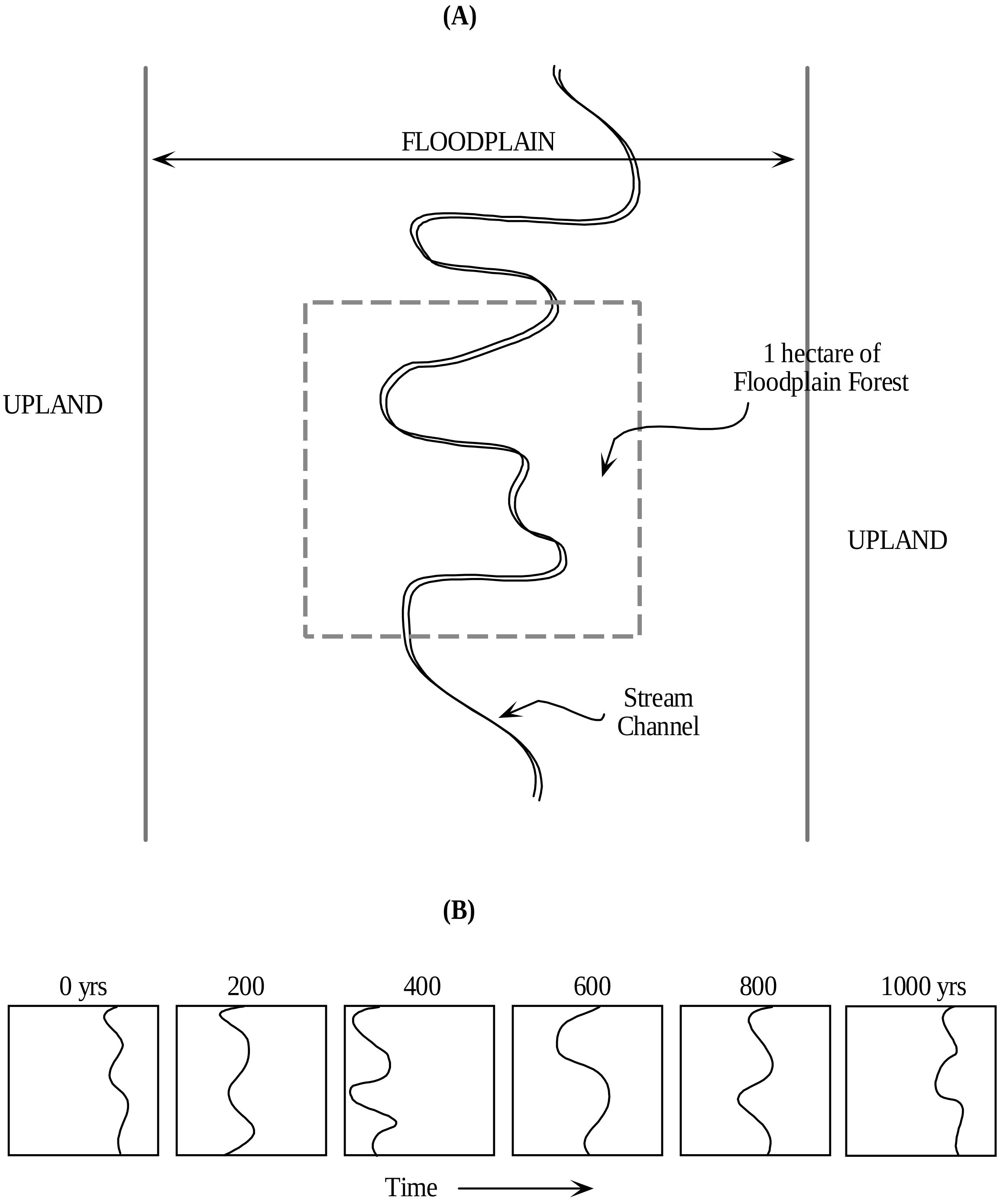


Figure 6. Schematic of floodplain ecosystem structure showing the 1 hectare area evaluated (A). The turnover time of the floodplain is illustrated in (B), where each box represents a 200 year migration of the stream channel, completing the entire cycle across the floodplain and back again in an estimated 1000 years.

both is that transpiration is required to drive biological processes and the limestone that is eroded is geologic contribution from a geologic storage built long ago. Both the biologic and geologic processes are coupled and are required for GPP. The transformity was calculated as the sum of the annual water use and contribution from geologic input divided by the energy of annual GPP.

Transformities for storages of the six ecosystems were calculated using the emergy driving the systems, except for the transformity of water storage, which was assumed to be a weighted average of rainfall and run-in (Figure 7). Live biomass was the sum of all live above ground biomass including trees, shrubs and understory vegetation. The transformity for biomass was calculated by multiplying annual emergy inputs (sum of transpiration and geologic input) by the turnover time of the biomass, and subsequently dividing by the energy of standing stock..

Soil organic matter results from the accumulation of un-decomposed plant matter. Turnover time was calculated by dividing the organic matter storage by the accumulation rate, which was derived by subtracting decomposition from litterfall (Dighe 1977). Emergy of the peat storage was calculated as the annual emergy input to the ecosystem multiplied by turnover time of the peat storage. Dividing the result by the energy content of the soil storage yielded the transformity.

Transformity of basin structure in the cypress dome, shrub/scrub, and marsh was calculated by dividing the emergy required to create the depression (annual emergy inflow multiplied by time for development) by the mass of the displaced limestone. The transformity of the floodplain structure was calculated using the same rationale, thus,

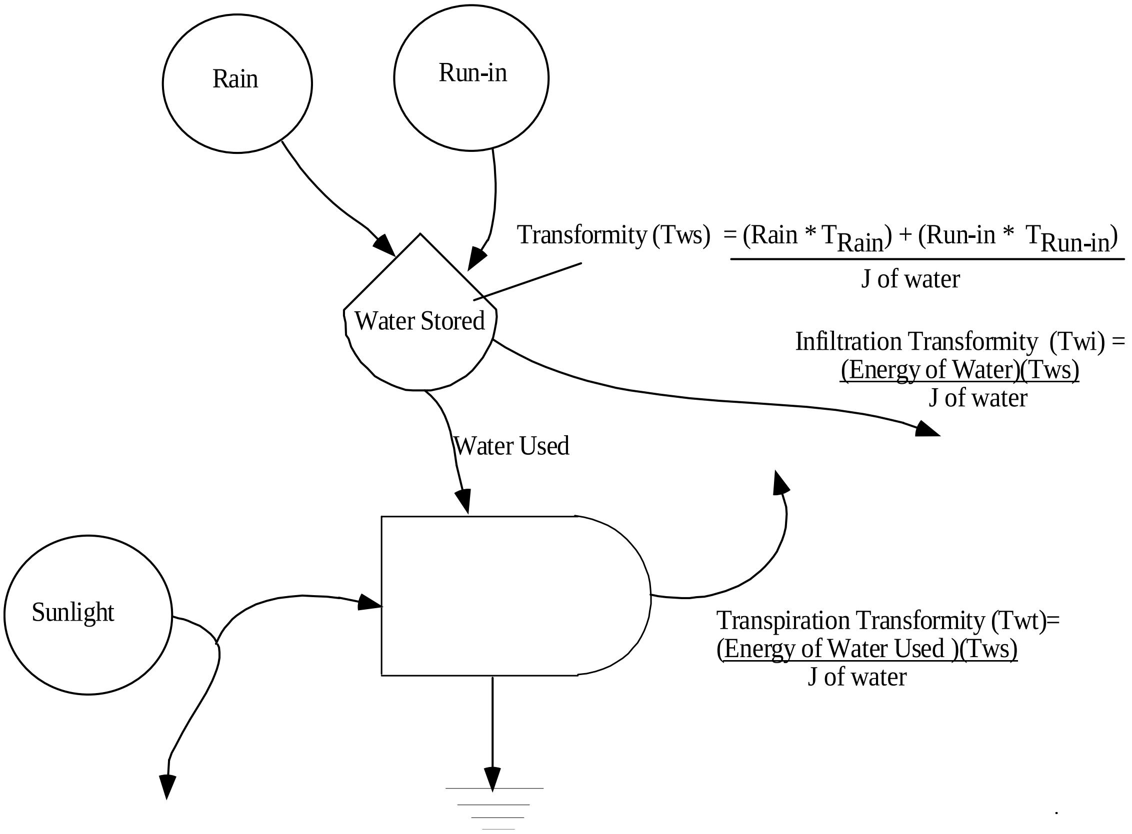


Figure 7. Diagram of transformity calculations for water stored, infiltration, and transpiration.

Emdollar Evaluation

For comparative purposes and to provide units more familiar to the public, emergy values were expressed as emdollars. Emdollars were calculated by dividing the emergy value of environmental services and natural capital by the emergy/money conversion ratio for the USA economy in 2000, which was equal to 0.96E+12 sej/$. The emergy/money ratio for 2000 was obtained using methodology employed by Odum (1996), and data from the U.S. Statistical Abstract (2001). The emergy money ratio is calculated by dividing the total emergy used in driving the U.S. economy by the Gross National Product (GNP) of the United States. Figure 8 shows emergy money ratios from 1980 to 2000. This ratio expresses the amount of emergy required per dollar of circulation. By dividing emergy flows and storages of the ecosystems by the emergy money ratio, the flows and storages are equated with the amount of currency they could drive in circulation.

Emergy Evaluation of a Constructed Forested Wetland

Constructed wetland projects can be divided into three main stages: first, a wetland ecologist with a consulting firm performs a preliminary site selection. Elevations of the property and surrounding wetlands are surveyed to use as template for the creation and design of the constructed wetland. Second, upon completion of the necessary surveys and permitting paperwork, construction begins. The site is cleared of the existing vegetation, excavated, contoured, and when the time and/or hydrology are favorable, planted with desired vegetation. Lastly, several success criteria stipulated in the permit application are monitored for an average of 3 years. Ecological data is collected annually to ascertain compliance with the success criteria, and annual

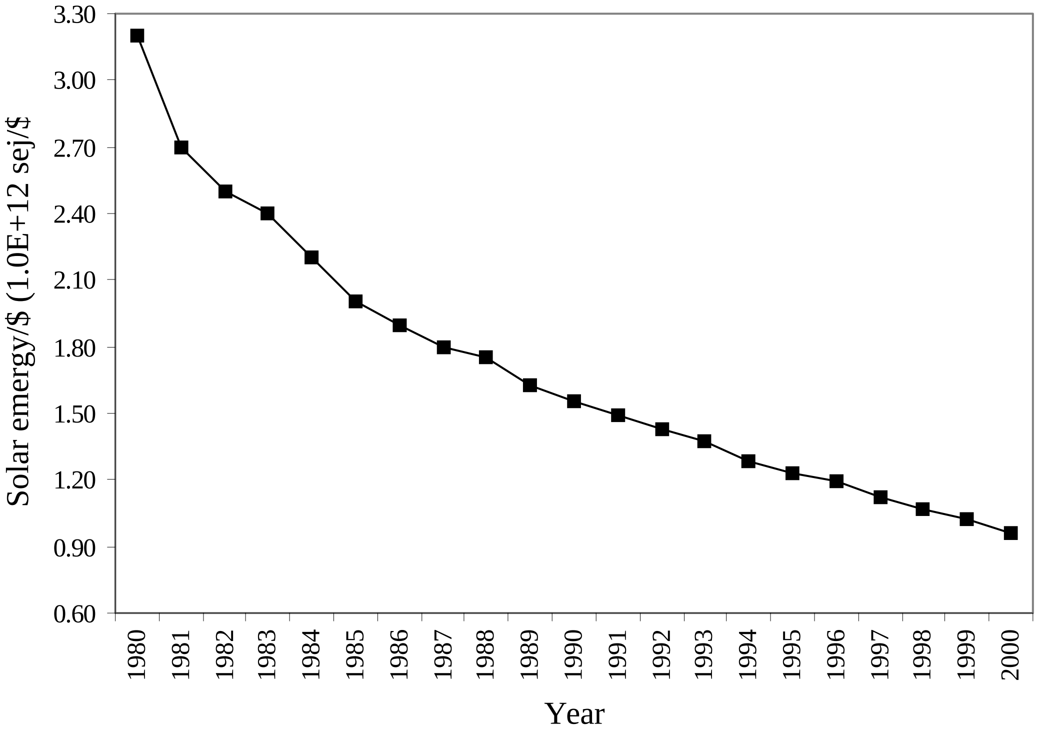


Figure 8. Emergy per dollar (sej/$) of the United States from 1980-2000. Values from 1980-1993 taken from Odum (1996), while from 1994-2000 calculated using data from the U.S. Statistical Abstract (2001) and the same methods employed by Odum (1996).

monitoring reports are submitted to the appropriate agencies. Exotic and nuisance species are manually removed or sprayed when needed. The mitigation site is considered successful when the following parameters have been achieved:

1) 80% survival of planted trees
2) At least 80% cover of herbaceous species
3) Less than 10% cover of exotic and nuisance species
4) Hydrologic conditions that conform to those observed in adjacent natural wetlands.

Data from a newly constructed forested wetland in North Florida were used to evaluate the inputs necessary to create a wetland in order to calculate environmental costs and benefits of wetland creation. The entire mitigation consisted of 5.26 ha of constructed forested wetland and 2.4 ha of freshwater marsh. Only the forested wetland was used for the evaluation since the marsh was not completed. Costs were prorated to eliminate costs associated with marsh construction.

Extensive groundwork was done on site. Though the area was already several feet below grade, elevation surveys revealed that even lower elevations were necessary to support wetland vegetation with longer hydroperiods. Approximately 100,000 cubic meters of fill were removed from the site and stock piled on a mound next to the created wetland. No donor topsoil was laid in the forested wetland area. Instead, raised beds were constructed to provide more aeration for the seedling root zone. Construction costs for the forested wetland were approximately $122,000.

Vegetation planting occurred on January 21, 2002. The site was partially flooded and soils were saturated. Sixteen people participated in the planting. Over 8,800 seedlings of eight different species were planted. Seedlings averaged 25 cm in height. Fifty-six percent of seedlings were pond cypress, while the remaining 44% was shared by blackgum, red maple, dahoon holly, white ash *(Fraxinus pennsylvanica)*, silver bay *(Magnolia virginiana)*, sweetbay, and river birch *(Betula nigra)*. Total plant costs were approximately $4,600.

Figure 9 is a generalized systems diagram of a constructed wetland ecosystem showing the main driving energies and purchased inputs from the economy that were evaluated. Sunlight, wind, and rainfall were again taken as average values for North Central Florida. Inputs from the economy included construction costs, imported vegetation, fertilizer, and human labor. Additionally, environmental losses of natural capital, such as biomass from the cleared vegetation and organic matter, were also added to the costs of construction. Monitoring efforts extend approximately 3 years after construction and planting, and include labor (monitoring and spraying) and material (herbicide). Since this site was only recently completed, monitoring efforts were estimated from other mitigation sites that have already been released.

Simulation Models

Forested Wetland Simulation Model

A simulation model was developed to analyze energy, emergy and transformity values of a mature forested wetland. The model simulates successional trends in a forested wetland, with particular emphasis on forest biomass and organic matter. In addition to simulating energy flows, emergy and transformity values of biomass and organic matter storages were also calculated.

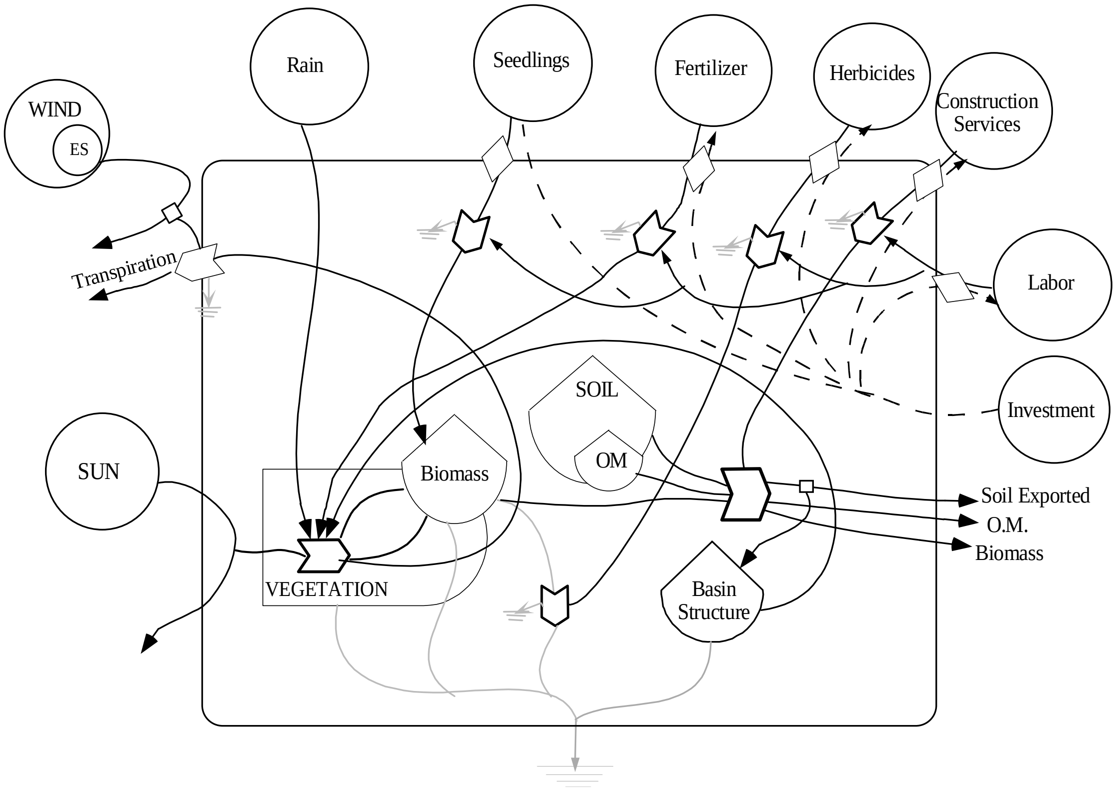


Figure 9. Systems diagram of a constructed forested wetland showing the renewable energies and the economic inputs to the system as well as the loss of soil organic matter and biomass resulting from excavation.

Tilley (1999) identified three rules for simulating emergy dynamics of ecosystem storages. When the energy storage is increasing, the net accumulation of emergy is the sum of all inputs minus the exports of “used” emergy. Unlike depreciation, which was defined as a process necessary for the maintenance of the storage without subtraction of emergy, exports carry away emergy with a transformity equal to that of the storage. When the energy storage is decreasing, the emergy lost is equal to the energy exported times its transformity. When energy stored is in steady-state, the accumulated emergy remains the same.

Model Parameters and Calibration

Data from the literature were used to calibrate the model. Coefficient values were calculated for the mature “steady-state” conditions, i.e. storage values are constants and therefore inflows to a storage equal outflows from the storage at steady state. The energy model simulates 400 years of forest growth. Emergy and transformity simulations of biomass were run for 200 years, while the emergy and transformity of organic matter were simulated for 2000 years.

In the baseline simulation initial biomass and organic matter values were set at 1% of their steady state values, while the nutrient storage was set at 10% of its steady state value. Multiple simulations were run by setting the organic matter initial storage at 25%, 50%, and 90% of its steady state value.

Constructed Wetland Cost Recovery Model

A simple linear, cost recovery model was simulated for a newly constructed wetland to calculate the time required for the ecosystem to recover the costs of construction. Simulated GPP flows from the forested wetland model were converted to emdollar flows and added to the negative values (costs) of construction and monitoring. At time step 0, the simulation began with a negative value of 103,111 em$/ha, the equivalent of construction costs. At time step 1, the first year GPP value from the forested wetland model was added to the costs of construction, and the first year operational costs of maintenance, 703 em$/ha, subtracted. The same methodology was employed for years 2 and 3, while at year 4 only the GPP emdollars were added. Yearly GPP values were taken from the simulation model so that beginning values were relatively small and increasing with time to the steady-state values. The simulation was run for 150 years.

RESULTS

Emergy Evaluation of Ecosystems

Energy, Emergy, and Transformity of Ecosystems

The emergy evaluation tables for the six ecosystems are given in Appendix B, Tables 10 through 21. Details of calculations and data sources are given as footnotes to each table. Emergy signatures for each ecosystem are shown in Figure 10. The emergy signature of an ecosystem depicts the set of environmental energy flows on which its processes and storages depend. The main driving emergy of the depressional wetland ecosystems was geologic input. Geologic input to forested wetlands (Figure 10) is nearly 5 times the driving emergy of rain or run-in (5.5E+15 sej/ha/yr versus 1.17E+15 sej/ha/yr respectively). Geologic input in the shrub/scrub wetland was only slightly higher than rain or run-in (1.21E+15 sej/ha/yr versus 1.17E+15 sej/ha/yr and 1.18E+15 sej/ha/yr respectively). Similar to the forested wetland, geologic input to the herbaceous marsh is 4.2 times the driving emergy of rain or run-in (4.95E+15 sej/ha/yr versus 1.17E+15 sej/ha/yr). River geopotential was the main driving emergy of the floodplain forest, contributing nearly twice and 1.5 times the emergy of rain and run-in (2.2E+15 sej/ha/yr versus 1.17E+15 and 1.49E+15 sej/ha/yr respectively). Geologic input to the floodplain forest was very small (0.2E+15 sej/ha/yr) compared to the other wetland ecosystems. The main driving emergy of the upland ecosystems was rain, which contributed nearly 6 times the emergy of geologic input in both the mesic hardwood forest and pine flatwoods

(1.17E+15 sej/ha/yr versus 0.2E+15 sej/ha/yr respectively).

A comparison across ecosystems showed that run-in and geologic input varied considerably between wetland and upland ecosystems. Run-in was highest in the floodplain forest (1.49E+15 sej/ha/yr), which receives its input from the adjacent stream, while the upland ecosystems had no run-in. Geologic input was highest in the cypress dome and herbaceous marsh ecosystems (5.5E+15 and 4.95E+15 sej/ha/yr respectively); both had nearly 5 times the emergy than the shrub/scrub ecosystem (1.21E+15 sej/ha/yr) and 25 times more than the floodplain forest and the terrestrial ecosystems (0.2E+15 sej/ha/yr).

Annual driving emergy of the six ecosystems is shown in Figure 11. Annual driving emergy for the floodplain forest was the sum of transpiration, geologic input and river geopotential, while for the other ecosystems it was the sum of transpiration and geologic input. In all, the wetland ecosystems had between 3 and 9 times (range of 2.2E+15 and 6.17E+15 sej/ha/yr) the annual driving emergy of the terrestrial ecosystems (range of 6.98E+14 and 8.74E+14 sej/ha/yr). A majority of this difference resulted from differences in geologic inputs.

Ecosystem services of transpiration and infiltration are shown in Figure 12. The emergy of transpiration for the floodplain forest (1.58E+15 sej/ha/yr) was approximately twice the value of all other ecosystems. Infiltration was similar in the forested wetland (0.76E+15 sej/ha/yr), herbaceous marsh (0.72E+15 sej/ha/yr), floodplain forest (0.81E+15 sej/ha/yr), and mesic forest (0.46E+15 sej/ha/yr). However, it was considerably lower for the shrub/scrub (0.17E+15 sej/ha/yr) and pine flatwoods

ecosystem (0.02E+15 sej/ha/yr). Transformity of transpiration and infiltration were higher in the wetland ecosystems (mean of 26,887 sej/J) than in the terrestrial ecosystems (18,199 sej/J), due to their lack of run-in.

GPP varied for the 6 ecosystems (Figure 13). The floodplain forest (3.21E+12 J/ha/yr) was twice as productive as the forested wetland (1.54E+12 J/ha/yr), and these two ecosystems had considerably higher energy values than all other ecosystems (average of 5.46E+11 J/ha). Transformity of GPP varied between 0.96E+3 and 14.4E+3 sej/J, and it was 7 times higher in the wetland ecosystems than upland ecosystems (mean of 7.0E+3 and 1.0E+3 sej/J respectively). The forested wetland had the highest GPP emergy (6.17E+15 sej/ha/yr).

Emergy storages of biomass (Figure 14) were nearly an order of magnitude higher in forested wetlands (cypress and floodplain forest) than in forested uplands (average of 23.4E+16 sej/ha in wetlands and 2.6E+16 sej/ha in uplands). While the floodplain forest had slightly higher biomass energy storage (3.3E+12 J/ha) than the forested wetland (2.9E+12 J/ha), once the energy storages were multiplied by their respective transformity, the forested wetland had approximately twice as much stored emergy than the floodplain forest (3.09E+17 versus 1.59E+17 sej/ha respectively). The herbaceous marsh had the lowest emergy storage of biomass (8.7E+15 sej/ha). Transformity of biomass ranged from a high of 10.7E+4 sej/J in the forested wetland to a low of 9.9E +3 sej/J in the pine flatwoods.

Organic matter storage (Figure 15) was greatest in the herbaceous marsh (9680 E15 sej/ha) and smallest in the pine flatwoods (27 E15 sej/ha). Storages of organic matter were over fifteen times larger in the wetland ecosystems (49E+16 sej/ha) than in

the terrestrial ones (3.2E+16 sej/ha). Transformity of organic matter ranged from a high of 12.3E+4 sej/J in the forested wetland to a low of 1.91E+4 sej/J in the mesic forest.

Soil water is a function of the amount of organic matter in the system. The storage of water in the wetland ecosystems was assumed to be the water content of the peat soil plus the average standing water in the wetland (estimated as half the wetland depth). Differences of more than two orders of magnitude exist in emergy values of water storages (Figure 16) between the wetland and terrestrial ecosystems (5.9E+14 sej/ha and 4.4E+12 sej/ha respectively). Transformity of water storage and flows (transpiration and infiltration) in the wetland ecosystems was calculated as the weighted average of the inputs of rainfall (1.82E+4 sej/J) and run-in (from 4.6E+4 to 5.2E+4 sej/J).

Geologic structure (Figure 17), the result of thousands of years of geologic work, was the highest emergy storage in each of the wetland systems, and ranged from 11.2 E18 sej/ha in forested wetlands to 3.97E18 sej/ha in floodplain forests. Transformity of geologic structure (emergy per gram of material eroded to create the basin or channel) ranged from 1.12E+9 sej/g for forested wetlands to 1.8E+9 sej/g for the shrub/scrub ecosystem.

Emdollar Values of Ecosystems

Representative emdollar values of ecosystem services and natural capital for each ecosystem are given in the last column of each of the evaluation tables (Appendix B, Tables 10-21) and summarized in Tables 1 and 2.

Ecosystem services of transpiration, infiltration, and GPP are given in Table 1. Total ecosystem services, represented by GPP only to avoid double counting, ranged

Table 1. Summary of emdollar values of environmental services of six Florida ecosystems.

Ecosystem Type	Transpiration	Infiltration	GPP
		(em$/ha/yr)	
Forested Wetland	$701	$787	$6,430
Shrub/Scrub Wetland	$1,034	$177	$2,295
Freshwater Marsh	$887	$754	$6,043
Floodplain Forest	$1,642	$841	$4,140
Mesic Hardwood Forest	$702	$479	$911
Pine Flatwoods	$519	$18	$727

(See Appendix B, Tables 10-21)

from 6,430 em$/ha/yr in forested wetlands to 727 em$/ha/yr in pine flatwoods. Wetland ecosystems contribute almost six times the environmental services of upland ecosystems (averages of 4,727 and 819 em$/ha/yr, respectively).

Emdollar values of ecosystem storages (Table 2) ranged from 12.6 million em$/ha/yr for forested wetlands to 49,819 em$/ha/yr for pine flatwoods. This significant difference in value is due to the large contribution of geologic structure to the wetland ecosystems. Geologic structure accounted for as much as 93% of total emdollar values. Without the geologic structure, herbaceous marshes had the highest emdollar value of 1,018,641 em$/ha. After subtracting geologic structure, organic matter (peat) accounted for nearly 99% of herbaceous marsh value.

Organic matter had the second largest emdollar value in the four wetland ecosystems, and it was the highest contribution of upland ecosystems. Organic matter ranged from over 1,000,000 em$/ha in herbaceous marshes to 28,000 em$/ha in pine flatwoods. Organic matter accounted for, on average, 56% of total stored value in pine flatwoods and mesic forests.

The range of emdollar values for live biomass was relatively large. The emdollar value of forested wetland biomass was about 35 times as large as that of a typical marsh wetland (321,510 and 9,065 em$/ha/yr respectively). The floodplain forest biomass storage value was the second highest at 165,582 em$/ha, with shrub/scrub, mesic forest and pine flatwoods following at 45,896, 27,321, and 18,698 em$/ha/yr respectively.

Finally, the emdollar values of stored water were the lowest of the four storages evaluated, accounting for less than 1% of total stored values.

Replacement Values of Ecosystems

Table 3 summarizes the estimated replacement values of each ecosystem assuming complete elimination. The environmental services lost are calculated as the annual services (GPP) times half the recovery time of the newly constructed ecosystem (assuming construction of new wetlands to replace those destroyed). This was done to reflect that as a newly constructed wetland matures some services are replaced annually until a mature system has developed. Recovery times were estimated to be 60 years for forested wetland and floodplain forest, 50 years for mesic forest, 40 years for pine flatwoods, and 16 and 4 years for shrub/scrub and marsh wetlands, respectively. The value of ecosystem structure (natural capital) that is destroyed is equal to the sum of biomass, peat and water, as shown in Table 3. The storage value of geologic structure was not included in the totals for natural capital since elimination of a wetland does not eliminate the underlying geologic structure (see Figure 1). The total calculated replacement values ranged between 1,081,230 and 64,362 em$/ha.

Emergy Evaluation of a Constructed Forested Wetland

Emdollar costs of one hectare of constructed wetland are shown in Table 4. The table is divided into four sections: renewable energy sources, purchased goods and services, environmental losses, and longterm monitoring efforts. Footnotes to each item appear in the following pages. Items 1-3 are the renewable energies that contribute to the system. These are also called “free” inputs as no money (dollars) circulates to pay for those services, and they are the same contributions evaluated in the six Florida ecosystems (Tables 10-21). Items 4-11 are the economic contributions to the

Table 3. Summary of replacement values per hectare assuming complete elimination of wetland ecosystem.

Ecosystem Type	**Environmental Services[(a)]**	**Natural Capital[(b)]**	**Total value[(c)]**
		(Em$/ha)	
Forested Wetland	$192,906	$888,325	$1,081,230
Shrub/Scrub Wetland	$18,358	$283,286	$301,645
Freshwater Marsh	$12,086	$1,018,641	$1,030,727
Floodplain Forest	$124,187	$406,576	$530,763
Mesic Forest	$22,768	$70,909	$93,677
Pine Flatwoods	$14,543	$49,819	$64,362

(a) Replacement value of environmental services is the emdollar value of GPP over 1/2 recovery time. Estimate 60 years for both cypress and floodplain forest, 16, and 4 years for shrub/scrub, and marsh systems respectively, 50 years for mesic hardwood forest and 40 years for pine flatwoods.

(b) Replacement values of natural capital are the sum of storages in each ecosystem. The loss of basin structure was not considered.

c) Total replacement value is the sum of environmental services and natural capital.

Table 4. Emergy evaluation of the inputs to construct a forested wetland in Florida (J/ha).

Note	Item	Data	Units	Transformity (sej/unit)	Solar Emergy (E+15 sej)	Em$ Value* (2000 em$)
	Renewable Energy Sources					
1	Sun	4.19E+13	J/yr	1	0.04	$44
2	Wind	2.96E+09	J/yr	1496	0.004	$5
3	Rain, chemical potential	6.42E+10	J/yr	18199	1.17	$1,217
	Total Renewable Energy (taken as largest to avoid double counting)					**$1,217**
	Purchased Goods and Services					
4	Construction services	2.33E+04	$	1.12E+12	26.08	$27,170
	Vegetation Planting					
5	Biomass	8.39E+07	J	40000	0.00	$3
6	Cost	$870	$	1.E+12	0.83	$870
	Fertilizer					
7	Active ingredients	6.68E+03	g	2.80E+09	0.02	$19
8	Cost	$102	$	9.60E+11	0.10	$102
	Labor					
9	Planting	3.06E+07	J	2.5E+07	0.75	$783
10	Planning and permitting	5.54E+07	J	7.3E+07	4.06	$4,229
11	Costs	$4,125	$	9.6E+11	3.96	$4,125
	Environmental losses					
12	Biomass	2.53E+12	J	1.2E+04	30.60	$31,875
13	Organic Matter	1.96E+12	J	1.9E+04	37.47	$39,030
	Total Goods and Services and Environmental Losses (Items 4, 6, 8, 9, 10, 12, 13)					**$103,111**
	Longterm monitoring efforts					
14	Chemicals (Herbicides)	$64	$	9.60E+11	0.06	$64
	Labor					
15	Spraying	1.15E+07	J	2.5E+07	0.28	$294
16	Monitoring	2.29E+07	J	7.3E+07	1.68	$1,750
	Total					**$2,108**
	Per year					**$703**

* em$ = solar emergy in column 6 divided by 0.96E+12 sej/$ for U.S. in 2000.

Notes to Table 4.

RENEWABLE ENERGY SOURCES

1SOLAR INSOLATION (assume 1 year of sunlight)

Area of wetland = 1.00ha
Mean Net Radiation = 274Ly (Henning 1989)
=(1.0E+04 m^2/ha)(274 Ly)(10 Cal/m^2/Ly)(4186 J/Cal)(365 days)
= 4.19E+13J/ha/yr
Transformity =defined as 1 (Odum 1996)

2WIND (assume 1 year of wind)

Area =1.00E+04 m^2
Density =1.3 Kg/m^3
Drag. Coefficient =1.00E-03 (Odum 1996)
Av. Annual Velocity =1.16 mps (Jones et al.1984)
Geostrophic wind =1.93 (observed winds are about 0.6 of geostrophic wind)
=(area)(density)(Drag Coeff.)$(velocity)^3$(3.15E7 sec/yr)
=2.96E+09 J/ha/yr
Transformity =1,496 sej/J (Odum 1996)

3RAIN, CHEMICAL POTENTIAL (assume 1 year of rain)

Area =1.00E+00 ha
Rainfall =1.3 m/yr (NOAA 1985)
Gibbs Free Energy =4.94 J/g2
=(1.00E+04 m^2/ha)(1.3 m)(4.94 J/g)(1.00E+06 g/m^3)
= 6.42E+10J/ha/yr
Transformity = 18,199 (Odum 1996)

PURCHASED GOODS AND SERVICES

4CONSTRUCTION SERVICES

Six weeks of earthwork for entire site (7.66 ha: 5.26 ha of forested wetland and 2.4 ha of freshwater marsh) using the following equipment: 5 pans, 3 dozers, 1 backhoe, 2 trucks, and 1 motor grader. Total cost of construction (including labor) was approximately $175,000. Cost for forested area (70% of total area) approximately $122,500, or $23,289/ha.

Cost = 23,289$/ha
Transformity = 9.60E+11sej/$

5VEGETATION BIOMASS

Planting for forested wetlands occurs on 7-10 foot centers. 8 tree species were planted at this site: *Taxodium ascendens*, *Nyssa aquatica*, *Acer Rubrum*, *Persea palustris*, *Magnolia virginiana*, *Betula nigra*, *Ilex cassine,* and *Fraxinus americanus*. Total number of tree seedlings was 8790.

Number of seedlings = 8790seedlings
Average dry weight/seedling = 3g
Biomass =(3 g/seedling)(8790 seedlings)(4 kcal/g)(4186 J/kcal)/5.26 ha
= 8.39E+07J/ha
Transformity = 4.00E+04sej/J (estimate)

Notes to Table 4 continued.

6VEGETATION COST

Cost of seedlings only was $4574.

Cost =870 $/ha

Transformity =9.60E+11 sej/$ (Odum 1996)

7FERTILIZER, ACTIVE INGREDIENTS

The slow release fertilizer "Agriform" was applied to each hole in which a seedling was planted. One 10 g tablet for each seedling. Main ingredients are: 20% Total N, 10% Phosphoric Acid (P_2O_5), 5% soluble Potash (K_2O), 2.8% Ca, 2% Na, .5% Fe, .5% Mg, and binding agents.

Fertilizer =(10 g/seedling)* 8790 seedlings/5.26ha

=16711 g

Active Ingredients =6684 g (40% of mass)

Transformity =2.80E+09 sej/g (weighted ave., Lagerberg and Brown 1999)

8FERTILIZER, COST

Agriform: 1 box (1000, 10g tablets) = $61. No. of boxes for this site: 8.8. Total cost $537, or $102/ha.

Cost =102 $/ha

Transformity =9.60E+11 sej/$ (Odum 1996)

HUMAN LABOR

9HUMAN LABOR, PLANTING: 16 people for 1 day (8 hours).

Combined days of work=16 days

Human Input=(16 days)(2,400 kcal/day)(4186 J/kcal)/5.26ha

= 3.06E+07J/ha

Transformity = 2.46E+07sej/J (Odum 1996)

10HUMAN LABOR, PLANNING AND PERMITTING: Surveying, Planning, Permitting and Monitoring. Pre-construction = 6 days; design = 8 days; construction oversight = 15 days.

Combined days of work= 29days

Human Input=(29 days)(2,400 kcal/day)(4186 J/kcal)

= 2.91E+08J/5.26 ha

= 5.54E+07J/ha

Transformity = 7.33E+07sej/J (Odum 1996)

11HUMAN LABOR, COSTS

Total Costs for forested wetland = $21,700$/5.26 ha

Per hectare = $4,125$/ha

Transformity = 9.6E+11sej/$ (Odum 1996)

Notes to Table 4 continued.

ENVIRONMENTAL LOSSES

12BIOMASS

Assume construction site was historically a mesic hardwood forest. Biomass structure taken from Table 19 in this study.

13ORGANIC MATTER

Assume construction site was historically a mesic hardwood forest. Organic matter structure taken from Table 19 in this study.

LONGTERM MONITORING EFFORTS

14CHEMICALS

Rodeo herbicide for aquatic conditions is used to spray exotic species. Based on 2 spray events/year for 3 years of monitoring for a total of 6 events. 2.5 gallons at $337.

Chemicals= 64$/ha (Forestry Suppliers catalog)

Transformity = 9.60E+11sej/$ (Odum 1996)

LABOR

15One person spraying for 1 day for each event. Two spray events per year for 3 years.

Combined work days= 6days

Labor=(6 days)(2,400 kcal/day)(4186 J/kcal)/5.26 ha

= 1.15E+07J/ha

Transformity = 2.46E+07sej/J (Odum 1996)

16Monitoring: 2 person 2 days/year for 3 years.

Work days = 12days

Labor =(12 days)(2,400 kcal/day)(4186 J/kcal)/5.26 ha

= 2.29E+07J/ha

Transformity = 7.33E+07sej/J (Odum 1996) construction of a wetland. Construction services make up approximately 84% of total purchased goods and services. Emdollar values of the other economic inputs (vegetation, fertilizer and labor) were calculated both on the basis of the dollar spent and the energy contributed. In the case of vegetation and fertilizer, the emergy contributed by the actual products was much smaller than the price paid for it. Items 12 and 13 represent the loss of natural capital (biomass and organic matter) of the ecosystem previously present on the constructed site. Wetlands are usually built on degraded uplands, therefore the values of biomass and organic matter for the mesic hardwood forest ecosystem were used to quantify those losses. When tabulating total emdollar costs, only items 4, 6, 8, 9, and 10, 12, and 13 were added to avoid double counting. Total construction costs were 103,111 em$/ha/yr. Environmental losses were almost 70% of total costs, with construction services accounting for 26%. Labor costs were about 4% of total costs, while vegetation and fertilizer accounted for the remainder.

Following construction, the created wetland is monitored for approximately 3 years. Total longterm monitoring efforts were equal to 2,108 em$/ha, or 703 em$/ha/yr. Labor accounts for 96% of those costs, while herbicides account for the remainder.

Simulation Models

Forested Wetland Simulation Model

Figure 18 is a system diagram of the ecosystem flows and storages included in the simulation model. The system boundary of the model is one hectare of forested wetland. Main driving energies of this ecosystem are sun, rain, run-in, and geologic input. Main ecosystem storages are soil water, biomass, organic matter, and nutrients. Nutrients are modeled as a storage rather than a flow through the system since in forested wetlands

nutrient turnover is tightly linked to biomass and organic matter turnover. Table 5 presents the mathematical equations and flow values used in the model, as well as the notes to those calculations. Table 6 provides the values used for each storage and the calibrated coefficients. Emergy and transformity of biomass and organic matter were calculated using formulas in Figure 19 and 20.

Energy, Emergy and Transformity of Forested Wetland Model

Figure 21 shows the simulation results of biomass and organic matter storages in the forested wetland model. Biomass grew at a faster rate than organic matter and reached 90% (2.61E+12 J/ha) of its maximum (2.9E+12 J/ha) after 165 years. Organic matter had much slower growth and reached 90% (3.98E+12 J/ha) of its maximum (4.42E+12 J/ha) by year 386.

Simulated emergy and transformity of biomass are given in Figure 22. While emergy values increase steadily from time 0, transformity values start out extremely high (1.9E+5 sej/J) and keep increasing for the first 11 years to a maximum of 1.14E+6. At year 12 they begin decreasing steadily until they reach steady state by year 924 at 4.3E+4 sej/J. Emergy of biomass storage reached steady state of 1.25E+17 sej/ha by 421 years.

Organic matter emergy and transformity values peaked around year 1700 (Figure 23). Transformity of organic matter rapidly increased until year 29 to a value of 3.15E+5 sej/J. Between year 29 and year 164, transformity decreased slightly to 7.88E+4 sej/J, and then began ascending until it leveled off by 1700 years at a value of 1.3E+5 sej/J. Emergy of organic matter reached a maximum value of 5.77E+17 by 1880.

Increasing the organic matter storage to 25%, 50%, and 90% of its steady state value had a considerable effect on biomass storage growth (Figure 24), but did not result

Table 5. Storage and internal flow equations for the forested wetland simulation model.

Note	Symbol	Equation	Value	Definition
Storage Equations				
$dB = J_1 - J_2 - J_3 - J_4$				
$dOM = J_5 - J_6 - J_7$				
$dN = J_8 + J_9 + J_{10} + J_{11} - J_{12} - J_{13}$				
$dSW = Rain + Run\text{-}in - J_{14} - J_{15} - J_{16}$				
Item Internal Flows				
1	R	$I/(1+K_0*SW*B*N*G)$	4.19E+12	Remaining Sunlight
2	J_0	k0*SW*B*N*G*R	4.19E+13	Sunlight Received by Trees
3	J_1	$k_1*SW*B*N*G*R$	2.05E+11	Net Primary Production
4	J_2	k_2*B	7.72E+10	Litterfall
5	J_3	k_3*B	6.63E+10	Exported Biomass
6	J_4	k_4*B	6.15E+10	Biomass depreciation
7	J_5	k_5*B	3.86E+10	Litter Accumulation
8	J_6	k_6*OM	1.27E+10	Exported OM
9	J_7	k_7*OM	2.59E+10	OM Depreciation
10	J_8	k_8*B	7.44E+05	Nutrients from Litter Decomposition
11	J_9	k_9*OM	3.84E+05	Nutrients from OM depreciation
12	J_{10}	$k_{10}*Rain$	3.99E+05	Nutrients in Rain
13	J_{11}	$k_{11}*Run\text{-}in$	4.70E+05	Nutrients in Run-in
14	J_{12}	$k_{12}*N$	4.99E+05	Exported Nutrients
15	J_{13}	$k_{13}*SW*B*N*G*R$	1.50E+06	Nutrient uptake by Trees
16	J_{14}	$k_{14}*SW*B*N*G*R$	2.57E+10	Transpiration
17	J_{15}	$k_{15}*SW$	3.49E+10	Evaporation
18	J_{16}	$k_{16}*SW$	2.88E+10	Runoff & Infiltration
19	J_{17}	$k_{17}*SW*B*N*G*R$	1.34E+12	Respiration
Item Constant Flows				
20	Rain		6.42E+10	Rain input to the system
21	Run-in		2.52E+10	Run-in input to the system
22	G		5.50E+06	Geologic Input

Notes and calculations to flow values in Table 5.

1 **Remaining Sunlight**
Estimated as 10% of Sunlight

2 **Sunlight Received by Trees** Table 10

3 **Net Primary Production** Table 10

4 **Litterfall**
Litterfall = 461g/m^2/yr (Deghi 1977)
Energy =(461 g/m^2/yr)(1.0E+04 m^2/ha)(4 Cal/g)(4186 J/Cal)
= 7.72E+10J/ha/yr

5 **Exported Biomass**
Calculated as NPP - Litterfall - Biomass depreciation
Exports = 6.63E+10J/ha/yr

6 **Biomass depreciation**
Approximately 30%of NPP

7 **Litter Accumulation**
Organic matter from litterfall 50%of litterfall (Deghi 1977)

8 **Exported OM**
OM in percolating waters = 100g/m^3 (Odum 1984)
=(100 g/m^3)*(.584 m)*(1E+4 m^2/ha)(5.2 Cal/g)(4186 J/Cal)
= 1.27E+10J/ha/yr

9 **OM Depreciation**
Calculated as OM from litter - Exported OM

10 **Nutrients from Litterfall Decomposition**
P in litter = 0.84mg/g dry weight (Brown 1978)
=(.84 mg/g)(461 g/m^2/yr)*(50% decomp.)*(1E+4 m^2/ha)
(1E-3 g/mg)(384 J/g)
= 7.44E+05J/ha/yr

11 **Nutrients from OM depreciation**
P from OM = P concentration in depreciation OM
OM Depreciation = 2.59E+10J/ha/yr
= 1.19E+06g/ha/yr
P in OM = 0.84 mg/g dry weight (assume same as litterfall)
P from OM = 3.84E+05J/ha/yr

12 **Nutrients in Rain**
P in rain = 0.08g/m^3 (Brown 1978)
Rain =(1.3 m)(1E+4 m^2/ha)(0.08 g/m^3)
1040g/ha/yr
P in rain =(1040 g P)(384 J/g)
= 3.99E+05J/ha/yr

Notes and calculations to flow values in Table 5 continued.

13**Nutrients in Run-in**

P in run-in= 0.24g/m^3 (Brown 1978)

Run-in =(.51 m)(1E+4 m^2/ha)(.24 g/m^3)

P in run-in = 1224g/yr

=(1224 g P)(384 J/g)

= 4.70E+05J/ha/yr

14**Exported Nutrients**

EXPORTED P = Balance $J_8 + J_9 + J_{10} + J_{11} - J_{13}$

15**Nutrient uptake by Trees**

P uptake by Biomass = 0.39g P/m^2/yr (Brown 1978)

= 1.50E+06J/ha/yr

16**Transpiration** Table109

17**Evaporation**

From water balance

Rain + Run-in = Transpiration + Evaporation + Runoff&Infil

= 3.49E+10J/ha/yr

18**Runoff&Infil** Table 10

19**Respiration** Table 10

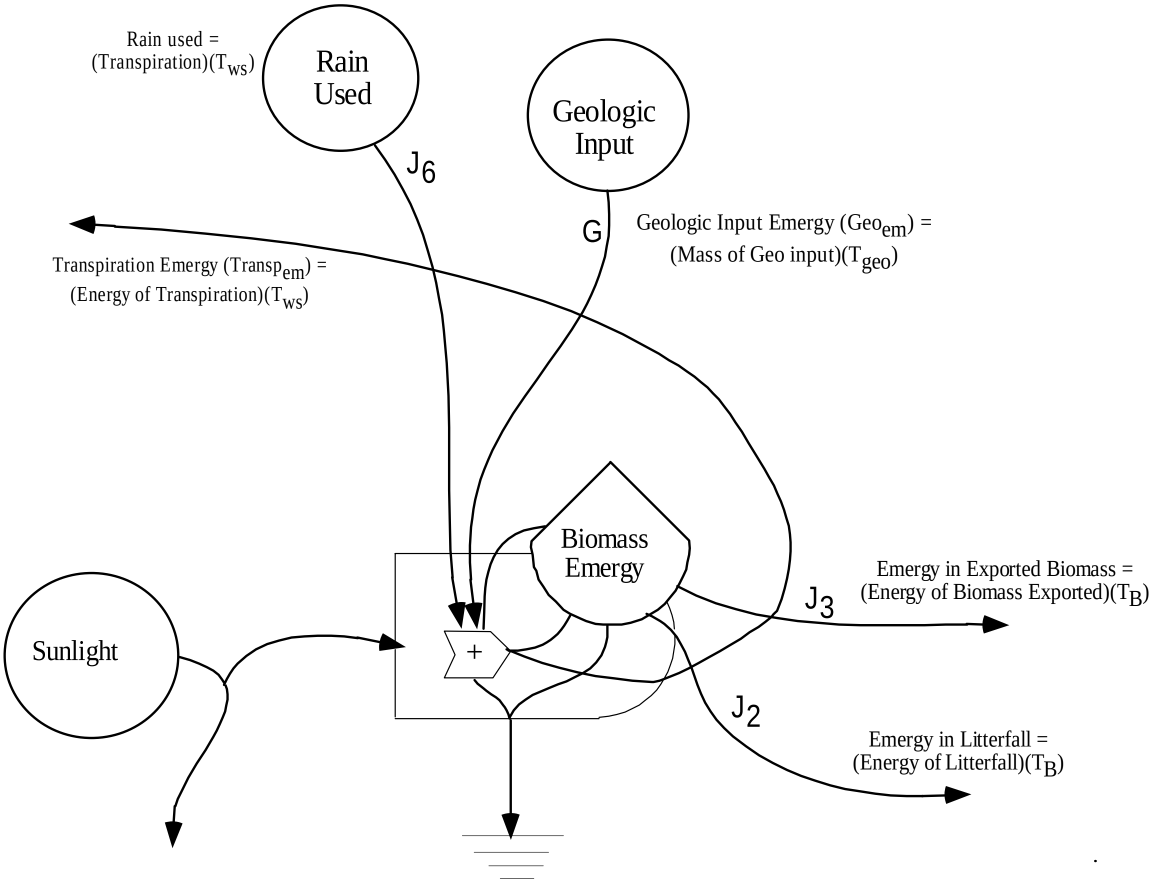
20**Rain input to the system** Table 10

21**Run-in input to the system** Table 10

22**Geologic input** Table 10

Table 6. Steady-state values of the storages and calibrated coefficients for the forested wetland simulation model.

Symbol	Value
Storages	
B	=2.90E+12
OM	=4.42E+12
N	=6.37E+07
SW	=1.87E+10
Coefficients	
k0	=4.73E-37
k_1	=2.57E-39
k_2	=2.66E-02
k_3	=2.29E-02
k_4	=2.12E-02
k_5	=1.33E-02
k_6	=2.88E-03
k_7	=5.86E-03
k_8	=2.56E-07
k_9	=8.68E-08
k_{10}	=6.22E-06
k_{11}	=1.87E-05
k_{12}	=7.83E-03
k_{13}	=1.88E-44
k_{14}	=3.23E-40
k_{15}	=1.87E+00
k_{16}	=1.54E+00
k_{17}	=1.52E-38

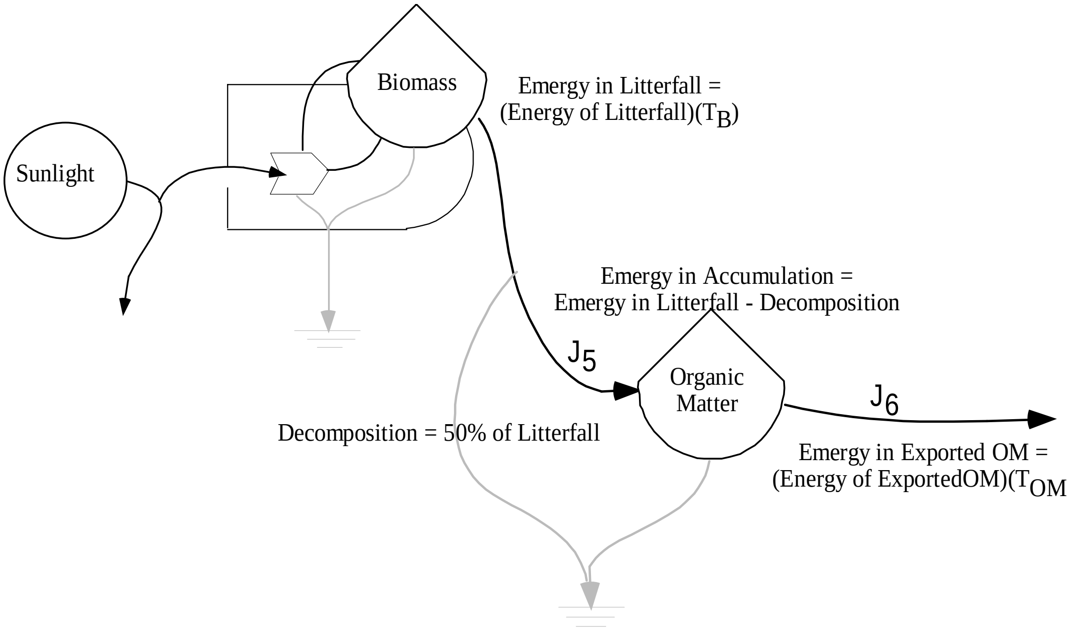


T_{ws} = 26202 sej/J T_{geo} = 1.00E+9 sej/g

Emergy of Biomass (B_{em}) = J6 * T_{ws}) + (G * Tgeo) - (J2 * T_B) - (J3 * T_B)
= [(k6*SW*B*N*G*R * T_{ws})] + [(G * T_{geo})] - [(k2 * B) * T_B]- [(k3 * B) * T_B]

Transformity of Biomass (T_B) = $\frac{\text{Emergy of Biomass}}{\text{Energy of Biomass}}$

Figure 19. Emergy system diagram showing calculations of emergy and transformity of biomass in the forested wetland simulation model.



Emergy of Organic Matter (OM_{em}) = Accumulation$_{em}$ - $ExOM_{em}$
= (J5 * T_B) - (J6 * T_{OM})
= [(k5* B) * T_B] - [(k5 * OM) * T_{OM}]

$$\text{Transformity of Organic Matter } (T_{OM}) = \frac{\text{Emergy of Organic Matter (sej/J)}}{\text{Energy of OM (J)}}$$

Figure 20. Energy diagram showing calculations of emergy and transformity of organic matter in the forested wetland simulation model.

in any changes to emergy and transformity of biomass. The 25%, 50%, and 90% increase resulted in biomass reaching 90% of its steady state within 141,119, and 98 years, respectively, instead of the 165 years required in the baseline simulation. Setting organic matter to 25% and 50% of its steady state value enabled the organic matter storage to reach 90% of its steady state value in 360 and 328 years, respectively, instead of the 386 years necessary in the baseline simulation (Figure 25).

Constructed Wetland Cost Recovery Model

Emdollar GPP flows for the forested wetland model are shown in Figure 26. GPP was calculated by adding NPP (J_1), and respiration (J_{17}). In the forested wetland model, GPP grows rapidly until year 50, after which growth is much slower and it begins to level off around 6.0E+3 em$/ha/yr at 214 years. Figure 26 depicts the recovery time of a constructed wetland ecosystem. At time 0, the ecosystem has a negative balance of 103,111em$/ha. Though the ecosystem begins to recover some of its initial costs with the addition of GPP, its balance is lower by year one because of the monitoring costs. The lowest balance occurs at year 3 (-105,000 em$/ha) with the last installment of monitoring costs. Then, the ecosystem begins to recover and as it matures more GPP services are added each year. The value of ecosystem services of GPP equals the costs of construction by year 54. At this time the ecosystem has paid off its debt and begins accruing positive value.

Increasing the baseline organic matter storage to 25%, 50% and 90% of its maximum had considerable effects on GPP rates and thus recovery time (Figure 27). Additionally, increasing the baseline organic matter storage also translated into decreased environmental losses, and thus decreased construction costs. Mesic hardwood

forests have approximately half of the organic matter of forested wetland (Appendix B, Table 11 and 19). Therefore, if the organic matter starts off at 25% of its steady state value in the simulation model, then initial construction costs amounted to 83,600 em$/ha (the original 103,111em$/ha minus 19,115 em$/ha, or 50% of organic matter of mesic hardwood forests). In this scenario, ecosystem services of GPP equal construction costs by year 48 (Figure 27). Similarly, increasing the organic matter storage to 50% in the simulation model resulted in construction costs of 64,081 em$/ha (original 103,111 em$/ha minus 39,030 em$/ha, or approximately 100% of organic matter value of mesic hardwood forests) and a recovery time of 42 years (Figure 27). Finally, if additional organic matter is imported from other sources to equal 90% of the forested wetland steady state value, construction costs remain at 64,081 em$/ha, but GPP slightly increases to yield a recovery time of 40 years (Figure 27).

DISCUSSION

Ecosystem Services and Natural Capital

This study calculated emergy and emdollar values for services and natural capital of six Florida ecosystems. Wetlands in Florida are protected by laws and regulations that prevent their uncompensated destruction. These policies are justified since this research showed that from an energetic analysis, wetland ecosystems are much more valuable than uplands both in terms of the yearly services they provide to society and in the natural capital (structure) they store. However, current policy that values wetlands between $45,000 and $75,000 per acre ($112,500 to $187,500 per hectare) seriously undervalues them.

The emdollar values of structure and environmental services (Tables 1 and 2) can be used to determine an approximate monetary value for wetlands and their environmental services. These values are appropriate for deriving fair mitigation ratios among different ecosystems and should not be confused with market values of wetlands. On an annual basis wetlands provide between 2,295 and 6,430 em$/ha/yr of value to regional human economies, compared to the two upland ecosystems values of 727 and 911 em$/ha/yr (Table 1). The natural capital of wetlands (without including geologic structure) ranges from approximately 283,000 to over 1,000,000 em$/ha (Table 2). Compared to the upland ecosystems, whose emdollar values ranges from approximately

50,000 to 71,000 em$/ha, wetlands, on the average, have almost 11 times as much value in their natural capital.

These values can be used to determine the monetary costs for replacing services and natural capital lost as a result of development. Whenever a "price" is placed on wetlands, it usually reflects the costs of building wetlands, which includes land acquisition, planning, construction, and monitoring. These values are costs in economic terms based on actual (or maybe perceived) costs to construct wetlands in Florida, but in reality they do not reflect the value of environmental services or structure that is lost when a wetland is destroyed. A better measure of what society loses with each hectare of wetland conversion is suggested by the replacement values (Table 3) calculated in this study. For instance, if a forested wetland were cut, the appropriate loss value could be calculated from the biomass storage and GPP loss. The current "price" for wetlands in Florida ranges between $112,500 and $187,500 per hectare. Even at the highest range, $187,500 per hectare is only about 17% to 62%, depending on the type of wetlands, of the value of ecosystem services and natural capital that is lost with the elimination of wetlands (Table 3).

Mitigation Ratios

The current trend in public policy concerning wetland losses associated with development is "no net loss". It is believed that no net loss can be achieved by constructing wetlands to replace those that are eliminated, or by enhancing degraded wetlands to replace functions and values lost from impacted ones. In most cases a wetland is built "on-site," but in mitigation banks, it may be built somewhere within the watershed (service area).

Under current regulations, a mitigation ratio is calculated by subjectively quantifying ecosystem value of the proposed impacted site, as well as accounting for the perceived ease of replacement and recovery time needed. Representatives of government agencies and consulting companies visit the proposed impacted site and "score" the wetlands using rapid assessment procedures. The wetland value achieved by this methodology is a result of perceived values by the scorers. Since no quantitative studies are required, mitigation ratios are thus affected by individual preferences rather than actual contributions. Problems arise when wetland scoring is done by hundreds of professionals throughout the state, each one evaluating wetlands according to their individual preferences. For this reason, mitigation ratios across the state and in different years may be highly variable. This methodology is even more questionable when mitigation ratios have to be calculated for wetlands that are not replaced type for type, as may occur with the onset of mitigation banks.

Static Replacement Ratios

One option to calculate mitigation ratios among different ecosystems is to use static replacement ratios of wetland value. Replacement values are based on several assumptions from the following rationale: when a wetland is eliminated, vegetation is cut, peat is removed, water is drained, and the depression might be filled and covered with impervious surface (roads or buildings). Consequently, annual ecosystem services are lost since the wetland no longer exists. A wetland that is eliminated and not replaced, cannot contribute environmental services and therefore, the loss of environmental services accumulates indefinitely. Conversely, if the wetland is replaced, eventually, the created wetland will provide the services that were provided by the original wetland, assuming the new ecosystem is similar to the destroyed one. Since a constructed wetland is a growing system, each year there is an incremental replacement of the lost services. If we assume that ecosystem services increase linearly, that is, approximately half the environmental services are gained over the replacement time of an ecosystem, then the replacement value is the emdollar value of structure plus half the environmental services multiplied by the recovery time (Table 3).

Examples of ratios calculated for the six Florida ecosystems using replacement values are given in Table 7. For instance, for every one hectare of forested wetland destroyed, 3.6 hectares of shrub/scrub are needed to replace the value lost. Similarly, 1.0 ha of herbaceous marsh is equivalent to 1 ha of forested wetland, and 2.0 ha of floodplain forest replace 1 ha of forested wetland. If the wetland is mitigated by an upland ecosystem, 11.5 ha of mesic forest and 16.8 ha of pine flatwoods are needed to replace 1 ha of forested wetland.

These static calculations, however, do not take into account the investment costs needed to construct a wetland and the fact that the natural capital is later replaced. While biomass and organic matter may be completely replaced if the constructed wetland is successful, the services of the mature ecosystem lost during the period of replacement are never recovered. A static calculation, however, yields a 1:1 ratio for type-for-type wetland replacement (Table 7), and thus, it does not account for the services lost.

Cost Recovery Mitigation Ratios

Results of the cost recovery model summarized in Figure 26 show that 54 years are required to pay back construction costs of a typical constructed forested wetland.

GPP em$ of mature ecosystems accumulated over the recovery time can be

calculated by multiplying yearly GPP values from Table 1 (6430 em$/ha/yr for the forested wetland ecosystem) by 54 years. Thus, after 54 years total em$ from GPP of a mature system equals 347,220 em$/ha. A growing system, on the other hand, will have lower initial GPP values, and as it matures, yearly GPP will approach that of a mature forested wetland. Using emdollar GPP values shown in Figure 26 and adding them for 54 years, yields 108,000 em$/ha. This results in a loss of ecosystem services equal to 239,220 em$/ha over 54 years. This loss is never recovered if the type for type mitigation ratio is 1:1. In other words, in order for a constructed wetland to reach 347,220 em$ of accumulated GPP, 100 years of growth are required. By that time, the mature ecosystem would have accrued 643,000 em$ (6430 em$/yr * 100 years), so the constructed wetland would always fall short of the original ecosystem. Therefore, a higher mitigation ratio is needed to recover those losses. Dividing accumulated GPP em$ values of the mature ecosystem by the GPP values of the created site at year 54 yields a 1.9:1 ratio for type-for-type mitigation.

When costs of construction are subtracted from GPP em$ of constructed wetlands, it takes 54 years for the new ecosystem to pay back its initial investment (Figure 26). So while a mature forested wetland would have accrued 347,220 em$ in 54 years, the constructed ecosystem is just beginning to provide a net benefit to society and its accrued value is merely 3000 em$. In this scenario, for the constructed wetland to accrue 347,220 em$, 119 years from the time of construction are required. By that time, a mature ecosystem would have accrued 765,000 em$/ha. This pattern is shown in Figure 28. If t=54 years is used to calculate the mitigation ratio, it would yield a value of 116:1. Clearly, this ratio is unreasonable considering that mitigation is a result of land scarcity and competition for this limited resource. When mitigation ratios are computed yearly, it is apparent that the ratios are decreasing, and though the two lines will never meet, by year 100 the ratio is reduced to 2.7:1 (Figure 29) and it will be as low as 1.2:1 by year 500.

This decrease in mitigation ratios begs the question: what is the appropriate time frame in which to calculate mitigation ratios? If mitigation sites are successful and protected in perpetuity, then long term trends in ecosystem services accrual show that, given enough time, constructed ecosystems recover close to 100% of the initial losses. Therefore, type-for-type mitigation ratios calculated over thousands of years can be as low as 1.05:1. However, when decisions are made to maximize contributions to society, this time frame is not appropriate. A more reasonable time frame would be 70-100 years, or the equivalent of one generation of human life. Mitigation ratios at year 70 and 100 are 5.5:1 and 2.7:1, respectively. That is, if society wants to recover the ecosystem services lost to impacts within 70 years of wetland creation, 5.5 hectares will have to be constructed for each hectare impacted. Similarly, if ecosystem services are to be recovered within 100 years of impacts, then 2.7 hectares of wetlands will have to be constructed for each hectare of impact. Thus, mitigation ratios decrease as the time frame allowed to recover ecosystem losses increases (Figure 29).

Simulation Model

Mature ecosystems are the work of decades of ecosystem services and natural capital accrual. When a forested wetland is cut down and replaced by a created one, a huge investment is needed from the economy to mitigate the wetland losses. While the created wetlands are usually monitored for only a few years, at least 165 years are

required for the ecosystem to reach 90% of its steady state biomass, and 386 years to achieve 90% of organic matter (Figure 21).

Some wetland scientists involved in wetland creation have been trying to “jump start” created sites by adding organic matter from the impacted sites or saving the on-site organic pool. The effects of “jump starting” constructed wetlands by adding organic matter prior to planting was illustrated in the simulation results by increasing the initial organic matter storage. The simulation model of a forested wetland showed that increasing the organic matter pool by 25%, 50%, and 90% of its maximum value increased biomass growth and decreased ecosystem recovery time by as much as 11% to 26%. A 25% increase in organic matter storage resulted in biomass reaching 90% of steady state value in 140 years, 35 years faster than with the baseline simulation (Figure 24). A 50% increase in organic matter storage resulted in biomass reaching 90% of steady state values in 119 years (Figure 24), 46 years faster than without the organic pool. Similarly, increasing the organic matter storage to 90% of its steady state value resulted in biomass reaching 90% of its steady state value by 98 years, 67 years faster (Figure 24). GPP rates were also positively affected, and translated into faster recovery times of constructed wetlands. While 54 years are required to recover costs of construction when no organic matter is added, this time frame is reduced to 48 years with a 25% increase of organic matter, 42 years with a 50% addition and 40 years with a 90% addition of organic matter (Figure 27). Saving the on-site organic matter pool not only increases growth rates, but it also decreases costs associated with construction.

Consequently, dynamic mitigation ratios also decrease as greater percentages of organic matter are added to the constructed wetland (Figure 30). For example, without organic matter, a mitigation ratio of 5.5:1 is necessary to recover losses within 70 years of wetland construction (Figure 30). Increasing the initial organic matter pool to 25%, 50%, and 90% of its steady state value yields mitigation ratios of 3.9:1, 3.1:1 and 2.7:1, respectively, for the 70 year time frame (Table 8). Similarly, in order to recover losses within 100 years of construction, mitigation ratios of 2.3:1, 2.0:1, and 1.9:1 are necessary with a 25%, 50%, and a 90% increase in organic matter, compared to the ratio of 2.7:1 calculated from the baseline simulation.

The simulated emergy and transformity values of biomass of forested wetlands (Figure 22) are slightly lower than the ones given in the emergy evaluation table (Table 11). This could be due to the fact that the tabulated value tends to overestimate total emergy inputs since the same steady state value (6.17E+15 sej/ha/yr) is multiplied by the turnover time. In reality, when an ecosystem is in early successional stages, transpiration rates are lower and therefore total driving emergy contributed from the process is also lower. On the other hand, organic matter emergy and transformity values (Figure 23) resulting from the simulation model are slightly higher than the tabulated ones (Table 10). This could be due to the slightly different calculation methodology employed in tabulating emergy and transformity, as explained in Table 11 and Figure 20. Transformity values of GPP, biomass, and organic matter for the six Florida ecosystems (Appendix B, Tables 10 through 21) in this study are substantially higher

compared to previous studies (Orrell 1998; Tilley 1999). This is primarily a result of calculations of annual driving emergy inputs, particularly the addition of geologic input to total driving emergy. Moreover, the simulated transformity values of biomass and organic matter storages in this study yield a different pattern than the one presented by Tilley (2000). Tilley found that transformity values increase as a function of time. In this study, transformity of biomass and, to a smaller extent, organic matter had higher initial values than steady state values (Figures 22 and 23). This is also a result of adding geologic input to the annual driving emergy of the ecosystem; in fact, annual driving emergy in the early stages of ecosystem growth is primarily in the form of geologic input. When this value is divided by the ecosystem energy storage to derive its transformity, it results in extremely high transformity values since the amount of biomass and organic matter energy present is still small. As the ecosystem matures, transpiration increases and begins contributing to annual driving emergy, but the ecosystem storages also increase, thus resulting in lower transformities.

Limitations and Suggestions for Further Research

This study relied on already published data for the ecosystem evaluations and the forested wetland model. While literature data were cross-referenced, sometimes the lack of published data resulted in educated estimates in order to carry out the evaluations. This problem was especially true for the floodplain forest and the upland ecosystems. For example, while I was able to gather data for the biota of the riparian wetland, understanding the processes and scale of floodplain formation posed several challenges. First, the system analyzed in this study was a lake-fed, black water, low flow stream for which there is virtually no data relating to floodplain formation and structure. Most of the stream studies focus on large, alluvial systems that usually pose a flooding threat to human development. Extrapolating structure and turnover times from those studies, and applying those values to this research yields approximations at best. Thus, the value of floodplain structure is reported with caution.

Similarly, the upland ecosystems lacked complete reports on organic matter storages, litterfall, and decomposition rates. While published decomposition rates in pine flatwoods appeared low compared to other upland and wetland systems, pine flatwoods experience frequent fires that arrest litter accumulation. However, published data on pine flatwoods decomposition rates largely ignored the effects of fire on this ecosystem.

As a result of relying on data specific to only a few sites within Florida, the ecosystems evaluations reflect conditions found at those sites, and average values for Florida should be derived with caution. The ecosystem tables can also be used as templates to generate values for other sites throughout Florida by inserting site specific data collected at those locations if available.

Ideally, the constructed wetland model that was developed to explore the benefits, costs, and recovery time of wetland creation should have been calibrated using actual GPP values from a mitigation site. In reality, mature constructed wetlands are rare and since developers are only required to monitor them until compliance, the fate of those wetlands post compliance is largely unknown. The mitigation ratios calculated in this study depend on GPP values from the literature, and thus are specific to the sites sampled in those studies.

Further Research

This research focused on quantifying the value of ecosystem services and natural capital of six Florida ecosystems to investigate differences among various ecosystems. Results from this study have shown that wetlands on average contribute more wealth to society than upland ecosystems. However, it is important to stress the fact that wetland mitigation should not be at the expense of all uplands in Florida. Mitigation ratios between ecosystems should vary as the relative abundance of upland ecosystems change. As certain ecosystems become scarce, for instance longleaf pine savannahs or maritime forests, their value should increase to reflect their "rarity" in the landscape. Abundance of ecosystems could be determined by reviewing Geographic Information Systems land use coverages of Florida over time. Based on results from these analyses, statewide policies could be implemented that valued ecosystems on the basis of their relative abundance as well as their contributions to society.

This study demonstrated that created forested wetlands require 54 years before the benefits (in the form of ecosystem services of GPP) from the created ecosystem outweigh the costs of construction (the sum of economic inputs to constructed wetlands as well as the environmental losses from the destruction of the pre-existing ecosystem). Mitigation ratios derived from the model have used data pertaining to constructed forested wetlands. Future research is needed to explore the concept of mitigation further and include calculations of mitigation ratios for different ecosystems, as well as for different mitigation alternatives, such as restoration, enhancement, and preservation. What are the appropriate ratios if we construct a freshwater marsh to replace a forested wetland? What range of mitigation ratios should we use for restored, enhanced, or preserved wetlands?

Under what conditions would restoration and enhancement be more appropriate than creation?

Long-term studies of mitigation sites should also be developed to ensure that the ecosystems survive beyond the first few years of monitoring. Do created wetlands ever become successful ecosystems? How much time does the created wetland require to achieve the structure and productivity of the forgone ecosystem? How can one accelerate growth and productivity of created sites in order to recover costs more quickly? What is the appropriate investment in terms of economic inputs into creating wetlands?

Finally, as regulatory agencies drift towards the use of mitigation banks, the costs and benefits of on-site and type-for-type mitigation versus mitigation banking should also be compared. Since mitigation banks are large-scale projects, the economic inputs to one hectare of ecosystem within a mitigation bank may be smaller than constructing one hectare of isolated wetland. Do economies of scale exist in wetland creation and are mitigation banks thus “cheaper” to build?

Conclusions

As long as there are competing interests in the use of a limited resource such as land, understanding the costs and benefits of decisions about appropriate use of the land is critical in ensuring society and ecosystem long-term success. Emergy analysis was used to evaluate the contributions of ecosystems services and natural capital to social welfare. This research provided several tools to appropriately value ecosystems and derive fair mitigation ratios.

Four main conclusions were generated from this study. First, wetland ecosystems are extremely valuable to our societies, with replacement values ranging from over

300,000 to 1,000,000 em$/ha. Their replacement is very costly (103,000 em$/ha) to society, due to the economic inputs required as well as the environmental losses of the pre-existing ecosystem. Second, ecosystem dynamics can be modeled in terms of energy, emergy and transformity and results of dynamic simulations can be incorporated into decision-making processes, as in the case of the constructed wetland model. For instance, the model showed that applying organic matter to growing ecosystems results in increased productivity, which translates into decreased recovery times by as much as 11-26%. Third, with an initial investment of 103,111 em$/ha, approximately 54 years are required for ecosystem services to offset costs of construction. Therefore, losses due to impacts alone cannot be mitigated in fewer than 54 years if we take construction costs into account. Recovery times can be decreased to 48, 42, and 40 years by adding up to 25%, 50% and 90% of the steady state value of organic matter to constructed sites; thus, the organic matter should be applied to constructed sites whenever available to increase productivity and decrease construction costs. Fourth, mitigation ratios cannot be calculated from static valuations, but require dynamic simulations of growth and ecosystem value accrual. In fact, mitigation ratios themselves are flexible rather than set values, and vary according to the time frame society decides to offset losses. In order to offset losses due to impacts in the shortest amount of time possible, higher ratios are required. Examples of type for type mitigation ratios for forested wetlands are 5.5:1 or 2.7:1 to offset losses within 70 and 100 years of wetland construction, respectively. These ratios are affected by initial construction costs as well as GPP rates. Therefore, adding organic matter to constructed sites provides a twofold benefit: 1) it decreases construction costs by alleviating environmental losses, and 2) it positively affects GPP rates. Mitigation ratios resulting from a 25%, 50%, and 90% addition of organic matter decrease to 3.9:1, 3.1:1 and 2.7:1, respectively, for a 70 year time frame, and are as low as 2.3:1, 2.0:1 and 1.9:1, respectively, for losses to be recovered within 100 years of construction.

APPENDIX B
EMERGY EVALUATIONS OF SIX FLORIDA ECOSYSTEMS.

Table 10. Emergy Evaluation of annual driving energies and environmental services of forested wetlands.

Note	Item	Data	Units	Transformity (sej/unit)	Solar Emergy (E+15 sej/yr)	Em$ Value* (2000 em$/yr)
	Energy Sources					
1	Sun	4.19E+13	J/ha/yr	1	0.04	$44
2	Wind	2.96E+09	J/ha/yr	1496	0.004	$5
3	Rain, chemical potential	6.42E+10	J/ha/yr	18199	1.17	$1,217
4	Run-in, chemical potential	2.52E+10	J/ha/yr	46589	1.17	$1,223
5	Geologic input	5.50E+06	g/ha/yr	1.00E+09	5.50	$5,729
	Functions (Env. Services)					
6	Transpiration (water use)	2.57E+10	J/ha/yr	26199	0.67	$701
7	GPP	1.54E+12	J/ha/yr	3999	6.17	$6,430
8	Infiltration	2.88E+10	J/ha/yr	26199	0.76	$787

* em$ = solar emergy in column 6 divided by 0.96E+12 sej/$ for U.S. in 2000.

Notes to Table 10.

1SOLAR INSOLATION

Area of wetland =1.00E+04 m^2

Mean Net Radiation =274 Ly (Henning 1989)

=(1.00 E4 m^2)(274 Ly)(10 Cal/m^2/Ly)(4186 J/Cal)(365 days)

=4.19E+13 J/ha/yr

Transformity =defined as 1 (Odum, 1996)

2WIND

Area =1.00E+04 m^2

Density =1.3 Kg/m^3

Drag. Coefficient =1.00E-03 (Odum 1996)

Av. Annual Velocity =1.16 mps (Jones et al.1984)

Geostrophic wind =1.93 (observed winds are about 0.6 of geostrophic wind)

=(area)(density)(Drag Coeff.)$(velocity)^3$(3.15E7 sec/yr)

=2.96E+09 J/ha/yr

Transformity =1,496 sej/J (Odum 1996)

3RAIN, CHEMICAL POTENTIAL

Area =1.00E+04 m^2/ha

Rainfall =1.3 m/yr (NOAA 2002)

Gibbs Free Energy =4.94 J/g

=(1.00E+04 m^2/ha)(1.3 m)(4.94 J/g)(1.00E+06 g/m^3)

=6.42E+10 J/ha/yr

Transformity =18,199 (Odum 1996)

4RUN IN, CHEMICAL POTENTIAL

Run-in =0.51 m/yr (Heimberg 1984)

Area =1.00E+04 m^2/ha

Gibbs Free Energy =4.94 J/g

=(0.51 m/yr)(1.00E+04 m^2/ha)(1.00E+06 g/m^3)(4.94 J/g)

=2.52E+10 J/ha/yr

Transformity:46,589 (calculated as 2.56 * transformity of rain assuming total rainfall is required to generate 39% avg. run-off)

5GEOLOGIC INPUT

Limestone Eroded =0.02750 cm/yr (Odum 1984)

Density of Limestone =2 g/cm^3

=(0.0275 cm/yr)(1.00E+08 cm^2/ha)(2 g/cm^3)

=5.50E+06 g/ha/yr

Transformity =1.00E+09 Sej/g (Odum 1996)

6WATER USE (TRANSPIRATION) calculated as daily summer transpiration rates times 240 days.

Transpiration =0.52 m/yr (Liu 1996)

Gibbs Free Energy =4.94 J/g

=(0.52 m)(1.00E+04 m^2/ha)(1.00E+06 g/m^3)(4.94 J/g)

=2.57E+10 J/ha/yr

Transformity =26,199 (Calculated as weighted average of rain and run-in)

7GROSS PRIMARY PRODUCTION

Net Primary Production =6.13 tn C/ha/yr (Brown 1978)

=(6.13 tn/ha/yr) (1,000,000 g/tn) (8 Cal/g) (4186 J/kcal)

=2.05E+11 J//ha/yr

Plant respiration =39.96 tn C/ha/yr (Brown 1978)

=(39.96 tn/ha) (1,000,000 g/tn) (8 kcal/g) (4186 J/Cal)

=1.34E+12 J/ha/yr

Gross Production =1.54E+12 J/ha/yr

Total annual emergy =Sum of transpiration and geologic input

=6.17E+15 Sej/ha/yr

Transformity =(6.17E+15 Sej/ha/yr / 1.54E+12 J/ha/yr)

=3,999 sej/J

8INFILTRATION

Infiltration Rate =0.0016 m/day (Heimburg 1984)

=0.584 m/yr

Gibbs free energy =4.94 J/g

=(0.584 m/yr)(4.94 J/g)(1.00E+06 g/m^3)(1.00E+04 m^2/ha)

=2.88E+10 J/ha/yr

Transformity =26,199 (Calculated as weighted average of rainfall and run-in)

Table 11. Emergy evaluation of storages of natural capital in forested wetlands.

Note	Item	Data	Units	Transformity (sej/unit)	Solar Emergy (E+15 sej)	Em$ Value* (2000 em$/yr)
	Structure (Natural Capital)					
1	Live Biomass	2.90E+12	J/ha	106613	309	$321,510
2	Organic Matter	4.42E+12	J/ha	123033	544	$566,304
3	Water	1.87E+10	J/ha	26199	0.5	$511
4	Basin Structure	1.00E+10	g/ha	1.12E+09	11222	$11,690,095

* em$ = solar emergy in column 6 divided by 0.96E+12 sej/$ for U.S. in 2000.

Notes to Table 11.

1LIVE BIOMASS

Biomass =266 tn/ha green biomass (Brown 1978)
Water weight =35 % (estimate)
Energy =(266 tn/ha)(.65 dry weight) (1,000,000 g/tn) (4 Cal/g) (4186 J/Cal)
=2.90E+12 J/ha
Time to maturity =50 yrs
Total annual emergy =sum transpiration, and geologic input
=6.17E+15 Sej/ha/yr
Transformity =(6.17E+15 sej/ha/yr * 50 yrs) / 2.90E+12 J/ha
=106,613 sej/J

2ORGANIC MATTER

Organic Matter =20.3 kg/m2 depth of 20 cm (Dierberg and Ewel 1984)
Heat Content =5.20 Cal/g
Peat =(20 kg/m2)(1.00 E+04 m2/ha)(1000 g/kg)(5.2 Cal/g)(4186 J/Cal)
=4.42E+12 J/ha
Accumulation =Litterfall - Decomposition
Litterfall =4.61E+02 g dry weight/m^2/yr (average, Deghi 1977)
Decomposition =2.31E+02 g dry weight/m^2/yr (50% of litterfall, Deghi 1977)
Turnover Time =Storage of Peat (g) / accumulation (g/yr)
Time to develop peat =88 yrs
Total annual emergy =Sum of transpiration and geologic input
=6.17E+15 Sej/ha/yr
Transformity =(6.17E+15 Sej/ha/yr * 87 yrs) / 4.42E+12 J/ha
=123,033 sej/J

3WATER

Volume of water taken as 89.6% moisture content of the volume of peat plus avg. standing water
Volume of Peat =2.00E+03 m^3 depth of 20 cm (Dierberg and Ewel 1984)
Peat water =1.79E+03 m^3
Standing water volume =2.00E+03 m^3
Gibbs Free Energy =4.94 J/g
=(3.79E+03 m^3)(1.00E+06 g/m^3)(4.94 J/g)
=1.87E+10 J/ha
Transformity:26,199 (Calculated as weighted average of rain and run-in)

4BASIN STRUCTURE

Mass Displaced of Basin =(density)(volume displaced)
Density =2 g/cm^3 (Odum 1984)
Volume displaced =5.00E+09 cm^3
=1.00E+10 g/ha
Time =1818 yrs (Odum 1984)
total annual emergy =Sum of transpiration and geologic input
=6.17E+15 Sej/yr
Transformity =(6.17E+15 sej/yr * 1818) / 1.00E+10 J/ha
=1.12E+09 sej/g

Table 12. Emergy evaluation of annual driving energies and environmental services of scrub-shrub wetlands.

Note	Item	Data	Units	Transformity (sej/unit)	Solar Emergy (E+15 sej/yr)	Em$ Value* (2000 em$/yr)
	Energy Sources					
1	Sun	4.19E+13	J/ha/yr	1	0.04	$44
2	Wind	2.96E+09	J/ha/yr	1496	0.004	$5
3	Rain, chemical potential	6.42E+10	J/ha/yr	18199	1.17	$1,217
4	Run-in, chemical potential	2.47E+10	J/ha/yr	47863	1.18	$1,231
5	Geologic input	1.21E+06	g/ha/yr	1.0E+09	1.21	$1,260
	Functions (Env. Services)					
5	Transpiration (water use)	3.76E+10	J/ha/yr	26439	0.99	$1,034
6	GPP	2.57E+11	J/ha/yr	8577	2.20	$2,295
7	Infiltration	6.42E+09	J/ha/yr	26439	0.17	$177

* em$ = solar emergy in column 6 divided by 0.96E+12 sej/$ for U.S. in 2000.

Notes to Table 12.

1SOLAR INSOLATION

Area of wetland = 1.00E+04m^2

Mean Net Radiation = 274Ly (Henning 1989)

=(1.00 E4 m^2)(274 Ly)(10 Cal/m^2/Ly)(4186 J/Cal)(365 days)

= 4.19E+13J/ha/yr

Transformity =defined as 1 (Odum 1996)

2WIND

Area =1.00E+04 m^2

Density =1.3 Kg/m^3

Drag. Coefficient =1.00E-03 (Odum 1996)

Av. Annual Velocity =1.16 mps (Jones et al.1984)

Geostrophic wind =1.93 (observed winds are about 0.6 of geostrophic wind)

=(area)(density)(Drag Coeff.)(velocity)^3(3.15E7 sec/yr)

=3.0E+09 J/ha/yr

Transformity =1,496 sej/J (Odum 1996)

3RAIN, CHEMICAL POTENTIAL

Area = 1.00E+04m^2/ha

Rainfall = 1.3m/yr (NOAA 2002)

Gibbs Free Energy = 4.94J/g2

=(1.00E+04 m^2/ha)(1.3 m)(4.94 J/g)(1.00E+06 g/m^3)

= 6.42E+10J/ha/yr

Transformity = 18,199 (Odum 1996)

4RUN IN, CHEMICAL POTENTIAL

Run-in = 0.5m/yr (Schwartz 1989)

Area = 1.00E+04m^2/ha

Gibbs Free Energy = 4.94J/g

=(0.5 m/yr)(1.00E+04 m^2/ha)(1.00E+06 g/m^3)(4.94 J/g)

= 2.47E+10J/ha/yr
Transformity: 47,863(calculated as 2.63 * transformity of rain assuming total rainfall is required to generate 38% runo-off)

5GEOLOGIC INPUT

Limestone Eroded =0.00605 cm/yr (78% less than Cypress based on infiltration)
Density of Limestone =2 g/cm^3
=(0.00605 cm/yr)(1.00E+08 cm^2/ha)(2 g/cm^3)
=1.21E+06 g/ha/yr
Transformity =1.00E+09 Sej/g (Odum 1996)

6WATER USE (TRANSPIRATION)

Transpiration = 2083g H_2O/m^2/day (Schwartz 1989)
Gibbs Free Energy = 4.94J/g
=(2083g H_2O/m^2/day)(365 days)(1.00E+04 m^2/ha)(4.94 J/g)
= 3.76E+10J/ha/yr
Transformity = 26439(Calculated as weighted average of rain and run-in)

7GROSS PRIMARY PRODUCTION

Net Primary Production = 164g C/m^2/yr (estimate from Flohrschutz, 1978)
=(164 g C/m^2/yr)(8 Cal/g) (4186 J/C)(1E+4 m^2/ha)
= 5.49E+10J//ha/yr
Plant respiration = 603g C/m^2/yr (estimate from Flohrschutz, 1978)
=(603 g C/m^2/yr)(8 Cal/g) (4186 J/Cal)(1E+4 m^2/ha)
= 2.02E+11J/ha/yr
Gross Production = 2.57E+11J/ha/yr
Total annual emergy =Sum of transpiration and geologic input
= 2.20E+15Sej/ha/yr
Transformity =(2.20 E+15 Sej/ha/yr / 2.57E+11 J/ha/yr)
= 8577sej/J

8INFILTRATION

Infiltration Rate = 0.13m/yr (Schwartz 1989)
Gibbs free energy = 4.94J/g
=(0.13 m/yr)(4.94 J/g)(1.00E+06 g/m^3)(1.00E+04 m^2/ha)
= 6.42E+09J/ha/yr
Transformity: 26439 (Calculated as weighted average of water and run-in)

Table 13. Emergy evaluation of storages of natural capital in scrub-shrub wetlands.

Note	Item	Data	Units	Transformity (sej/unit)	Solar Emergy (E+15 sej)	Em$ Value* (2000 em$/yr)
	Structure (Natural Capital)					
1	Live Biomass	1.41E+12	J/ha	31324	44	$45,896
2	Organic Matter	4.46E+12	J/ha	51089	228	$237,184
3	Water	7.48E+09	J/ha	26439	0.20	$206
4	Basin Structure	6.00E+09	g/ha	1.82E+09	10925	$11,379,949

* em$ = solar emergy in column 6 divided by 0.96E+12 sej/$ for U.S. in 2000.

Notes to Table 13.

1LIVE BIOMASS

Biomass =8400.5 g/m^2 (Schwartz 1989)
=(8400.5 g/m^2) (1.00E+04 m^2/ha) (4 Cal/g) (4186 J/Cal)
=1.41E+12 J/ha
Total ann. emergy =Sum of transpiration and geologic input
=2.20E+15 Sej/ha/yr
Time =20 yrs (Schwartz 1989)
Transformity =(2.20 E+15 sej/ha/yr * 20 yrs) / 1.41 E+12 J/ha
=31324 Sej/J

2PEAT

Peat Depth =15.00 cm (Schwartz 1989)
Bulk Density =1.05 g/cm^3 (Schwartz 1989)
% organic matter =0.13 as decimal (Schwartz 1989)
Organic Matter =(% OM)(bulk density)(depth)(1.0 E+4 cm2/m2)(1.0 E-3 kg/g)
=20.48 kg/m^2
Heat Content =5.20 Cal/g
=4.46E+12 J/ha
Accumulation =Litterfall - Decomposition
Litterfall =2.83E+02 g dry weight/m^2/yr (Schwartz 1989)
Decomposition =8.49E+01 g dry weight/m^2/yr (30% of litterfall, Schwartz 1989)
Turnover Time =Storage of Peat (g) / accumulation (g/yr)
Time to dev. peat =103 yrs
Total ann. emergy =Sum of transpiration and geologic input
=2.20E+15 Sej/ha/yr
Transformity =(2.20 E+15 Sej/ha/yr * 103) / 4.46E+10 J/ha/yr
=51089 Sej/J

3WATER

Volume of water taken as 89.6% moisture content of volume of peat plus avg. standing water
Peat Volume =1500 m^3
Peat water =1.34E+01 m^3
Avg. standing water Volume=1.50E+03 m^3
Gibbs Free Energy =4.94 J/g
=(2.84E+03 m^3)(1.00E+06 g/m^3)(4.94 J/g)
=7.48E+09 J/ha/yr

Transformity:26,439 (Calculated as weighted average of rain and run-in)

4BASIN STRUCTURE

Mass Displaced of Basin =(density)(volume displaced)
Density =2 g/cm^3 (Odum 1984)
Volume displaced =3.00E+09 cm^3 depth of 30 cm
=6.00E+09 g/ha
Time =4959 yrs (30 cm/0.00605 cm/yr) (estimate from Odum 1984)
total annual emergy =Sum of transpiration and geologic input
=2.20E+15 Sej/yr
Transformity =(2.20E+15 sej/yr * 4959) / 6.00E+9 J/ha
=1.82E+09

Table 14. Emergy Evaluation of annual driving energies and environmental services of herbaceous wetlands.

Note	Item	Data	Units	Transformity (sej/unit)	Solar Emergy (E+15 sej/yr)	Em$ Value* (2000 em$/yr)
	Energy Sources					
1	Sun	4.19E+13	J/ha/yr	1	0.04	$44
2	Wind	2.96E+09	J/ha/yr	1496	0.004	$5
3	Rain, chemical potential	6.42E+10	J/ha/yr	18199	1.17	$1,217
4	Run-in, chemical potential	2.25E+10	J/ha/yr	51867	1.17	$1,214
5	Geologic input	4.95E+06	g/ha/yr	1.00E+09	4.95	$5,156
	Functions (Env. Services)					
5	Transpiration (water use)	3.16E+10	J/ha/yr	26928	0.85	$887
6	GPP	4.02E+11	J/ha/yr	14436	5.80	$6,043
7	Infiltration	2.69E+10	J/ha/yr	26928	0.72	$754

* em$ = solar emergy in column 6 divided by 0.96E+12 sej/$ for U.S. in 2000.

Notes to Table 14.

1SOLAR INSOLATION

Area of wetland = 1.00E+04m^2

Mean Net Radiation = 274Ly (Henning 1989)

=(1.00 E4 m^2)(274 Ly)(10 Cal/m^2/Ly)(4186 J/Cal)(365 days)

= 4.19E+13J/ha/yr

Transformity =defined as 1

2WIND

Area =1.00E+04 m^2

Density =1.3 Kg/m^3

Drag. Coefficient =1.00E-03 (Odum 1996)

Av. Annual Velocity =1.16 mps (Jones et al.1984)

Geostrophic wind =1.93 (observed winds are about 0.6 of geostrophic wind)

=(area)(density)(Drag Coeff.)(velocity)^3(3.15E7 sec/yr)

=3.0E+09 J/ha/yr

Transformity =1,496 sej/J (Odum 1996)

3RAIN, CHEMICAL POTENTIAL

Area = 1.00E+04m^2/ha

Rainfall = 1.3m/yr (NOAA 2002)

Gibbs Free Energy = 4.94J/g2

=(1.00E+04 m^2/ha)(1.3 m)(4.94 J/g)(1.00E+06 g/m^3)

= 6.42E+10J/ha/yr

Transformity = 18,199 (Odum 1996)

4RUN IN, CHEMICAL POTENTIAL

Assume 1 to 1 watershed to wetland ratio and run-off coefficient of 0.35

Run-in = 0.455m/yr

Area = 1.00E+04m^2/ha

Gibbs Free Energy = 4.94J/g

=(0.455 m/yr)(1.00E+04 m^2/ha)(1.00E+06 g/m^3)(4.94 J/g)

= 2.25E+10J/ha/yr

Transformity: 51,867(calculated as 2.85 * transformity of rain assuming total rainfall is required to generate 35% runo-off)

5GEOLOGIC INPUT

Limestone Eroded =0.02475 cm/yr (9% less than Cypress based on infiltration)
Density of Limestone =2 g/cm^3
=(0.02475 cm/yr)(1.00E+08 cm^2/ha)(2 g/cm^3)
=4.95E+06 g/ha/yr
Transformity =1.00E+09 Sej/g (Odum 1996)

5WATER USE (TRANSPIRATION)

(estimate from Zolteck, 1979; Abtew, 1996; Rushton, 1996)

Transpiration = 0.64m/yr
Gibbs Free Energy = 4.94J/g
=(0.64 m)(1.00E+04 m^2/ha)(1.00E+06 g/m^3)(4.94 J/g)
= 3.16E+10J/ha/yr
Transformity = 26928 (Calculated as weighted average of water and run-in)

6GROSS PRIMARY PRODUCTION

Net Primary Production + Respiration

Net Primary Production = 600g/m^2/yr (estimate from Zolteck et al., 1979)
(600 g/m^2/yr)(4 Cal/g) (4186 J/Cal)(1.00E+04
=m^2/ha)
= 1.00E+11J//ha/yr
Plant respiration = 1800g/m^2/yr (based on 75% of GPP)
=(1800 g/m^2/yr)(4 Cal/g) (4186 J/Cal)(1.00E+04 m^2/ha)
= 3.01E+11J/ha/yr
Gross Production = 4.02E+11J/ha/yr
Total annual emergy =Sum of transpiration and geologic input
= 5.80E+15Sej/ha/yr
Transformity =(5.80 E+15 Sej/ha/yr / 5.69E+11 J/ha/yr)
= 14436sej/J

7INFILTRATION

Estimate from Rushton, 1996; 31% of water loss in marsh due to seepage.

Infiltration Rate = 0.54m/yr
Gibbs free energy = 4.94J/g
=(0.54 m/yr)(4.94 J/g)(1.00E+06 g/m^3)(1.00E+04 m^2/ha)
= 2.69E+10J/ha/yr
Transformity: 26928 (Calculated as weighted average of rain and run-in)

Table 15. Emergy evaluation of storages of natural capital in herbaceous wetlands

Note	Item	Data	Units	Transformity (sej/unit)	Solar Emergy (E+15 sej)	Em$ Value* (2000 em$/yr)
	Structure (Natural Capital)					
1	Live Biomass	1.17E+11	J/ha	74244	9	$9,065
2	Organic Matter	1.02E+13	J/ha	95185	968	$1,008,438
3	Water	4.06E+10	J/ha	26928	1	$1,139
4	Basin Structure	5.00E+09	g/ha	1.17E+09	5860	$6,104,113

* em$ = solar emergy in column 6 divided by 0.96E+12 sej/$ for U.S. in 2000.

Notes to Table 15.

1LIVE BIOMASS

Biomass = 700g dry weight/m^2 (estimate from Zolteck et al., 1979)
=(700 g/m^2/yr) (4 Cal/g) (4186 J/kcal)(1.00E+04 m^2/ha)
= 1.17E+11J/ha
Total ann. emergy =Sum of transpiration and geologic input
= 5.80E+15Sej/ha/yr
Time = 1.5yrs (estimate)
Transformity =(5.80 E+15 sej/ha/yr * 1.5 yrs)/ 1.17E+11 J/ha/yr
= 74244sej/J

2PEAT

Peat Depth =75.00 cm p. 49 (Zolteck et al. 1979)
Bulk Density =0.07 g/cm^3 p. 49 (Zolteck et al. 1979)
% organic matter =0.89 as decimal p. 49 (Zolteck et al. 1979)
Organic Matter =(% OM)(bulk density)(depth)(1.0 E+4 cm2/m2)(1.0 E-3 kg/g)
=46.73 kg/m^2
Heat Content =5.20 Cal/g
=1.02E+13 J/ha
Accumulation =Litterfall - Decomposition
Litterfall =5.60E+02 g dry weight/m^2/yr (estimate, 80% of biomass dieback)
Decomposition =2.80E+02 g dry weight/m^2/yr (50 % of litterfall, Zolteck et al. 1979)
Turnover Time =Storage of Peat (g) / accumulation (g/yr)
Time to dev. peat =167 yrs
Total ann. emergy =Sum of transpiration and geologic input
= 5.80E+15Sej/ha/yr
Transformity =(5.80 E+15 Sej/ha/yr * 173) / 1.02E+13 J/ha/yr
= 95185

3WATER

Volume of water taken as 89.6% moisture content of volume of peat plus avg. standing water
Peat Volume = 7.50E+03m3/ha
Peat water = 6.72E+03m^3/ha
Standing water volume = 1.50E+03m^3/ha
Gibbs Free Energy = 4.94J/g
=(8.22E+03 m^3/ha)(1.00E+06 g/m^3)(4.94 J/g)
= 4.06E+10J/ha/yr
Transformity: 26,928 (Calculated as weighted average of rain and run-in)

4BASIN STRUCTURE

Mass in Basin =(density)(volume displaced)
Density =2 g/cm^3 (Odum 1984)
Volume displaced =2.50E+09 cm3/ha
=5.00E+09
Time =1010 yrs (25cm/.02530cm/yr)
Total ann. emergy =Sum of transpiration and geologic input
=5.80E+15 Sej/yr
Transformity =(5.80E+15 sej/yr * 1010yrs) / 5.0E+09 J/ha
=1.17E+09 sej/g

Table 16. Emergy evaluation of annual driving energies and environmental services of floodplain forests.

Note	Item	Data	Units	Transformity (sej/unit)	Solar Emergy (E+15 sej/yr)	Em$ Value* (2000 em$/yr)
	Energy Sources					
1	Sun	4.19E+13	J/ha/yr	1	0.04	$44
2	Wind	2.96E+09	J/ha/yr	1496	0.004	$5
3	Rain, chemical potential	6.42E+10	J/ha/yr	18199	1.17	$1,217
4	Run-in, chemical potential	3.06E+10	J/ha/yr	48500	1.49	$1,547
5	River, geopotential	7.92E+10	J/ha/yr	27764	2.20	$2,290
6	Geologic Input	2.00E+05	J/ha/yr	1.00E+09	0.20	$208
	Functions (Env. Services)					
7	Transpiration (water use)	5.63E+10	J/ha/yr	27984	1.58	$1,642
8	GPP	3.21E+12	J/ha/yr	1236	3.97	$4,140
9	Infiltration	2.88E+10	J/ha/yr	27984	0.81	$841

* em$ = solar emergy in column 6 divided by 0.96E+12 sej/$ for U.S. in 2000.

Notes to Table 16.

1SOLAR INSOLATION

Area of wetland =1.00E+04 m^2

Mean Net Radiation =274 Ly (Henning 1989)

=(1.00 E4 m^2)(274 Ly)(10 Cal/m^2/Ly)(4186 J/Cal)(365 days)

=4.19E+13 J/ha/yr

Transformity =defined as 1 (Odum, 1996)

2WIND

Area =1.00E+04 m^2

Density =1.3 Kg/m^3

Drag. Coefficient =1.00E-03 (Odum 1996)

Av. Annual Velocity =1.16 mps (Jones et al.1984)

Geostrophic wind =1.93 (observed winds are about 0.6 of geostrophic wind)

=(area)(density)(Drag Coeff.)$(\text{velocity})^3$(3.15E7 sec/yr)

=3.0E+09 J/ha/yr

Transformity =1,496 sej/J (Odum 1996)

3RAIN, CHEMICAL POTENTIAL

Area =1.00E+04 m^2/ha

Rainfall =1.3 m/yr (NOAA 2002)

Gibbs Free Energy =4.94 J/g

=(1.00E+04 m^2/ha)(1.3 m)(4.94 J/g)(1.00E+06 g/m^3)

=6.42E+10 J/ha/yr

Transformity =18,199 (Odum 1996)

4RUN-IN, CHEMICAL POTENTIAL , That portion of River overflow that contributes to transpiration

From Water Balance =Rain + Run-in = Transpiration + Infiltration + Evaporation

1.3 + x = 1.25 + .58 + .09 (Brown 1978)

Rin-in =0.62 m/yr

Area =1.00E+04 m^2/ha

Gibbs Free Energy =4.94 J/g

=(0.62 m/yr)(1.00E+04 m^2/ha)(1.00E+06 g/m^3)(4.94 J/g)

=3.06E+10 J/ha/yr

Transformity:48,500 (Buenfil 2000)

5RIVER, GEOPOTENTIAL River channel maintenance

Total River Discharge - Average POR 1978-2000 = 64.61 ft3/s (USGS) or 1.83 m3/s

River Discharge =5.77E+07 m^3/yr (USGS 2002)
Change in height =1.4E-01 m over 100 m (boundary)
Density =1000.00 Kg/m3
Gravity accelleration =9.80E+00 m2/s
Power =7.92E+10 J/yr
Transformity =2.78E+04 sej/J (Odum 1996)

6GEOLOGIC INPUT

Limestone Eroded =1.00E-05 m/yr (Odum 2000)
Density of Limestone =2.00E+06 g/m^3
=(1E-05 m/yr)(2E+06 g/m^3)(1E+04 m^2/ha)
=2.00E+05 g/ha/yr
Transformity =1.00E+09 Sej/g (Odum 1996)

7WATER USE (TRANSPIRATION): calculated as daily summer transpiration rates times 220 days.

Transpiration =1.14 m/yr (estimate from Brown 1978)
Gibbs Free Energy =4.94 J/g
=(1.14 m)(1.00E+04 m^2/ha)(1.00E+06 g/m^3)(4.94 J/g)
=5.63E+10 J/ha/yr
Transformity =27,984 (Calculated as weighted average of rain and run-in)

8GROSS PRIMARY PRODUCTION

Net Primary Production =11.30 tn C/ha/yr (Brown 1978)
=(11.30 tn/ha/yr) (1,000,000 g/tn) (8 kcal/g) (4186 J/kcal)
=3.78E+11 J//ha/yr
Plant respiration =84.68 tn C/ha/yr (Brown 1978)
=(84.68 tn/ha) (1,000,000 g/tn) (8 kcal/g) (4186 J/kcal)
=2.84E+12 J/ha/yr
Gross Production =3.21E+12 J/ha/yr
Total annual emergy = Sum of transpiration, river geopotential, and geologic input
=3.97E+15 Sej/ha/yr
Transformity = (3.97E+15 Sej/ha/yr / 3.18E+12 J/ha/yr)
=1,236 sej/J

9INFILTRATION

Infiltration Rate =0.0016 m/day (estimate)
Gibbs free energy =4.94 J/g
=(0.0016 m/d)(365 d/yr)(4.94 J/g)(1.00E+06 g/m^3)(1.00E+04 m^2/ha)
=2.88E+10 J/ha/yr
Transformity =27,984 (Calculated as weighted average of rainfall and run-in)

Table 17. Emergy evaluation of storages of natural capital in floodplain forests.

Note	Item	Data	Units	Transformity (sej/unit)	Solar Emergy (E+15 sej)	Em$ Value* (2000 em$/yr)
	Structure (Natural Capital)					
1	Live Biomass	3.33E+12	J/ha	47754	158.96	$165,582
2	Organic Matter	2.26E+12	J/ha	101936	230.76	$240,376
3	Water	2.12E+10	J/ha	27984	0.59	$618
4	Geomorphic Structure	3.05E+09	g/ha	1.30E+09	3973.97	$4,139,553

* em$ = solar emergy in column 6 divided by 0.96E+12 sej/$ for U.S. in 2000.

Notes to Table 17.

1LIVE BIOMASS

Biomass =284 tn/ha green biomass (Brown 1978)
Water weight (%) =0.3 as decimal (estimate)
Energy =(284 tn/ha)(.70 dry weight) (1,000,000 g/tn) (4 Cal/g) (4186 J/Cal)
=3.33E+12 J/ha
Time to maturity =40 yrs (estimate)
Total annual emergy =Sum of transpiration, river geopotential, and geologic input
=3.97E+15 Sej/ha/yr
Transformity =(3.97E+15 sej/ha/yr * 40 yrs) / 3.33E+12 J/ha
=47,754 sej/J

2ORGANIC MATTER

Organic Matter =10.4 kg/m^2 (depth of 20 cm) (Brown 1978)
Heat Content =5.20 Cal/g
Peat =(10.4 kg/m2)(1.00 E+04 m2/ha)(1000 g/kg)(5.2 Cal/g)(4186 J/Cal)
=2.26E+12 J/ha
Accumulation =Litterfall - Decomposition
Litterfall =5.97E+02 g dry weight/m^2/yr (Brown 1978)
Decomposition =4.18E+02 g dry weight/m^2/yr (50% of litterfall, estimate, Deghi 1977
Turnover Time =Storage of Peat (g) / accumulation (g/yr)
Time to develop peat =58 yrs
Total annual emergy =Sum of transpiration, river geopotential, and geologic input
=3.97E+15 Sej/ha/yr
Transformity =(3.97E+15 Sej/ha/yr * 35 yrs) / 2.26E+12 J/ha
=101,936 sej/J

3WATER

Volume of water taken as 89.6% moisture content of the volume of peat plus avg. standing water
Peat Volume =2.00E+03 m^3
Peat water =1.79E+03 m^3
Standing water volume =2.50E+03 m^3 (Brown 1978)
Gibbs Free Energy =4.94 J/g
=(3.79E+03 m^3)(1.00E+06 g/m^3)(4.94 J/g)
=2.12E+10 J/ha
Transformity:27,984 (Calculated as weighted average of rain and run-in)

4GEOMORPHIC STRUCTURE Mass of channel + levee displaced

Mass of channel =(Width)(length)(height)(Sinuosity)

Channel Width =1.00E+01 m

Channel length =1.00E+02 m

Sinuosity =1.2 (estimate)

Channel Height =2 m

Channel Mass =2.40E+03 m^3

Levee Mass =(2 levees)(.3 m high)(2 m long)(120 m length of channel)

=144 m^3

Total Mass Displaced =2.54E+03 m^3

Bulk density =1.2 g/cm^3

=3.05E+09 g

Turnover Time = 1000 yrs

Total annual emergy =Sum of transpiration, river geopotential, and geologic input

=3.97E+15 Sej/yr

Transformity =(3.97E+15 sej/yr * 1000) / 3.05E+09 J/ha

=1.30E+09 sej/g

Table 18. Emergy evaluation of annual driving energies and environmental services of mesic hardwood forest.

Note	Item	Data	Units	Transformity (sej/unit)	Solar Emergy (E+15 sej/yr)	Em$ Value* (2000 em$/yr)
	Energy Sources					
1	Sun	4.19E+13	J/ha/yr	1	0.04	$44
2	Wind	2.96E+09	J/ha/yr	1496	0.004	$5
3	Rain, chemical potential	6.42E+10	J/ha/yr	18199	1.17	$1,217
4	Run-in, chemical potential	0	J/ha/yr	18199	0	$0
5	Geologic input	2.00E+05	g/ha/yr	1.00E+09	0.20	$208
	Functions (Env. Services)					
6	Transpiration (water use)	3.71E+10	J/ha/yr	18199	0.67	$702
7	GPP	8.04E+11	J/ha/yr	1088	0.87	$911
8	Infiltration	2.52E+10	J/ha/yr	18199	0.46	$479

* em$ = solar emergy in column 6 divided by 0.96E+12 sej/$ for U.S. in 2000.

Notes to Table 18.

1SOLAR INSOLATION

Area of wetland =1.00E+04 m^2

Mean Net Radiation =274 Ly (Henning 1989)

=(1.00 E4 m^2)(274 Ly)(10 Cal/m^2/Ly)(4186 J/Cal)(365 days)

=4.19E+13 J/ha/yr

Transformity =defined as 1 (Odum, 1996)

2WIND

Area =1.00E+04 m^2

Density =1.3 Kg/m^3

Drag. Coefficient =1.00E-03 (Odum 1996)

Av. Annual Velocity =1.16 mps (Jones et al.1984)

Geostrophic wind =1.93 (observed winds are about 0.6 of geostrophic wind)

=(area)(density)(Drag Coeff.)(velocity)^3(3.15E7 sec/yr)

=3.0E+09 J/ha/yr

Transformity =1,496 sej/J (Odum 1996)

3RAIN, CHEMICAL POTENTIAL

Area =1.00E+04 m^2/ha

Rainfall =1.3 m/yr (NOAA 2002)

Gibbs Free Energy =4.94 J/g

=(1.00E+04 m^2/ha)(1.3 m)(4.94 J/g)(1.00E+06 g/m^3)

=6.42E+10 J/ha/yr

Transformity =18,199 (Odum 1996)

4RUN IN, CHEMICAL POTENTIAL

Run-in =0 m/yr

Mesic Hardwood Forests are not net sinks of run-in.

5GEOLOGIC INPUT

Limestone Eroded =1.00E-05 m/yr (Odum 2000)

Density of Limestone =2.00E+06 g/m^3

=(1E-05 m/yr)(2E+06 g/m^3)(1E+04 m^2/ha)
=2.00E+05 g/ha/yr
Transformity =1.00E+09 Sej/g (Odum 1996)

6WATER USE (TRANSPIRATION)

Transpiration =0.75 m/yr (estimate, Liu 1996, Odum and Brown 1975)
Gibbs Free Energy =4.94 J/g
=(0.75 m)(1.00E+04 m^2/ha)(1.00E+06 g/m^3)(4.94 J/g)
=3.71E+10 J/ha/yr
Transformity =18,199 (Calculated as weighted average of rain and run-in)

7GROSS PRIMARY PRODUCTION

Net Primary Production =10 tn C/ha/yr (estimate, Joyce 1995))
=(9.3 tn/ha/yr) (1,000,000 g/tn) (8 kcal/g) (4186 J/kcal)
=3.35E+11 J//ha/yr
Plant respiration =14 tn C/ha/yr (estimate, 60% of GPP)
=(14 tn/ha) (1,000,000 g/tn) (8 kcal/g) (4186 J/kcal)
=4.69E+11 J/ha/yr
Gross Production =8.04E+11 J/ha/yr
Total annual emergy =Sum of transpiration and geologic input
=8.74E+14 Sej/ha/yr
Transformity =(8.74E+14 Sej/ha/yr / 8.04E+11 J/ha/yr)
=1,088 sej/J

8INFILTRATION

Infiltration Rate =1.40E-03 m/day (estimate from water balance)
Gibbs free energy =4.94 J/g
=(1.4E-3 m/d)(365 d/yr)(4.94 J/g)(1.00E+06 g/m^3)(1.00E+04 m^2/ha)
=2.52E+10 J/ha/yr
Transformity =18,199 (Calculated as weighted average of rainfall and run-in)

Table 19. Emergy evaluation of storages of natural capital in mesic hardwood forests.

Note	Item	Data	Units	Transformity (sej/unit)	Solar Emergy (E+15 sej)	Em$ Value* (2000 em$/yr)
	Structure (Natural Capital)					
1	Live Biomass	2.53E+12	J/ha	12087	30.60	$31,875
2	Organic Matter	1.96E+12	J/ha	19126	37.47	$39,030
3	Water	2.59E+08	J/ha	18199	0.00	$5

* em$ = solar emergy in column 6 divided by 0.96E+12 sej/$ for U.S. in 2000.

Notes to Table 19.

1LIVE BIOMASS

Biomass =216 tn/ha green biomass (Cost and McClure 1982)
Water weight=30 % (estimate)
Energy =(216tn/ha) (0.70 dry weight)(1,000,000 g/tn) (4 Cal/g) (4186 J/kcal)
=2.53E+12 J/ha
Time to maturity =35 yrs
Total annual emergy =sum transpiration, and geologic input
=8.74E+14 Sej/ha/yr
Transformity =(8.74E+14 sej/ha/yr * 35 yrs) / 2.53E+12 J/ha
=12,087 sej/J

2ORGANIC MATTER

Organic matter depth =1.50E+01 cm (estimate)
Bulk density =1.50 g/m^3 (est., USDA 1985, ave. Millhopper-Bonneau-Arredondo)
% organic matter =0.040 as decimal (estimate, USDA 1985)
Organic matter =(% OM)(bulk density)(depth)(1.0 E+4 cm2/m2)(1.0 E-3 kg/g)
=9.0 kg/m^2
Heat Content =5.20 Cal/g
=1.96E+12 J/ha
Accumulation =Litterfall - Decomposition
Litterfall =7.00E+02 g dry weight/m^2/yr (estimate, Lugo et al. 1980)
Decomposition =4.90E+02 g dry weight/m^2/yr (estimate 70% of litterfall, Lugo et al. 1980)
Turnover Time =Storage of Peat (g) / accumulation (g/yr)
Time to dev. OM =43 yrs
Total annual emergy =Sum of transpiration and geologic input
=8.74E+14 Sej/ha/yr
Transformity =(8.74E+14 Sej/ha/yr * 43 yrs) / 1.96E+12 J/ha
=19,126 sej/J

3WATER

Assume same moisture holding capacity as pine flatwoods (3.5%)

Soil Volume =1500 m^3

Soil water =5.25E+01 m^3

Avg. water depth =0.00E+00 m

Gibbs Free Energy =4.94 J/g

=(5.25E+01 m^3)(1.00E+06 g/m^3)(4.94 J/g)

=2.59E+08 J/ha

Transformity:18,199 (Calculated as weighted average of rain and run-in)

Table 20. Emergy evaluation of annual driving energies and environmental services of pine flatwoods.

Note	Item	Data	Units	Transformity (sej/unit)	Solar Emergy (E+15 sej/yr)	Em$ Value* (2000 em$/yr)
	Energy Sources					
1	Sun	4.19E+13	J/ha/yr	1	0.04	$44
2	Wind	2.96E+09	J/ha/yr	1496	0.004	$5
3	Rain, chemical potential	6.42E+10	J/ha/yr	18199	1.17	$1,217
4	Run-in, chemical potential	0.00E+00	J/ha/yr	0	0.00	$0
5	Geologic input	2.00E+05	g/ha/yr	1.00E+09	0.20	$208
	Functions (Env. Services)					
6	Transpiration (water use)	2.74E+10	J/ha/yr	18199	0.50	$519
7	GPP	7.23E+11	J/ha/yr	965	0.70	$727
8	Infiltration	9.38E+08	J/ha/yr	18199	0.02	$18

* em$ = solar emergy in column 6 divided by 0.96E+12 sej/$ for U.S. in 2000.

Notes to Table 20.

1SOLAR INSOLATION

Area of wetland =1.00E+04 m^2

Mean Net Radiation =274 Ly (Henning 1989)

=(1.00 E4 m^2)(274 Ly)(10 Cal/m^2/Ly)(4186 J/Cal)(365 days)

=4.19E+13 J/ha/yr

Transformity =defined as 1 (Odum, 1996)

2WIND

Area =1.00E+04 m^2

Density =1.3 Kg/m^3

Drag. Coefficient =1.00E-03 (Odum 1996)

Av. Annual Velocity =1.16 mps (Jones et al.1984)

Geostrophic wind =1.93 (observed winds are about 0.6 of geostrophic wind)

=(area)(density)(Drag Coeff.)$(\text{velocity})^3$(3.15E7 sec/yr)

=3.0E+09 J/ha/yr

Transformity =1,496 sej/J (Odum 1996)

3RAIN, CHEMICAL POTENTIAL

Area =1.00E+04 m^2/ha

Rainfall =1.3 m/yr (NOAA 2002)

Gibbs Free Energy =4.94 J/g

=(1.00E+04 m^2/ha)(1.3 m)(4.94 J/g)(1.00E+06 g/m^3)

=6.42E+10 J/ha/yr

Transformity =18,199 (Odum 1996)

4RUN IN, CHEMICAL POTENTIAL

Run-in =0 m/yr

Pine Flatwoods are not net sinks of run-in. (Sun 1995)

5GEOLOGIC INPUT

Limestone Eroded =1.00E-05 m/yr (Odum 2000)
Density of Limestone =2.00E+06 g/m^3
=(1E-05 m/yr)(2E+06 g/m^3)(1E+04 m^2/ha)
=2.00E+05 g/ha/yr
Transformity =1.00E+09 Sej/g (Odum 1996)

6WATER USE (TRANSPIRATION)

Transpiration =0.554 m/yr (average from Liu 1996)
Gibbs Free Energy =4.94 J/g
=(0.554 m)(1.00E+04 m^2/ha)(1.00E+06 g/m^3)(4.94 J/g)
=2.74E+10 J/ha/yr
Transformity =18,199 (Calculated as weighted average of rain and run-in)

7GROSS PRIMARY PRODUCTION

Net Primary Production =8.6 tn C/ha/yr (Golkin and Ewel 1984)
=(8.6 tn/ha/yr) (1,000,000 g/tn) (8 kcal/g) (4186 J/kcal)
=2.88E+11 J//ha/yr
Plant respiration =13 tn C/ha/yr (Golkin and Ewel 1984)
=(13 tn/ha) (1,000,000 g/tn) (8 kcal/g) (4186 J/kcal)
=4.35E+11 J/ha/yr
Gross Production =7.23E+11 J/ha/yr
Total annual emergy =Sum of transpiration and geologic input
=6.98E+14 Sej/ha/yr
Transformity =(6.98E+14 Sej/ha/yr / 7.23E+11 J/ha/yr)
=965 sej/J

8INFILTRATION

Infiltration Rate =5.20E-05 m/day (Golkin and Ewel 1984)
Gibbs free energy =4.94 J/g
=(5.2E-05 m/d)(365 d/yr)(4.94 J/g)(1.00E+06 g/m^3)(1.00E+04 m^2/ha)
=9.38E+08 J/ha/yr
Transformity =18,199 (Calculated as weighted average of rainfall and run-in)

Table 21. Emergy evaluation of storages of natural capital in pine flatwoods.

Note	Item	Data	Units	Transformity (sej/unit)	Solar Emergy (E+15 sej)	Em$ Value* (2000 em$/yr)
	Structure (Natural Capital)					
1	Live Biomass	2.11E+12	J/ha	9926	20.94	$21,814
2	Organic Matter	1.06E+12	J/ha	25331	27	$28,000
3	Water	2.25E+08	J/ha	18199	0.004	$4

* em$ = solar emergy in column 6 divided by 0.96E+12 sej/$ for U.S. in 2000.

Notes to Table 21.

1LIVE BIOMASS

Biomass =180 tons/ha green biomass (Cost and McClure 1982)
Water weight =30 % (estimate)
Biomass (dry weight)=126 tons/ha
Energy =(126 tn/ha) (1,000,000 g/tn) (4 Cal/g) (4186 J/Call)
=2.11E+12 J/ha
Time to maturity =30 yrs (estimate, Gholz and Fisher 1982)
Total annual emergy =sum transpiration, and geologic input
=6.98E+14 Sej/ha/yr
Transformity =(6.98E+14 sej/ha/yr * 30 yrs) / 2.11E+12 J/ha
=9,926 sej/J

2ORGANIC MATTER

Organic Matter Depth =1.30E+01 cm (Gholz and Fisher 1982)
Bulk density =1.25 g/m^3 (Gholz and Fisher 1982)
% organic matter =0.03 as decimal (Gholz and Fisher 1982, Edmisten 1963)
Organic matter =(% OM)(bulk density)(depth)(1.0 E+4 cm2/m2)(1.0 E-3 kg/g)
=4.88 kg/m^2
Heat Content =5.20 Cal/g
=1.06E+12 J/ha
Accumulation =Litterfall - Decomposition
Litterfall =4.22E+02 g dry weight/m^2/yr (Gholz et al. 1991)
Decomposition =2.95E+02 g dry weight/m^2/yr (70% litterfall, estimate)
Turnover Time =Storage of Peat (g) / accumulation (g/yr)
Time to dev. OM =38.51 yrs
Total annual emergy =Sum of transpiration and geologic input
=6.98E+14 Sej/ha/yr
Transformity =(6.98E+14 Sej/ha/yr * 38.51 yrs) / 1.06E+12 J/ha
=25,331 sej/J

3WATER

Moisture Holding capacity of sandy soils ranging from 3-12 % depending on fire regimes (Edmisten 1963). An average of 7% was used in this calculation. Assume 1/2 year soil saturated, 1/2 moist, therefore 50% of saturation = 3.5% moisture holding capacity.

Soil Volume =1300 m^3
Soil water =4.55E+01 m^3
Avg. water depth =0.00E+00 m^3
Gibbs Free Energy =4.94 J/g
=(1.16E+03 m^3)(1.00E+06 g/m^3)(4.94 J/g)
=2.25E+08 J/ha
Transformity:18,199 (Calculated as weighted average of rain and run-in)