Notes to Primary Data Sources Table

Marine Systems

Marine systems perform many key functions, from regulating the biosphere to the processing of elements into countless configurations of food webs, sediments, and water column forms. We have focused here on a subset of important functions to which we felt some value could or should be assigned. These include the development of food webs leading to harvestable food and raw materials, nutrient cycling, and the role the ocean plays in regulating gas exchanges with the atmosphere. Where possible, we tried to provide a range of value estimates, recognizing that different sets of assumptions can result in wide divergence in the assigning of value. For food and raw materials production, market values were determined from the best available sources. For biogeochemical fluxes, we attempted to compute replacement values if the natural ecosystems were no longer able to supply the particular service. Finally, we used estimates of real estate price differentials (hedonic pricing) as a surrogate for the service that marine ecosystems perform in enhancing the cultural fabric of society.

Some important values are more difficult to quantify than even the difficult evaluations we did carry out, and for this reason were left out of the current analysis. This includes the assessment of value of biodiversity as such and the services of higher trophic levels as controllers and amplifiers of ecosystem processes. Many of these services simply have no convenient economic analog (e.g., what is the replacement value of a species, or a species assemblage? surely it depends on the species and the assemblage). While acknowledging that these services are probably important, we left them out for now.

Open Oceans

1. Gas Regulation

Oceans play a critical role in the balance of global gas regulation. Oxygen and carbon cycles are intimately linked, as are N, P, and S cycles. We focused on the role of the oceans as (1) a sink for CO_2, since transfers of CO_2 to the atmosphere result in increases in greenhouse warming, and (2) a producer of methane, a secondary greenhouse gas.

A. Two estimates of CO_2 absorption by the world's oceans:

1) Schlesinger (1991) estimated net storage of organic C in marine sediments at ca. 0.1×10^{15} g C y^{-1}, which = 0.366×10^{15} g CO_2 y-1
2) Butcher et al. (1992) discuss a simple model of the global carbon cycle, in which the net input of C to the oceans from the atmosphere is 1×10^{16} mol y^{-1}, which = 44×10^{16} g CO_2 y^{-1}.

Obviously there is a large discrepancy between these estimates. On page 309 of Schlesinger, net inputs of C to the oceans is 2.4×10^{15} g C y^{-1}, and the atmospheric pool is 720×10^{15} g C. Thus, if the ocean were to cease absorbing the net amount of C, it would take 300 yr to double the C pool in the atmosphere, which would lead to an increase of 3 °C. Fankhauser and Pearce (1994) estimated the economic cost of CO_2 as $20.4 per MT carbon. Using the most and least conservative estimates of net removal of CO_2 as C in marine sediments, we arrive at:

a) 0.1×10^{15} g C y^{-1} = 100×10^{6} MT y^{-1} / 32200×10^{6} ha = 0.003 MT C ha^{-1} y^{-1}

0.003 MT C ha-1 y-1 x \$20.4 MT^{-1} = \$0.61 ha^{-1} y^{-1}

b) 1×10^{16} mol C y-1 = 12×10^{10} MT C y-1 / 32200 x 106 ha = 3.73 MT C ha^{-1} y^{-1}

3.73 MT C ha-1 y-1 x \$20.4 MT^{-1} = \$76 ha^{-1} y^{-1}

The average of this low and high estimate is **\$38.3 ha^{-1} y^{-1}**

B. Methanogenesis by the world's oceans

Schlesinger (1991) estimated: 10 x 1012 g CH4 y-1 = 7.5 x 1012 g C y-1 . Fankhauser and Pearce (1994) also estimated the price of CH_4 as a greenhouse gas as \$110 per MT CH_4. This yields: 10×10^{6} MT CH_4 y_{-1} x \$110 MT^{-1} / 32200×10^{6} ha = \$0.03 ha^{-1} y^{-1}. This is negligible compared to the CO_2 benefits.

8. Nutrient cycling.

Oceans are critical in maintaining global nutrient cycles. Here we focus only on nitrogen (N) and phosphorous (P), the major "macronutrients". While we recognize that other macronutrient cycles (eg. sulphur, potassium, silica) and a host of micronutrients are also important, we have ignored them in the current study, implying a conservative estimate. The value of the oceans for global N and P cycling derives from their role as N and P sinks. If the oceans were not there, we would have to recreate this function by removing N and P from land runoff and recycling it back to the land. We took two approaches to evaluating this function.

We assumed that the oceans and coastal waters are serving as sinks to all the world's water that flows from rivers, and that the receiving marine waters provide a nutrient cycling service. If we assume that roughly one-third of this service is provided by estuaries (Nixon et al. 1996 in press) and the remainder by coastal and open ocean, (assume 1/3 by shelf and 1/3 by ocean), then the total quantity of water treated is 40 x 10^{12} m^3 y^{-1}. Replacement costs to remove N and P were estimated at $0.15 - 0.42 m^{-3} (Richard et al. 1991 as quoted in Postel and Carpenter 1997). Thus, the replacement cost for each biome's (1/3) contribution to the total value is $2.0 x 10^{12} - $5.6 x 10^{12} By hectare, the value for ocean (32200 x 10^6 ha) is then **$62.1 - 174 ha^{-1} y^{-1}.**

11. Biological Control

See data (Note 13, below) on estimates of fish production. We assumed that the control function of upper trophic levels is at least 30% of the value of the catch (even though the production in those trophic levels is 3-5 times the catch) (Source: R. D'Arge, personal communication), yielding an estimate of **$5 ha^{-1} y^{-1}**

13. Food production

The following table summarizes data on global fish production, catch and potential catch for both upwelling and open ocean areas.

Ecosystem	Area (10^8 ha)	Pr.Prod (g C m^{-2} y-1)	Fish Prod. (g m^{-2} y^{-1}) (1988-89)	Fish Catch (g m^{-2} y^{-1})	Potential Catch (g m^{-2} y^{-1})	(MT ha^{-1} y^{-1})
Upwelling	5	225	23.2	3.54[1]	4.97	0.0497
Oceanic	332	57	2.46[2]	0.256	0.59	0.0059

Source: Houde and Rutherford 1993 (except for footnotes).

These numbers are probably as good as we can get, and are probably within a factor of 5. Average 1993 price, calculated from imports and exports of total marine fish catches (by continent) is $2.28 kg^{-1} (± $1.18 s.d.) (FAOSTAT Database Collections (on WWW). The value of fish catches, in $ $ha^{-1}y^{-1}$, is assumed to be the average price times the quantity (see main text for a discussion of this assumption). Thus for the total potential catches in these biomes, the value is:

1.Also not given by Houde and Rutherford. I used the catch values provided in Table 1 in Pauly and Christensen for total catch in 1988 and divided that by the shelf area given in Houde and Rutherford (which is 6 times the area of shelf determined by Pauly and Christensen, 1995).

2.This number is likely to be a gross underestimate of ocean fish production, since it assumes production 2.5 trophic levels beyond primary producers. Most of the open ocean fish biomass is not commercially harvested and is composed of secondary consumers (e.g., myctophiids). If one follows the calculations of Houde and Rutherford (1993), substituting trophic level 2 in place of trophic level 2.5, the resulting annual ocean fish production is 4.66 g m-2 y-1; however, potential catch is unlikely to change since most of the "excess biomass"is unlikely to be directly marketable.

Ecosystem	Area (10^8 ha)	Potential Catch $g\ m^{-2}\ y^{-1}$	MT $ha^{-1}\ y^{-1}$	Value (MT x $2280/MT) $\$\ ha^{-1}\ y^{-1}$
Upwelling	5	4.97	0.0497	113
Oceanic	332	0.59	0.0059	13.5
		Area weighted average (upwell + open)		**$15**

14. Raw materials

Considering only one product, i.e. the formation of limestone in shallow ocean basins (and then "spreading" it out over the entire ocean floor):

Estimate #1. Source: Holland 1978: 0.5 mg $cm^{-2}\ yr^{-1}$ = 5 g $m^{-2}\ yr^{-1}$ (from a study by Broecker and Takahashi 1966 on Bahama Grand Banks)

Estimate #2. Source: Schlesinger 1991. 1.5 x 10^{15} g y^{-1} (taken from Wollast 1981.) divided by the area of ocean = 332 x 10^{12} m^2 = 4.52 g $m^{-2}\ y^{-1}$.

These estimates are roughly equivalent to 0.05 MT $ha^{-1}\ y^{-1}$. The market price of limestone (f.o.b., determined by telephone interviews with quarry managers) is approximately $10 MT^{-1}. If we assume that 84% of the price covers capital and labor costs, then the ecosystem "value added" amount is worth $1.60 MT^{-1}. The estimated value of oceans for limestone production is: 0.05 MT $ha^{-1}\ y^{-1}$ x $1.60 MT^{-1} = **$0.08 $ha^{-1}\ y^{-1}$** .

17. Cultural Values

As reflected in literature, song, education, and other ways, humans place tremendous value on coastlines and oceans. One tangible economic manifestation of the cultural value placed on these ecosystems is the willingness to pay for real estate in proximity to estuaries and oceans, compared to the price of comparably sized inland real estate (all other things being equal). Price differentials between inland and waterfront properties in a rich and a poor part of the United States were collected. We then assumed that this differential would be valid for the world's wealthy nations (developed) and would be 100 times lower in the remainder of the world's nations.

California: $0.5 x 10^6 / 0.046 ha = $10.8 x 10^6 ha^{-1}

Alabama: $0.1 x 10^6 / 0.186 ha = $0.54 x 10^6 ha-1

Coastline: "Developed": 194,435 km
"Undeveloped": 284,795 km

Assume that the value extends from the shoreline and back 0.5 km from shore. Then the area of real estate is

Developed 9.7 x 10^6 ha
Undevel. 14.2 x 10^6 ha .

Using the spread in real estate price differentials above, and assuming prices are 100 times less on undeveloped lands, we obtain

Developed values (total): $5.24 to $105 x 10^{12}
Undeveloped: $0.077 to $0.158 x 10^{12}
Total value: $5.32 to 105.2 x 10^{12}

If we divide this value by the area of all marine ecosystems except the open ocean (4102 x 10^6 ha) and amortize over 20 years, the areal values become $65 to $1282 $ha^{-1}\ year^{-1}$ for estuaries, shelves, coral reefs and seagrass ecosystems. If we instead divide this value by the total marine area (36.302 x 106 ha), then the annual value "flow" is $7 to $145 $ha^{-1}\ y^{-1}$ or an average of **$76 $ha^{-1}\ y^{-1}$**

Estuaries

3. Disturbance Regulation

Extrapolated from estimates in Thibodeau and Ostro (1981) and de Groot (1992) on damage prevention in the Netherlands.

8. Nutrient cycling

As we did for oceans, We assumed that the oceans and coastal waters are serving as sinks to all the world's water that flows from rivers, and that the receiving marine waters provide a nutrient cycling service. If we assume that roughly one-third of this service is provided by estuaries (Nixon et al. 1996 in press) and the remainder by coastal and open ocean, (assume 1/3 by shelf and 1/3 by ocean), then the total quantity of water treated is 40 x 10^{12} m^3 y^{-1}. Replacement costs to remove N and P were estimated at $0.15 - 0.42 m^{-3} (Richard et al. 1991). Thus, the replacement cost for each biome's (1/3) contribution to the total value is $2.0 x 10^{12} - $5.6 x 10^{12} . By hectare, the value for estuaries (180 x 10^6 ha) is then **$11,100 - $31,100 ha^{-1} y^{-1}**;

11. Biological Control

See data (Note 13, below) on estimates of fish production, and notes for Ocean for assumptions.

Area (10^8 ha)	Production ($g\ m^{-2}\ y^{-1}$)	Value ($\$\ ha^{-1}\ y^{-1}$)
1.8	39.2	**$ 78**

13. Food production

See notes for Ocean for methods and further details

Ecosystem	Area (10^8 ha)	Pr.Prod (g C m^{-2} y-1)	Fish Prod. ($g\ m^{-2}\ y^{-1}$) (1988-89)	Fish Catch ($g\ m^{-2}\ y^{-1}$)	Potential Catch ($g\ m^{-2}\ y^{-1}$)	(MT $ha^{-1}\ y^{-1}$)
Estuaries	1.8	354	**39.2**	8.5[3]	**10.2**	**0.102**

Source: Houde and Rutherford 1993 (except for footnotes).

Ecosystem	Area (10^8 ha)	Potential Catch $g\ m^{-2}\ y^{-1}$	MT $ha^{-1}\ y^{-1}$	Value (MT x $2280/MT) $\$\ ha^{-1}\ y^{-1}$
Estuaries	1.8	10.2	0.102	**$ 233**

14.Raw materials

The main resources harvested in estuaries are shell (used for hardening trails, indurating roads, mortars and fertilizers); sand for construction of dikes, roads and as fill for residential areas. de Groot (1992) estimated the total value of these products at $25 ha^{-1} y^{-1}.

16. Recreation

Estuaries provide space and suitable environment conditions for many recreational activities and the maintenance of the natural qualities of the area is a prerequisite to safeguard their continued attractiveness for most of these recreational activities. The most common recreational activities are: boating, windsurfing, sportfishing, game

[3] n.b. This estimate not given in Houde and Rutherford for the world's estuaries. For this, I used the total animal catches (for 1988) listed under coastal and coral systems , and the diadromous catches under freshwater systems, given by Pauly and Christensen (1995).

hunting and shore-beach recreation. de Groot (1992) estimated the total value of these activities at \$195 - \$567 $ha^{-1} y^{-1}$, with an average of \$381 $ha^{-1} y^{-1}$

17. Cultural

Many estuarine areas are important sources of historic information as well as scientific and artistic studies. de Groot (1992) estimated the total value of these activities at \$25 - \$34 $ha^{-1} y^{-1}$, with an average of \$29 $ha^{-1} y^{-1}$

Seagrass/Algae Beds

8. Nutrient cycling

For calculation methods, see notes for Ocean. Area = 200 x 10^6 ha, value= **\$10,000 - 28,000 $ha^{-1} y^{-1}$.**

11. Biological Control

Not estimated, but probably considerable value.

12. Habitat/Refugia

Not estimated, but probably considerable value.

13. Food Production

Not estimated, but probably considerable value.

14. Raw materials

Norse (1993) states that seaweeds, agar, and carageenans are worth \$400 M y^{-1}. Dividing this by area of seagrass/algae beds (see note 8 above), we obtain \$ 2 $ha^{-1} y^{-1}$.

Coral reefs

General

Coral reefs are highly productive, diverse and attractive ecosystems producing a wide range of valuable goods and services. From the studies that were found, the services of disturbance regulation and recreation were particularly well quantified. Food production constitutes another important and quantifiable benefit from coral reefs. The diversity of the additional values is only an indication that there are many goods and services still unquantified, such as medicines and research and education.

Continental Shelves

8. Nutrient cycling

See notes for Ocean for assumptions. Area = 2660 x 10^6 ha. Value= **\$752 - 2,110 $ha^{-1} y^{-1}$**

11. Biological Control

See data (Note 13, below) on estimates of fish production, and notes for Ocean for assumptions.

Ecosystem	Area (10^8 ha)	Production ($g\ m^{-2} y^{-1}$)	Value (\$ $ha^{-1} y^{-1}$)
Shelves	23	15.5	**\$ 39**

13. Food production

See notes for Ocean for methods and further details

Ecosystem	Area (10^8 ha)	Pr.Prod (g C m^{-2} y-1)	Fish Prod. (g m^{-2} y^{-1}) (1988-89)	Fish Catch (g m^{-2} y^{-1})	Potential Catch (g m^{-2} y^{-1})	(MT ha^{-1} y^{-1})
Shelves	23	162	15.5	0.174	2.98	0.0298

Source: Houde and Rutherford 1993.

Ecosystem	Area (10^8 ha)	Potential Catch g m^{-2} y^{-1}	MT ha^{-1} y^{-1}	Value (MT x $2280/MT) $ ha^{-1} y^{-1}
Shelves	23	2.98	0.0298	**$ 68**

Terrestrial Systems

Terrestrial systems provide a large number of services, but valuation studies have examined these services unevenly. Little economic information was available for the valuation of soil formation, waste treatment, gas regulation, biological control, pollination, or refugia, though it is clear that these systems contribute significantly to these processes as well. Much of these contributions that we lack information for, however, are included in larger scale studies and are included in the tally for total, global ecosystem services.

Forests

General

Forests have obvious direct use values, as a source of many harvestable products, ranging from timber to food and drug products. They have a more indirect value by providing a variety of ecosystem services. Through their role in moderating rainfall impacts and water absorption, they enhance geophysical stability, reducing erosion of soils. Excessive erosion would not only interfere with aquatic processes but would reduce soil fertility itself and impede normal nutrient and hydrologic cycling. They provide valuable air purification functions, removing lead and other potential toxins from the atmosphere. Forests protect against pest infestations and help assure quality water supplies. Trees are important in water storage processes storing water themselves, playing a critical role in evapotranspiration, and providing pathways for water retention in subsurface reservoirs. The result is a more reliable and constant flow of water downstream, reductions in peak flooding events and a larger average stock of available water supplies. They provide important climate regulation services from local to global scales. These services are a result of transpiration processes, albedo and roughness effects, and carbon cycling. Local rainfall can be reduced as a result of deforestation, since water storage and evapotranspiration are diminished. Forests serve to protect against storm damages, acting as windbreaks and creating roughness effects in diminishing storm intensities. Global warming potential from deficiencies in carbon sequestration capacity is well known. Forests provide option values associated with support of species and genetic diversity. They also have broader cultural values through their importance in folklore and broad cultural support.

Valuation of services of forests must take the types of service flows, such as timber and climate regulation, and assign monetary values to them. These monetary values can be of two basic types: benefits received or costs avoided by provided equivalent services in another manner. For example, the benefits received marginal value of timber would equal stumpage values; i.e., market prices of timber net of harvest costs. The costs avoided marginal value of timber would be cost savings from using timber rather than other structural materials. In well functioning markets, these two valuations would be approximately similar at the margin. Climate regulation values, for which there are no well-defined markets, can reflect benefits received, measured by enhanced incomes, reduced product prices or damage costs avoided, such as health costs. Alternatively, costs avoided valuation would include the cost savings from not having to control carbon dioxide emissions in economic processes. In well functioning social policy markets, these two valuations would be approximately similar at the margin. However, this may be less likely than the assumptions for well functioning markets for material commodities. There is considerable debate whether the benefits of climate control exceed the costs of control.

As with other ecosystem types, the services and values of those services are not globally homogeneous. Brazil nuts are harvested in Brazilian rain forests but not in Madagascar. Erosion protection of fisheries may be an important function in Mexico but not equally so in all forested locations. Furthermore, valuation of those services may differ significantly, depending upon supply and demand conditions and incomes. Spatial generalizability of valuation results is inherently problematic (Pearce and Moran, 1994).

Services of ecosystems are flows stemming from the natural capital stock. Therefore, services have an inherent "sustainability" connotation. Keeping with this implication, services of ecosystems can be valued on a "sustainable basis. Forests have value for their sustainable flow of timber raw material, food products, carbon sequestration, erosion control, etc. It is highly debatable whether existing flows of services, particularly timber, are sustainable. We have attempted to use estimates of sustainable services flows in estimating forest service values below.

2. Climate Regulation

Estimates for the climate regulation value of forests were based largely on average damage avoided cost studies (e.g., Lampietti and Dixon 1995) or avoided costs of alternative controls (e.g., Krutilla 1991). These studies typically estimate the carbon storage capacity that would be lost under various forms of forest degradation, and relate that to future damages or current costs avoided. So forest conversion to other land uses, such as agriculture or pasture, releases a flux of carbon during conversion and reduces global carbon storage capacity. For example, Adger, et al. (1995) estimated the avoided climate related damages from losses of forests in Mexico at $62 per hectare per year. Indexing to $1996 results in an estimated damage cost savings of $70 per hectare per year. Krutilla (1991) estimated the costs of alternative controls from forest loss at $4200 per hectare, implying an annualized value of $336 (using 8%) when indexed up to $1996. A summary of studies of tropical forests suggest high and low values of $482 and $88 per hectare per year, respectively, with an average of $223 per hectare per year.

These are partial valuations in several ways. While carbon sequestration in forests would be proportionate to forest biomass, increasing loss of forests may alter other ecosystems so dramatically as to change their function in the carbon cycle. For example, forest loss may alter temperature regimes and ocean temperatures, change the carbon cycling value of oceans. Secondly, damages from reductions in carbon sequestration capacity may be highly non-linear, perhaps with damages increases more than proportional to forest loss. Finally, even if damages were proportional to forest loss, the value of those damages may not be proportional. For example, global temperature may be linearly related to forest loss, and crop yields linearly related to temperature. However, the economic value of crop loss may be more than proportional to that crop loss. In other words, there may be good reasons to expect that the marginal value of forests for climate control may increase with forest loss. If so, the marginal valuation methods used here may dramatically underestimate the economic value of total forest climate control services.

3. Disturbance Regulation

Disturbance regulation services were based on a damage-avoided cost study of Cameroon tropical forests (Lampietti and Dixon 1995).

4. Water Regulation

Water regulation value estimates were based on damage costs incurred when deforestation leads to reduction in water quality or fisheries production (Adger et al. 1995, Kumari 1995, Kramer et al. 1992), or on damages avoided by forest preservation.

5. Water Supply

Only one study was used for estimates of water supply service (Kumari 1995) based on market values of water lost to reduced quality created by deforestation.

6. Erosion Control

Erosion control services of forests refer to soil retention functions. Forest loss would result in increased siltation of streams and dams. Degradation in stream quality would impede fishing and recreational activities, while dam siltation results in shorter lifespans. Valuing these losses directly would be using the damages avoided valuation method. Alternative valuation would use the avoided costs of mitigating siltation damages, such as installing sediment trapping devices. Both valuation methods have been used. For example, Chomitz and Kumari (1995) estimated the avoided costs of alternative controls to be worth $54 per hectare in Ecuadorian tropical forests. Adger, et al. (1995) estimate damages avoided to be worth only $0.04 per hectare per year, while Dixon and Hodgson (1992) estimated marine effects of runoff on fishing and tourism incomes. These valuations were indexed to global incomes per capita using the Purchasing Power of GNP per Capita. High and low values were $657 and $0 per hectare per year for tropical forests, respectively, with an average value of $185 per hectare per year.

13. Food Production

Forest production of food products was estimated as an average for the production of fruits, nuts, game, and swidden agriculture from several tropical forests of Asia, Central and South America (e.g., Lampietti and Dixon 1995, Kumari 1995, Pinedo-Vasquez et al. 1992). These studies estimated gross incomes in some cases, and net incomes, the correct measure, in other cases. In some cases native peoples were asked their willingness to pay for these services (Lampietti and Dixon, 1995). These are benefits type measures, and do not reflect the costs of seeking alternative food sources in the absence of forests. These values were scaled to global incomes using the Purchasing Power adjustment. Food products illustrate the valuation problems. For market based cultures, net incomes reasonably reflect the value of food products. Howevever, for subsistence cultures, food products may have an infinite consumer surplus, since human existence is the benefit. Alternative costs of food supplies could be used to estimate values in these cases, but none of these estimates were available. Furthermore, products are unique to ecosystems. Even if there is a generally marketed product, such as Brazil nuts, estimated to be worth nearly $100 per hectare (Mori, 1992), one cannot generalize this value from the Brazilian forests. For example, while the harvesting of wild fruit and latex in Peruvian Amozonia is estimated to be worth over $6000 per hectare (Peters, et al. 1989), this is not very generalizable. These harvest values must deduct harvest costs to obtain net forest contribution.

14. Raw Materials

The valuation of forest raw materials includes values of extractables, including timber and non timber forest products. The goal was to estimate these material flows on a sustainable yield basis, since that would represent the service flows from ecosystem capital. However, there was no attempt made to determine whether current flows of materials are sustainable. They are most likely non sustainable, implying that current flow valuations inflate sustained yield valuations. While the proper measure of value is net of harvest cost, the values of extractables sometimes were estimated net of harvest costs and in other cases were not. Timber values were estimated from global value of production, adjusted for average harvest costs. Average harvest costs were assumed to be 20% of revenues (Sharma, 1992). This value was used for all forests, both temperate and tropical.

15. Genetic Resources

Genetic resource value includes the present and future value of fauna and flora for medicinal purposes. Present values would reflect the “in situ” value of currently used drugs, net of processing and development costs. Future values would be a form of option value. For example, the pharmaceutical firm Merck has paid Cost Rica’s National Institute of Biodiversity $1 million for rights to develop future plant species. In principle, this value would reflect the minimum expected net profits Merck would anticipate from future development. The net social value may be considerably larger, reflecting the social value of cures for disease, which is likely to be much greater than Merck's profits. Most of the studies estimated the market value of pharmaceuticals derived from tropical forests. The correct measure of value is market value net of costs of bringing the raw materials to their marketable, medicinal form. Unfortunately, the cost adjustments could not be made. When drug sales in the US were the basis for an estimate, the US value was extrapolated globally by assuming that citizens of developed countries in Europe, Australia, New Zealand, and Japan would purchase the same value of drugs per capita. This acknowledges an income effect in the demand for drugs, and a weakness of economic valuation. Persons of low income may place high values on life saving and enhancing drugs, but these values would not be reflected in the market place. For this reason, the genetic valuation may severely underrepresent the social value of genetic services.

16. Recreation

Recreation value estimates were based on various methods in different country settings, including travel cost methods (Lampietti and Dixon, 1995) and contingent valuation methods (Kramer et al. ,1992 and Sharma , 1992). These are proper methods of measurement for this value. Generalizability is an obvious problem for recreation values, depending both on the quality of the forests and proximity to demanding populations. The current recreation value of many forests may be near zero. Estimated generalized forest values may reflect potential value, but this may be an overestimate since the recreational value per hectare would undoubtedly diminish is more forests were effectively added to the recreational supply.

17. Cultural

Values for cultural services were based on studies of aggregate willingnesses to pay, primarily for existence values of ecosystems or endangered species in the US (e.g., Pope and Jones 1990). These values are very likely to depend upon income levels of the culture in question. So they have been adjusted to worldwide values using the Purchasing Power of GNP per Capita.

Grass/Rangelands

General

We calculated the net rent for grassland and shrubland areas worldwide at \$57.04 ha^{-1} yr^{-1}. This value is a weighted average of the net rent of those USA states for which the "potential" vegetation was grassland or shrubland (Kuchler, 1964) (KS, IA, MT, ND, NV, UT, AR, NM, TX, OK, NE, SD, MO, IL, IN, CO). Data were obtained from the Census of Agriculture 1992 (US Dept. of Commerce, 1995).

1. Gas regulation

We made independent estimates of this service for carbon dioxide, nitrous oxide, and methane.

a. Carbon dioxide: We used estimates of C losses associated with agricultural use from grassland soils across the Great Plains of USA from Burke et al. (1989). C losses ranged from 0.8 to 2 kg m^{-2} . We used a value of 1 kg m^{-2} in our calculations. We multiplied this number by the cost of CO_2 emissions: \$0.02 (Fankhauser and Pearce 1994). The total cost of releasing this C was \$200 ha^{-1} . To calculated an annual value, we assumed that this amount was released during a 50 years period. We used a discount rate of 5%.

b. Nitrous oxide: Mosier et al. (1991) showed that cultivation of grasslands increase significantly the emissions of nitrous oxide (a greenhouse gas) in the shortgrass steppe of northeastern Colorado. We estimated the annual costs of nitrous oxide emissions based upon the difference in emissions between grasslands and adjacent wheat fields (0.191 kgN ha^{-1} yr^{-1}) and the cost per unit of nitrogen emitted as nitrous oxide: \$2.94 kg N^{-1} (Fankhauser and Pearce 1994).

c. Methane: Cultivation reduces by half the uptake of methane by grassland soils (Mosier et al. 1991). To calculate the cost of methane emissions we used the same approach as for nitrous oxide: we multiply the difference in methane uptake between grasslands and adjacent wheat fields (0.474 kg C ha^{-1} yr^{-1}) times the cost per unit of methane (\$ 0.11 kg CH_4^{-1}).

2. Climate regulation

By using a mesoscale climate model (Pielke et al. 1992, Pielke et al. 1996), Copeland et al. (submitted) estimated that landuse change have caused an increase of 0.16 ^{o}C in the North American Great Plains as a consequence of the reduction of green cover and transpiration during part of the year. Nordhaus (1994) estimated that an increase of 3 ^{o}C in global temperature will produce a decrease in the global economic output of 4%. Assuming a proportional effect of temperature, the impact of 0.16 ^{o}C would be 0.2% of the net economic output (net rent): \$ 0.11 ha^{-1} yr^{-1} .

4. Water regulation

We use data on runoff for grassland and cropland watershed for the southern plains of USA (Jones et al. 1985). We assumed that the difference in runoff between cropland and rangeland watershed is an measure of the water regulation service provided by grasslands. For this particular site (Bushland,Texas, average precipitation 462 mm) there was an increase in runoff from 1.7% for grassland watersheds up to 7.5% for cropland watersheds. The increase of runoff will result in a reduction of water availability. Using Sala et al. (1988) equation on the relationship between precipitation and aboveground net primary production (ANPP), it is possible to estimate the reduction in ANPP derived from an increase in runoff by subtracting runoff from PPT. The calculated difference in potential ANPP between cropland and grassland watershed was 7%. Using Oesterheld et al. (1992) equation on the relationship between ANPP and domestic herbivore biomass, we estimated a reduction in carrying capacity of 10.5%. Assuming an average net return for livestock production of \$25.4 ha^{-1} yr^{-1}, the unit value for water regulation is \$2.54 ha^{-1} yr^{-1}. This calculation considers only the on-site value of water regulation by grassland ecosystems.

6. Erosion control

We valued soil losses based on the reduction of agricultural yields. We assumed that loosing the first 10 cm of the soil will result in a reduction of agricultural yields of 50%. A reduction of yields of 50% will reduce the net rent of grasslands, at least, proportionally. Based on an average net rent for grassland worldwide of \$ 57.04 ha^{-1} (see general assumptions above) the costs of soil erosion control service will be \$ 28.5 ha^{-1} yr^{-1}. This estimate compare reasonable well to the aggregated value provide by Pimentel (1995), \$ 26.7 ha^{-1} yr^{-1}. This estimate considers only on-site services of erosion control.

7. Soil formation

The estimate was derived from studies on carbon accumulation rates in old-fields in eastern Colorado, US (Burke et al. 1995, Ihori et al. 1995). These studies showed that after 50 years of abandonment, C stocks have increased 3000 kg/ha. The costs of CO_2 emissions (calculated based upon the negative effects that increasing CO_2 has on climate) was \$20.4 per ton of C released (Fankhauser and Pearce 1994). The service provide by grasslands in capturing C was calculated as the rate of C accumulation (3000 $kg.ha^{-1}$ / 50 years = 60 kg $ha^{-1}yr^{-1}$) times the cost of C (\$0.0204 kg C^{-1}), \$ 1.2 ha^{-1} yr^{-1} .

9. Waste treatment

Data from Pimentel et al (1996).

10. Pollination

Data from Pimentel et al (1996).

11. Biological control

Data from Pimentel et al(1996).

13 and 14. Food and raw material production

We use the average agricultural net rent for central USA (see above) as an estimate of the value of food and raw material production worldwide.

15. Genetic resources

The majority of the centers of origin of domesticated plants and animals are located in grassland and shrubland areas (McNeely et al. 1995). The estimate of the value of preserving genetic resources of grassland areas was derived from data of the effect that incorporating genetic resistance to disease from wild varieties have in wheat production. Perrings (1995) value the effect of production of incorporating genetic resistance to diseases at \$50 millions per year.

16. Recreation

We provide 3 independent estimates of the recreation value:

a. Hiking/ecotourism: We used data on ecotourism opportunities for the Fynbos area in South Africa (Cowling et al. 1996, Higgins et al. 1996) (\$22 $visitor^{-1}$ day^{-1} , 0.01 visitor ha^{-1}). To extrapolate worldwide we assumed that only 1% of the grassland and shrubland areas are attractive enough for visitors.

b. Big game hunting: Based on data for Wyoming (USA) (Brookshire, 1982): \$250 hunting $trip^{-1}$ and 800 ha $hunter^{-1}$.

c. Wildlife tourism revenue: Based on data presented by Pearce and Moran (1994): \$ 40 ha^{-1} yr^{-1}. As in case a we assume that only 1% of the grassland and shrubland areas have a wildlife density large enough to attract tourists.

Wetlands

General

For the purpose of this study, the wetland biome was divided into freshwater wetlands (swamps, bogs, riparian wetlands and floodplains) and coastal wetlands (tidal marshes and mangroves). Estuaries have been included with the marine-coastal biome. One reason for including tidal marshes and mangroves in one category is due the fact that they perform similar functions in the temperate and tropical climatic regions, respectively.

Wetlands are highly productive and dynamic systems, performing many services to society in their natural state. At the same time, these characteristics have led man to convert wetlands to single-purpose uses (mainly cultivation) at the expense of the loss of most other functions, and the original surface area of wetland-ecosystems has decreased dramatically. Some of these conversions have led to considerable economic damage, like the loss of the dampening effect of riverine forests and floodplains on peak-discharges of rivers (e.g. Mississippi-flooding in 1994 and the floods in Europe in 1993 and 1994)

The estimates included in table 2 are based on actual case studies in various parts of the world; of course both the social and economic value of most functions will vary considerably, depending on the geographic and economic situation of the country involved. For example, the food-production value of a floodplain is valued differently in Africa (US$ 12/ha/year - Barbier et. al. 1991) than in Austria (US$ 90/ha/year - Gren 1994) both because of difference in market-values and in the informal (non-market) economy. While in Africa people may depend on it for a large proportion of their daily subsistence needs, in other countries it is only a small portion of the food-items available .

An even more extreme example of these discrepancies between “developed” and “less developed” countries is the value placed on (drinking) water provided by freshwater-swamps. In the USA this function was valued at over US$ 15,000/ha/year (Gupta and Foster 1975)while the same function was valued at a little over US$ 100/ha/year in Malaysia (Kumari 1995), which may partly be caused by differences in water quality standards, costs and/or availability of alternatives and market values. We have attempted to compensate for these differences as much as possible [see general discussion] but some discrepancies remain.

Wetland-functions that are of particular ecological and economic importance are flood-control , storm protection, nutrient cycling and waste recycling, accounting for almost 80% of their economic value. Within one ecosystem (or biome) some functions are not evenly distributed and we have attempted to correct for these spatial restrictions as much as possible: e.g. recreational activities will focus on the most attractive and accessible parts of the ecosystem so values found for the recreational importance of floodplains or mangroves have not been multiplied for the total surface area but only 30 %.

Within the scope of this survey, it was not possible to make an extensive analysis off all the information available on the functions and values of these biomes and also some wetland functions are under-exposed or not included in the table yet, although their ecological and economic importance is considerable, like their influence on local and even global climate, both through their physical influence on temperature and precipitation, and their influence on gas-exchange with the atmosphere.

Also, except for their importance as nursery areas and migration habitat, little information was found on the economic importance of other biological aspects of the functioning of wetland-ecosystems (e.g. biological control and genetic resources). Thus, the totals given in Tables 2 and 3 should be seen as a very conservative estimate of the total economic value of wetland ecosystems.

1. Gas Regulation

Only one reference was found for the economic value of carbon sequestration in Malaysia, representing a value of 265 US$/ha/y. This value could also be placed under the climate regulation function (2), since the economic calculations were based on avoided damage through reduction of the enhanced greenhouse effect.

3. Disturbance regulation

Disturbance regulation (3) mainly related to flood control (by swamps and floodplains) and storm protection (by tidal marshes and mangroves).

Flood control and storm protection values are based on estimations of prevented damage or the potential, and in some cases actual, costs of replacing this function of the wetland by artificial constructions. Since these data were not available for all types of wetlands, we made a –best professional judgment” to convert these figures into a total value for this function for all wetlands. For floodplains in the USA, this service was valued at US$ 11,137/ha/y (Thibodeau & Ostro, 1981). For swamps, no data was found, but since they are usually found in places that are less sensitive to major disruptions from flooding, their value was estimated to be about 30% of the floodplain value. The total average value was therefore put at US$ 3,341/ha/y in Table 2.

Storm protection values for tidal marshes range from US$ 1/ha/y for estimated damage costs in the USA (Farber & Costanza, 1987), to US$ 567/ha/y in willingness-to-pay for maintenance of a tidal marsh for this function (Costanza et al., 1989) and US$ 7.337/ha/y for replacement costs of the storm protection function of tidal marshes in the UK (Turner, 1989). The average was put at US$ 1,839 for this function in Table 2, which is close to the value found for the substitution cost of the storm protection function of mangroves in Malaysia: US$ 1,701 (Christensen, 1982).

4. Water Regulation

Only one reference was found on the value of the swamp area in Malaysia for buffering irrigation water for rice paddies; the effect on productivity was estimated to be worth 30 US$/ha/y (Kumari, 1995).

5. Water Supply

The water supply function of the swamps and floodplains was estimated to be worth US$ 7600/ha/y, being the average of two very different studies: cost savings in drinking water treatment by a swamp area in Malaysia was estimated to represent a value of US$ 104/ha/y (Kumari, 1995) while a study in the USA showed that the (additional) costs to obtain water from the next best alternative source would be US$ 15,095/ha/y (Gupta & Foster, 1975).

6. Erosion Control and 7. Soil Formation

For erosion control and soil formation no explicit references were found in this (short) study, although wetlands certainly play an important role here. Large, shallow floodplains, for example, accumulate silt (thus trapping soil particles lost by erosion elsewhere) and are often used for grazing or cultivation during part of the year. Usually the value of these functions is included in economic calculations of other functions, notably disturbance regulation (3) and food production (13).

8. Nutrient cycling and 9. Waste Treatment

Because of their high productivity and dynamic nature (both with regard to abiotic factors and food web structures), wetlands play a very important role in nutrient cycling and waste treatment. They can absorb and recycle large amounts of nutrients and other chemical substances without negative side-effects to the overall functioning of the ecosystem. Especially the waste treatment function has a considerable economic value which is increasingly being recognized. Calculations are mainly based on cost-saving calculations and (potential) costs of replacing this wetland function by means of artificial waste treatment. In only one case was a survey conducted to determine the willingness-to-pay for the maintenance of this ecosystem service. The total economic value of this function, even if it is limited to sustainable use levels, is considerable: almost US$ 4,500 for coastal wetlands and about US$ 1,700 for freshwater wetlands. In the case of coastal wetlands, data was only available for tidal marshes and it was assumed that the contribution of mangroves to this function, on a sustainable basis, is about 30%.

10. Pollination and 11. Biological Control

Pollination and biological control are two functions for which wetlands are less important, at least no references were found on these functions in relation to wetlands, although there are indications that cultivated areas adjacent to (natural) wetlands do benefit from the pest control and pollination function of certain wetland species.

12. Habitat/Refugia

The habitat/refugia function of wetlands is important, both with regard to their value as nursery areas for commercially important species (fish and crustaceans) and as resting and feeding areas for many migratory (and sedentary) species. The nursery value was calculated to be worth US$ 170/ha/y (based on market prices), the habitat value for protection of (migratory) species was mainly derived from willingness-to-pay studies, adding up to an average of US$ 439/ha/y.

13. Food Production and 14. Raw Materials

Because of their high productivity and nutrient turnover, wetlands are able to provide a large array of food items and raw materials in considerable quantities on a sustainable basis, including for example fish and shellfish (both through harvesting and aquaculture), furbearers (for food and fur), reed and forest products (including fuelwood and charcoal). Values found in literature run up to US$ 2,752/ha/y for commercial fishing in mangroves in Australia (Hamilton & Snedaker, 1984) and US$ 1,142/ha/y for harvesting of forest products in mangroves in Thailand (Christensen, 1982).

15. Genetic resources

No data was found on genetic resources provided by wetlands although they certainly provide a habitat for species which have important genetic material, medicinal biochemicals or other useful properties.

16. Recreation

Recreational benefits of wetlands mainly related to sportfishing and hunting; also animal observation (especially bird watching) and other –non-consumptive” forms of recreation (like hiking) are important.

17. Cultural

The cultural value of wetlands is considerable although little research has been done on this service. The only references found relate to calculations of the influence of the aesthetic value of wetlands on real estate prices.

Freshwater Lakes and Rivers

General

The freshwaters of the world perform several services of economic value: Fresh water fisheries, excess nutrient reductions, pollution (BOD) reductions, irrigation, industrial, residential water supply , hydropower , water-based recreation and navigation. In all cases, the possibility of water recycling or reuse was considered negligible.

4. Water Regulation

The value for water regulation is derived from a mean estimate for hydropower of $10/acre-foot (1980 $) calculated from 27 sites on the Columbia/Snake River system, 9 sites on the Tennessee River, and 6 sites on the Colorado River and extrapolated to the to globe (Gibbons 1986). An inflator of 1.8 was used on the total 1980 value to convert it to 1994 dollars (US Census Bureau 1995).

5. Water Supply

The estimates for water supply are based on in-stream flow calculations using a total annual renewable freshwater supply of 40,673 km^3 and current annual consumptive use of 3240 km^3 (domestic 8%, industrial 23%, irrigation 69%) (World Resources Institute 1994). An inflator of 1.8 was used on the total 1980 value to convert it to 1994 dollars (US Census Bureau 1995).

8. Nutrient cycling

We realize that the if we did not have the dilution effect of fresh water, pollution controls would be needed to reduce the nutrient loads from cities, farms and industries. The estimate of the ecosystems service value is based on the idea that fresh water bodies provide a nutrient cycling service and that value is also taken from Postel and Carpenter (1996). The value is based on the assumption that normal freshwater nutrient cycling would be equivalent to, and would have to be replaced by, advanced water treatment of municipal wastes (200 $km^3 y^{-1}$for the world, at \$0.25 m^{-3}) plus industrial wastes (295 $km^3 y^{-1}$ at \$0.35 y^{-1}). Flows and costs were taken from Richard et al. (1991) and Shiklomanov (1993).

9. Waste Treatment

To represent the natural service supplied by the breakdown of pollution in fresh water bodies, we used the cost of waste treatment plants that would accomplish the same goal. Waste Treatment cost $2.27/acre-foot (1980 $'s) as an average regional value for dilution of BOD (Gibbons 1986). The value of water supply for consumptive uses $100/acre-foot (1980 $) for irrigation, based on a mean (n=17) of $131/acre-foot (1980 $) for 8 crops in 6 western US states (Gibbons 1986), a mean (n=9) of $151/acre-foot (1972 $) for eastern US states (Gibbons 1986) and a range of values from $10-$100/acre-foot (1971 $'s) for California crops (Howe and Easter 1971). The value for industrial uses of $70/acre-foot (1980 $) is a mean (n=4) for cooling, cotton mills, textile mills and steel production (Gibbons 1986). The estimate of $58.33/acre-foot (1980 $) for domestic use is a mean (n=6) of values given by Gibbons (1986) for Tucson, Raleigh, and Toronto and extrapolated to the world. A consumer index inflator of 1.8 was used to raise each of the 1980 dollar totals to their 1994 equivalent (US Census Bureau 1995).

13. Food Production

The ecological service value estimate for food production (Column 13) is the value of total freshwater fisheries production (UN FAO 1994 as given directly in Postel and Carpenter 1996).

16. Recreation

The recreation (Column 16) estimate is a minimal value based on expenditures for sport fishing in the United States (Felder and Nickum 1992 as given by Postel and Carpenter 1996).

Other Biomes

We were not able to identify any valuation studies for some of the biomes listed in Table 3, notably Desert, Tundra, Ice/Rock, and Urban. In addition, only the food production service of agroecosystems (cropland) has been included. These are obviously areas in need of further study.

Cross-biome Estimates

Some literature contains estimates of the value of ecosystem services as a total for the globe, rather than for specific biomes. In these cases, we took the global values and redistributed back to per hectare estimates. For example, Pimentel et al. (1996) estimates the replacement cost of natural decomposition of wastes from societal activities. Based on global estimates of population for humans, domestic animals, and crop residues, they estimate a total annual production of 38 billion tons of organic waste. If it were necessary to replace natural decomposition with technology, costs would be in the neighborhood of current costs for disposing of wastes. Einstein (1995, cited in Pimentel et al. 1996) gives values of $0.04/kg to $0.045/kg for 2 US cites. Pimentel et al. (1996) use a very conservative value of $0.02/kg to arrive at a global total of $760 billion/y. Assuming that forests and grasslands share the present decomposition service, this total is distributed in Table 1 according to hectare coverage of the biomes.

Pimentel et al. (1995) estimate that soil organisms help produce 1 t/ha/y of topsoil on agricultural soils and about half that amount on natural soils. Topsoil costs $12/ton (Pimentel et al. 1995), yielding an estimate for soil formation of $6/ha that should be applied to grassland and forest biomes.

Various pest control methods are estimated to save $90 billion/y in crops in the US (Pimentel In Press) and natural enemies are estimated to contribute $12 billion of this total (Pimentel et al. 1996). Since the US has 10% of the world's agriculture, a global estimate of $120 billion can be made. This total can be distributed to grassland and agroecosystems at $23/ha. Based on data in McLean (1985) and Crawford and Jennings (1989), Pimentel et al, (1996) estimate an additional $4/ha for biological control in temperate forest systems.

Pimentel et al. (1996) estimate the value of pollinators to U.S. crops at $182 million to $18.9 billion, depending on assumptions. (based on Southwick 1992 and Heinrich 1979) Conservatively, we can estimate $2 billion. Assuming that the US has 10% of the world's crop value, we can estimate $20 billion globally or $14/ha for agroecosystems. The estimates of pollination benefits to insect-pollinated legume pasture in the US is approximately $20 billion (Gill 1991, Robinson et al. 1989). Assuming that the global value is 5 times the U.S. value, this gives a global total of $100 billion or $25/ha for grasslands.

Munasinghe and McNeeley (1994) estimate the value of worldwide ecotourism between $0.5 and $1 trillion/y. Pimentel et al. (1996) choose a conservative figure of $500 billion, yielding $42/ha if we distribute this activity over all of the natural biomes.

A worldwide estimate of $84 billion/yr for pulp and timber products is given by Groombridge 1992 (Cited in Pimentel et al. 1996.

Pimentel et al. 1996 give a value for over-the-counter plant-based drugs at $84 billion worldwide, based on Pearce and Moran (1994).

Pimentel et al. 1996 given an estimate of $88 billion global as the value of forest sequestering of carbon. Pearce (1991) argues for $13 per ton of carbon sequestered in terms of reducing the coastal damage from sea level rise. Pimentel et al (1996) estimate 1.5 t/ha/yr sequestered for temperate forests and 10t/ha/yr for tropical forests. So $19.5/ha for temperate and $130/ha for tropical forests. They point out that this is a very conservative value that only accounts for damages from sea level rise.

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