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Rethinking Ecosystem Services from an Intermediate Product Perspective

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Abstract

The Earth's ecosystems provide myriad goods and services that are essential to human wellbeing. This paper offers a typology of ecosystem services that emphasizes the means by which humans experience the service rendered. The typology distinguishes between services that are directly experienced, and those that are indirect. The paper offers an illustration of how indirect services can be valued when they contributed to production of a marketed product. The intermediate product method described is amenable to indirect services that are one stage removed (Tier 2), two stages removed (Tier 3), or even farther removed from the direct services that humans experience. The intermediate product approach to ecosystem service valuation is illustrated by an example of biological pest management to support soybean food production.

Rethinking Ecosystem Services from an Intermediate Product Perspective

The Earth's ecosystems provide myriad goods and services that are essential to human well-being. As the human footprint on the planet grows larger, people are faced with decisions over whether to abandon, protect, or enhance existing ecosystems, which inevitably involve tradeoffs at many levels. One key approach to obtaining an informed resolution to these tradeoffs is to incorporate economic values of ecosystem services (ES) into the environmental policy decision-making process. In particular, the economic values of ecosystem services should be assessed and compared with the economic values of activities that may compromise them (NRC 2004). This laudable goal raises difficult questions about how to gauge the monetary value of specific ecosystems and their services.

Beginning a decade ago, a number of scientists took on the ambitious task of characterizing broad categories of ES that are fundamentally important to humans. Some have gone farther yet: Costanza et al.(1997) not only characterized the Earth's major ES, but also estimated their "aggregate annual monetary value." That particular attempt to put a price sticker on the planet's entire ES has been justly criticized by environmental economists for violating microeconomic principles of diminishing marginal utility, budget constraints, and comparison of most feasible alternatives (e.g. Pearce 1998, Bockstael et al. 2000, and Daily et al. 2000). But the continuing, frequent citation of Costanza et al.'s (1997) article highlights the felt need by many to link monetary values to ES.

Values of ES are difficult to measure for some of the same reasons that ecosystems themselves are threatened: Most ES are public goods, whose values are not directly expressed in market prices (Goulder and Kennedy 1997). The lack of a formal system of appraising or monitoring the value of natural assets complicates the task of weighing off natural assets against human projects whose benefits are measured in money terms. To a very real degree, to have no price is to have no worth. The recently released report on valuing ES by the National Research Council's Committee on Assessing and Valuing the Services of Aquatic and Related Terrestrial Ecosystems places high priority on research into developing a more explicit and detailed mapping between ES, as typically conceived by ecologists, and the services that people value (and hence to which economic valuation approaches or methods can be applied) (NRC 2004).

This paper reviews existing typologies of ecosystem services and complements them by offering a structure that permits economic valuation to be applied in a meaningful way. It then applies that structure to illustrate how this structure could be adapted to valuation by developing an example from two kinds of ES whose value to humans can be partially estimated via intermediate products in the production of marketed goods and services.

Ecosystem Services: Definition and Scope

Defining ES

From a biophysical perspective, Daily (1997) defines ES as the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life. This definition implies that ES is inherently an anthropocentric

concept—it is the presence of human beings as welfare-maximizing agents that enables the translation of basic ecological structures and processes into value-laden entities (De Groot et al. 2002). These ecosystem structures and processes, also called ecosystem functions, are only referred to as ecosystem services when they are of use to humans in one way or another. In principle, ES need not be anthropocentrically defined, for any species can conceivably obtain services from the ecosystem. A biocentric definition of ES naturally emerges from the view that “species and other natural things have intrinsic rights to exist and prosper independent of whether or not human beings derive satisfaction from them” (Goulder and Kennedy 1997). But while theoretically valid and ethically defensible, the biocentric definition of ES is impractical for three reasons. First, humans are the dominant species on earth, and the values that we humans perceive underpin how we rule this planet. Second, humans have limited ability to discern the preferences of other species, beyond crude measures of demographics and physical health. Third, for purposes of valuation, the tools of economics are based upon human preferences and are scarcely developed for any other species (for a rare exception, see Tschirhart, 2004). Hence, with the great majority of researchers using the term “ecosystem services,” we define them in terms of benefits to humans.

The issue of whether ES must be beneficial is troublesome. Most analysts argue that a service must be beneficial, *ipso facto*. Yet humans vary dramatically in terms how they perceive the role of a particular ecological function. A service to one human can be a nuisance to another. Likewise, ES may be a matter of degree. For example, nutrients carried by rivers are needed to nourish many oceanic organisms, but too much nutrient influx can lead to hypoxia that stifles marine life by depriving it of oxygen. We prefer to

define ES as affecting human welfare in both positive and negative ways. That is, our definition of ES embraces what some would call damaging ecosystem effects as well as beneficial ones.

Scope of ES

Part of what distinguishes *Homo sapiens* is the species' great success not only at gleaned goods and services from existing ecosystems, but also at adapting and managing ecosystems to optimize the production of ES for human ends. A continuum of degree of human activity in ecosystems is illustrated in Figure 1. It ranges from pristine (no human involvement) to human-invaded to human-managed. By "human invaded," we refer to systems where humans intrude partially in natural setting. Examples of human invasive activities include harvesting timber in natural forests, fishing wild fish, and even air pollution. By "human-managed" (or "human-engineered"), we refer to ecosystems that are intentionally manipulated by humans for desired outcomes. Examples include agriculture, sewerage treatment facilities, and planted forests.

The kinds of goods and services that human society receives from ecosystems vary along the spectrum from natural to managed ecosystems (Tilman et al., 2002). The widely-cited thirteen types of ES characterized by Daily (1997)¹ and an even longer list of ES developed by De Groot et al. (2002) emphasize those ES provided by *natural* ecosystems that maintain biodiversity and the production of ecosystem goods (such as food, fodder, fuel wood, and raw materials). Other studies such as Costanza et al. (1997) refer to ecosystem goods and services together as ES and therefore broaden the spectrum to include both natural and managed ecosystems. In the following discussion of ES, we

¹ Two of Daily's (1997) 13 ES have been subdivided for Table 1.

adopt the ampler definition that includes the production of ecosystem goods from managed ecosystems.

Listing ES

The literature characterizing comprehensive sets of ecosystem services includes at least seven published studies and major websites (Costanza et al. 1997; Daily, 1997; ESA; ESP; EcoValue Project; Firth, 2004; De Groot et al., 2002). As reported in Table 1, the current inventory includes 27 ES that are roughly clustered into production of goods and services directly valued by humans, regulation of environmental media that maintain life (e.g., air, water, soil), supporting services that facilitate the production ES, and aesthetic and recreation services. Comparing across studies, five out of the 27 services are noted in all seven studies (climate regulation [#2], regulation of river flows and groundwater levels [#5], waste absorption and breakdown [#14], pollination of crops and natural vegetation [#16], and biological control of pests and pathogens [#18]). Twelve more are mentioned by at least four of the seven studies: purification of air, regulation of atmospheric chemistry, protection from the sun's harmful UV radiation, water purification, soil formation, renewal of soil fertility, erosion control, soil nutrient regulation and storage, provision of habitat for various organisms, maintenance of biodiversity, aesthetic and spiritual amenities, and support of diverse human cultures (#1, #3, #4, #7, #9, #10, #11, #12, #20, #22, #25, and #27). At the other extreme, five ES are only mentioned in a single study. For example, regulation of oceanic chemistry (#8) and ecosystem resistance to invasive species (#17) are only brought up in Firth (2004), the most recent study included in the inventory.

These simple counts reveal that scientists' understanding of ES is evolving over time. Not only has a broad consensus on the comprehensive list of ES not yet been reached, but there is no reason to expect that one ever will be. The list evolves with our scientific understanding of ecosystems. More useful than a comprehensive list is a consensus on the broad categories of potential goods and services that can be derived from all ecosystems (NRC 2004).

Categorizing Ecosystem Services

The earliest taxonomies of ES either did not categorize them (Costanza et al., 1997; Daily, 1997) or listed them by environmental medium or geographical setting (Heinz Center, 2003). If we could take a mental picture of how they affect humans, it might look something like Figure 2 where all ES are felt by humans, and humans alone.

As social scientists have engaged in thinking about ES, they have sought ways to organize them around human needs. Heal (2000) made the broad distinction between life-supporting and life-enhancing ES. The former concerns the basic need for survival, whereas the latter involves the quality of life. In an empirical study of a watershed in Australia, Binning et al. (2001) identify ES in terms of contributions to fulfilling the specific human needs of subsistence, protection, affection, understanding, participation, leisure, creation, identity, and freedom.

De Groot et al. (2002) offer a helpful organizing framework that bridges the ecological classifications to the human ones in classifying ecosystem functions and associated ES into four categories: regulation, habitat, production, and information. The logic underlying their ordering is that the first two functional groups (regulation and

habitat) are essential to the maintenance of natural processes and components, and therefore underpin the other two functional groups. They further present the important idea of “supporting ES” to cover those ES that enable the others to function. The function-based taxonomy of De Groot et al. (2002) has been recognized by the international Millennium Ecosystem Assessment and largely adopted by the National Research Council panel study (NRC 2005),

But while we have argued for an anthropocentric definition of ES, that definition need not imply that all ES benefits are directly felt by humans. The biocentrists are correct that all species receive beneficial services from ecosystems. So indirectly, humans benefit from ES that support those ES that humans experience directly. Based on how direct is their influence on human welfare, we classify ES by tiers of influence (Figure 3). Tier 1 includes those ES directly experienced by humans. It includes ES that 1) protect human health and property protection, 2) supply food and raw materials, and 3) offer aesthetics, recreation, and culture. Tier 2 ES are not directly experienced by humans, but they play crucial supporting roles in governing the flow of Tier 1 ES. Examples of Tier 2 ES include natural pest control, pollination, and nutrient cycling that are intermediate inputs to the production of Tier 1 service of “food and raw material supply.” By extension, Tier 3 ES are ecological structures and functions that support Tier 2 services. Figure 4 illustrates how these three tiers are linked. For the Tier 1 ES of food supply, soybeans are an important food for humans. Soybean aphid (*Aphis glycines*) is an important pest that reduces soybean yield. The Asian lady beetle (*Harmonia axyridis*) is a natural predator of soybean aphid (Fox et al. 2004), so its aphid predation constitutes a Tier 2 ES to humans. But soybean aphids are not present throughout the life cycle of the

Asian lady beetle. In early spring, after the beetles emerge but before the aphids do, the lady beetles feed on dandelion pollen.² Hence, the dandelion offers a Tier 3 ES to humans via its role as a critical food source for Asian lady beetles. Of course, dandelions may also damage soybean yields, creating a negative Tier 2 ES distinct from the positive Tier 3 effect on lady beetles.

Clearly, each actor in the ES tiers may affect lower level tiers in more than one way; likewise, each actor is affected differently by many actors in higher level tiers. As illustrated in Figure 3, all species and their abiotic environments interact in a hierarchical, neural network, where the global network is comprised of tiers, each one comprised of myriad local networks, with each actor representing a node on a local network.

Valuing ES Using Direct and Indirect Effects:

The Intermediate Product Approach

The mechanisms by which people value the three classes of Tier 1 ES are distinct. Many ES in the categories of “health and property protection” and “aesthetics, recreation, and culture” lack direct markets. Their values must be inferred indirectly, often via revealed or stated preferences interpreted through market processes. The role of markets is crucial, because it introduces the core ideas of consumer demand and relative scarcity of supply. Functioning markets exist for most food products and raw materials. The availability of market price information for these ES greatly facilitates estimating the value of higher tier ecosystems through the production functions that link those ecosystem processes to production of the marketed product. Using the imagery of Figure 3, a key part of the value of Tier 3 and Tier 2 ES can be calculated via their effects

² Stuart Gage, personal interview, Professor of Entomology, Michigan State University (Feb. 16, 2005).

on the marketed Tier 1 ES. The essence of using this intermediate product approach is to estimate the partial equilibrium effects of how changes in the Tier 3 and Tier 2 ES affect the supply of the Tier 1 ES.

In the production economics literature, an intermediate product is one that is produced to become an input in a subsequent stage of the production process (Heady, 1952). A classic example is the production of forage crops for livestock feed. A more nuanced case would be the case of leguminous crops whose nitrogen fixation affects the mineral nitrogen available to subsequent cereal crops. When produced by a leguminous crop (say, soybean), nitrogen fixation tends to be viewed by farmers and agricultural economists as a by-product (Beattie, Thompson and Boehlje, 1974). Viewed in a more appreciative light, mineral nitrogen fixed is a joint product of soybean production that can serve as an intermediate product for a cereal crop. Ecological functions that yield many joint products are the norm rather than the exception. Mangrove estuaries produce woody biomass, but they also provide habitat for fish fry that maintain fish stocks (Barbier, 2000).

In order to illustrate the intermediate product approach to valuation of Tier 3 and Tier 2 ES, we return to the illustrative example of how lady beetles contribute to soybean production. Recall that Asian lady beetles prey upon aphids, including soybean aphid, which reduces soybean yields. But in early spring, before soybean aphids hatch, lady beetles feed on dandelion pollen. So Tier 2 pest control (by the lady beetle) has value because the soybean aphid acts as a pest that damages soybean. Tier 3 nutrition of the lady beetle (by the dandelion) has value because the lady beetle offers pest control ES. Yet the same dandelion whose flowers nourish lady beetles in early spring may later

compete with young soybean plants for water and nutrients, meaning that it creates negative Tier 2 ES (damages) to no-till soybean fields. The values resulting from these mixed effects can be parsed by thinking of the ecosystem relationships as mathematical functions.

Because humans stand at the center of our definition of ecosystem services, consider a utility-maximizing farmer who manages ecosystems to produce a marketed good y , say soybean. If we assume his or her utility is defined only on marketed consumption goods subject to a budget constraint, then the farmer's objective becomes equivalent to profit maximization. Soybeans provide a human food ES and have a market, so their sale generates revenue for the farmer from selling output y at price p_y . Soybean requires other inputs to grow, as defined by the convex, separable production function, $y = Y(\cdot)$. The factors and relationships involved in estimating the value of Tier 2 ES from lady beetles and Tiers 2 & 3 services from dandelions can be developed from the following static, mathematical model:

$$\underset{N,H,x}{Max} \pi = p_y Y\{x, W(W^0, H), I(I^0, N, L[L^0, N, W(W^0, H)])\} - p_N N - p_H H - p_x x \quad (1)$$

Equation (1) models the soybean farmer's profit maximization by choosing insecticide N , herbicide H , and yield increasing inputs x in the production of y . It assumes that soybean suffers yield loss from aphid insect pest I , so $\partial Y / \partial I < 0$, where aphid population is increasing in initial level, I^0 , decreasing in insecticide, N , $\partial I / \partial N < 0$, and decreasing in lady beetle population, L , $\partial I / \partial L < 0$. This last relationship describes the Tier 2 ecosystem service of natural pest control provided by lady beetles. Lady beetle population, in turn, is increasing in initial level, L^0 , decreasing in insecticide N , $\partial L / \partial N < 0$ (meaning that insecticide has the unwelcome side-effect of killing lady beetles), and increasing in

dandelion population $\partial L / \partial W > 0$, the early season beetles' food source. This last relationship is the Tier 3 nutritional ES that dandelion provides to the lady beetle. But dandelion, of course, is also a weed causing damage to soybean, $\partial Y / \partial W < 0$. Finally, dandelion populations are increasing in initial level, W^0 , but decreasing in herbicide, $\partial W / \partial H < 0$. For simplicity, we assume that y is the only Tier 1 ecosystem good provided by the agricultural ecosystem that brings monetary profit to the producer and that its market price, p_y , is exogenously determined, as are prices of the purchased inputs, p_N , p_H and p_x .

Assuming an interior solution (i.e., $W(H)$ convex, $Y(\cdot)$ concave in x and convex in W and I , $L(\cdot)$ and $I(\cdot)$ both convex in N), we can derive the following first order conditions for maximization of profit in Equation (1):

$$\frac{\partial \pi}{\partial H} = p_y \frac{\partial Y}{\partial W} \frac{\partial W}{\partial H} + p_y \frac{\partial Y}{\partial I} \frac{\partial I}{\partial L} \frac{\partial L}{\partial W} \frac{\partial W}{\partial H} - p_H = 0 \quad (2)$$

$$\frac{\partial \pi}{\partial N} = p_y \frac{\partial Y}{\partial I} \frac{\partial I}{\partial N} + p_y \frac{\partial Y}{\partial I} \frac{\partial I}{\partial L} \frac{\partial L}{\partial N} - p_N = 0 \quad (3)$$

$$\frac{\partial \pi}{\partial x} = p_x \frac{\partial Y}{\partial x} - p_x = 0 \quad (4)$$

Rearrange equation (2), we have the following condition for optimal herbicide use:

$$MVP_H = MIC_H = p_H - MIC_{H[W(L)]} \quad (5)$$

where MVP_H ³ on the left hand side (LHS) denotes the marginal value product from protecting soybean yield from weed damage by herbicidal weed control,

$$MVP_H = p_y \frac{\partial Y}{\partial W} \frac{\partial W}{\partial H} . MIC_H \text{ denotes the marginal input cost of herbicide, which is}$$

³ Many environmental economics texts that analyze the problem in terms of social welfare derive conditions for marginal costs and marginal benefits aggregated to societal scale. As this illustration focuses on private effects to a farmer, it uses the language of production economics focusing on the value of production and cost of inputs.

composed of herbicide's unit price, p_H , plus an additional term accounting for the marginal cost of H realized through the yield damage from aphid insect pests due to reduced pest control by lady beetles as a result of controlling dandelions with herbicide,

$$MIC_{H[w(L)]} = p_y \frac{\partial Y}{\partial I} \frac{\partial I}{\partial L} \frac{\partial L}{\partial W} \frac{\partial W}{\partial H} < 0. \text{ Note this means that } MIC_{H(W(L))} = MVP_{W(L)} \frac{\partial W}{\partial H},$$

where $MVP_{W(L)}$ denotes the marginal value product of dandelions not as weeds, *per se*, but rather as nutrition for lady beetles. Since $MIC_{H(W(L))} < 0$, the right-hand side of condition (5) is larger than p_H alone, implying that the optimal level of herbicide use (H_{es}^*) must be lower than it would be if ES are not taken into account (see Figure 5).

Assuming that artificial pest control (using N) and natural pest control (using L) are equally effective, then a similar logic follows for the insecticide case as in the herbicide case. Rearranging Equation (3), we obtain the optimal insecticide use condition:

$$MVP_N = MIC_N = p_N - MIC_{N(L)} \quad (6)$$

where MVP_N denotes the marginal value product of insecticide N , $MVP_N = p_y \frac{\partial Y}{\partial I} \frac{\partial i}{\partial N}$, and

MIC_N denotes the marginal cost of N , composed of the unit price of insecticide N (p_N) minus the effect of N on marginal value product due to yield loss resulting from aphid insects that would have been controlled by lady beetles what are killed by the insecticide

application ($MIC_{N(L)} = p_y \frac{\partial Y}{\partial I} \frac{\partial I}{\partial L} \frac{\partial L}{\partial N} \leq 0$). As with weed control, $MIC_{N(L)}$ can be

expressed in terms of the marginal value product of lady beetle predation services,

$MVP_L \frac{\partial L}{\partial N}$. Because $MIC_{N(L)} \leq 0$, the right-hand side of Condition (6) is greater than the

cost of insecticide alone, so as in the herbicide case, the optimal level of insecticide use is

lower than it otherwise would be were ES not taken into account (analogous to the illustration in Figure 5).

Using this intermediate product approach, the value of pest control ES from the lady beetle (and the dandelion on which it depends) can be distilled into two general components: 1) changes in value of marginal yield effects, and 2) changes in input costs. If full information were available to estimate the ecosystem functions relating soybean yields to soybean aphid and dandelion populations, soybean aphids to lady beetle predation and insecticide use, lady beetle predation to dandelion population, and dandelion population to herbicide use, then the value of pest control ES from lady beetles could be estimated. The value of lady beetle pest control ES equals:

- (Indeterminate) Value of soybean yield change from lady beetle pest control instead of pest control by soybean aphid insecticide,
- (Plus) Cost saved from soybean aphid insecticide,
- (Minus) Increased soybean yield loss from permitting dandelion survival,
- (Plus) Reduction in herbicide costs from permitting dandelion survival.

These mixed effects in contributing to a market-based valuation of pest control ES from lady beetles illustrate how full accounting differs from the conventional approximations. For example, estimating ES value solely from cost savings due to averting use of the soybean aphid insecticide might overestimate value if soybean yield suffered greatly from permitting dandelion survival (a necessary condition for lady beetles to survive to offer pest control). Alternatively, estimating ES value only from the value of averted soybean yield loss from aphids would likely overestimate the value even more by ignoring efficacious soybean aphid insecticides, which may cost less than the value of

yield that they protect. Again, the higher level ES effects of permitting dandelion survival would be missed in this approach as well.

A major challenge to implementing an intermediate product valuation model like the one illustrated here is estimating the various ecosystem functional relationships. As noted above, the functions involved include soybean yield ($y=Y(x,W,I)$), soy aphid population ($i=I(I^0,N,L)$), lady beetle population ($L=L(L^0,N,W)$), and dandelion population ($W=W^0,H$). Estimates of these functional relationships are typically not available from secondary sources and may be costly to estimate. Of course, if one wanted to extrapolate these effects at larger scale, it might be necessary to abandon the partial equilibrium assumption and estimate price response to changes in pesticide input demand and soybean supply (Just et al., 1982).

As presented, this model is based solely on relationships associated with production of marketed soybeans in the category of Tier 1 ES that meet human needs for food and raw material supply. A full accounting of pest control ES from lady beetles would also examine effects on humans via changes in the other Tier 1 ES on health and property protection as well as aesthetics, recreation and culture. Extending the valuation to include these would involve mixing market-based values with nonmarket value estimates for the health and aesthetic effects. If lady beetles are less damaging to human health than insecticides and herbicides and if their beauty balances off any nuisance effects, then the “total economic value” from this fuller accounting of pest control ES from lady beetles would exceed the estimate from market-based effects only.

Concluding Remarks

This paper offers a typology of ecosystem services that emphasizes the means by which humans experience the service rendered. The typology distinguishes between services that are directly experienced, and those that are indirect. The paper offers an illustration of how indirect services can be valued when they contributed to production of a marketed product. The intermediate product method described is amenable to indirect services that are one stage removed (Tier 2), two stages removed (Tier 3) or even farther removed from the direct services that humans experience.

The intermediate product approach to valuation has three limitations. First and foremost, it offers only a partial value, one that is typically a lower bound. In the instance illustrated, the value of pest predation services from lady beetles was estimated in terms of the marginal value of yield change and averted insecticide and herbicide costs. But the analysis here omitted the effects of health risks from pesticides. These effects, which have been examined elsewhere (Swinton, 1998), would add further value to the pest regulation ES of lady beetles.⁴ Second, the analysis here is static, so it ignores dynamic effects on crop, pest or predator populations from pest population regulation over time. These effects on the value of pest regulation by lady beetles are likely to be indeterminate, depending upon the size of base pest populations maintained under pesticide vs. lady beetle regulation, the probability that pests develop resistance to the regulator (be it insecticide or beetle), and the effects of technological change on soybean pest control. Third, the model developed here for heuristic purposes involved

⁴ It is important to recognize that the value of pest regulation ES from lady beetles is just that; it is not an estimate of the total value of lady beetles to humans. The latter would need to touch upon the many other ways that humans experience lady beetles, including aesthetic enjoyment, clothing staining and home invasion (by the Asian lady beetle), etc.

differentiable pesticide dose response functions. However, most pesticides are recommended for use in binary fashion, akin to pharmaceutical drugs. If used at all, they should be applied according to the labeled rate. Introducing this element would have made the mathematics more complicated without having changed the general results.

Notwithstanding these limitations, the intermediate product approach to valuation of ES provides lower bound valuation estimates for supporting ES whose effects on humans are moderated through other biotic processes and markets (e.g., in Tier 2 and Tier 3). This exploratory look at the intermediate product approach to ES valuation can spawn various future research directions. One logical extension of the model presented here would be to calculate optimal levels of ES provision, especially in intensely managed ecosystems. That would make endogenous the provision of ES that are intermediate products, a logical step for an optimizing human. Another potential line of research would be to investigate how the value of higher tier ES change as they become more distant from the human experience that gives them value.

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Table 1. Ecosystem services recognized in recent literature*

	Daily (1997)	Costanza et al. (1997)	ESA	ESP	EcoValue Project	De Groot et al. (2002)	Firth (2004)
<i>Regulation Functions</i>							
1 Purification of air	x		x			x	x
2 Climate regulation	x	x	x	x	x	x	x
3 Regulation of atmospheric chemistry		x			x	x	x
4 Protection from the sun's harmful UV radiation	x		x			x	x
5 Regulation of river flows and groundwater levels	x	x	x	x	x	x	x
6 Water supply		x			x	x	
7 Purification of water	x		x	x		(1)	x
8 Regulation of oceanic chemistry							x
9 Soil formation	x	x	x		x	x	
10 Renewal of soil fertility	x		x	x		x	x
11 Erosion control		x	x	x	x	x	x
12 Nutrient regulations and storage	x	x	x		x	x	x
13 Dispersal of seeds	x		x				
14 Waste absorption and breakdown	x	x	x	x	x	x	x
15 Disease control (Regulate disease carrying organisms)			x			x	x
16 Pollination of crops and natural vegetation	x	x	x	x	x	x	x
17 Ecosystem resistance to invasive species							x
18 Biological control of pests and pathogens	x	x	x	x		x	x
<i>Habitat Functions</i>							
19 Provision of shade and shelter				x			
20 Provision of habitat for various organisms		x		x	x	x	
<i>Production Functions</i>							
21 Production of food, fiber, turf, and fuel		x				x	x
22 Maintenance of biodiversity and generic resources	x	x	x	x		x	x
23 Medicinal resources						x	
24 Ornamental resources						x	
<i>Information Functions</i>							
25 Aesthetic and spiritual amenities	x			x	x	x	
26 Recreation		x			x	x	
27 Support of diverse human cultures	x	x		x		x	

(1) De Groot et al.'s (2002) water supply function includes provision of water for consumptive use, which may cover the water purification function.

*Table format adapted from De. Groot et al.'s (2002) function-based taxonomy.

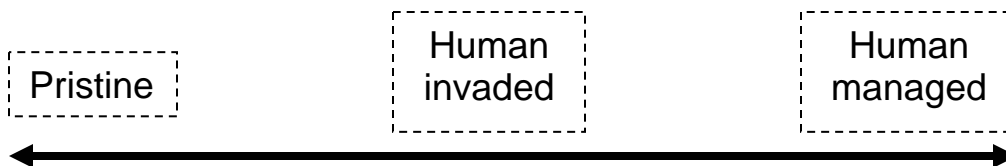


Figure 1. Spectrum of ecosystems by degree of human activity.

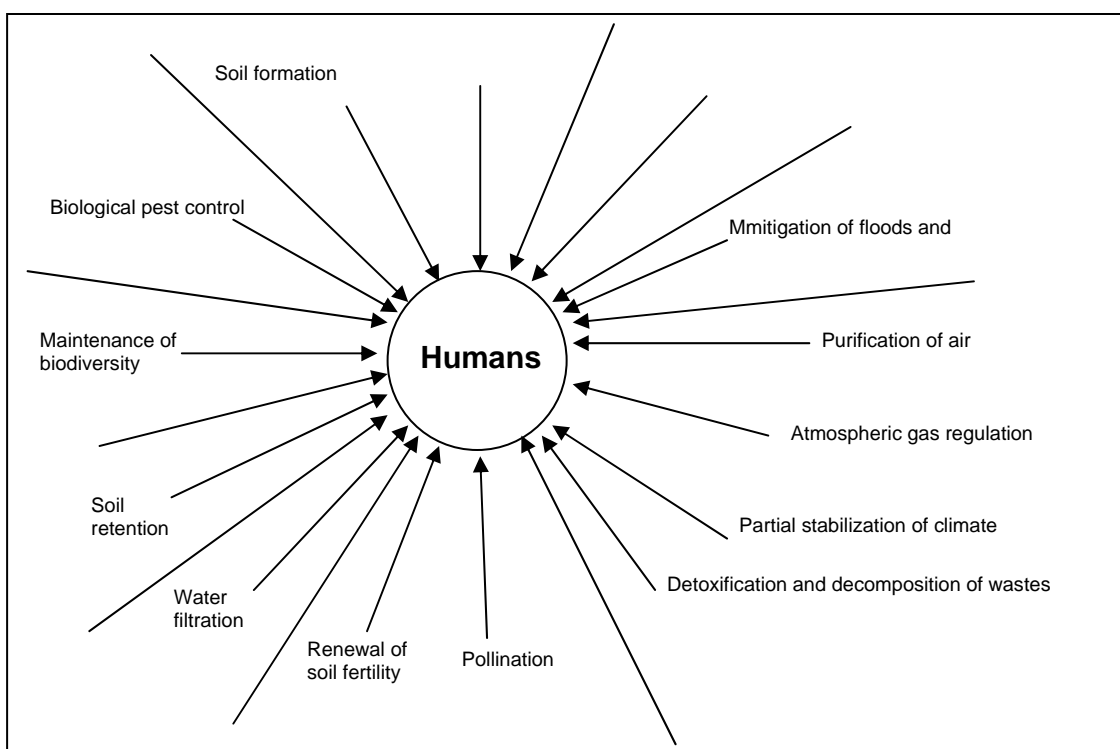


Figure 2. Ecosystem services as directly impinging on human welfare.

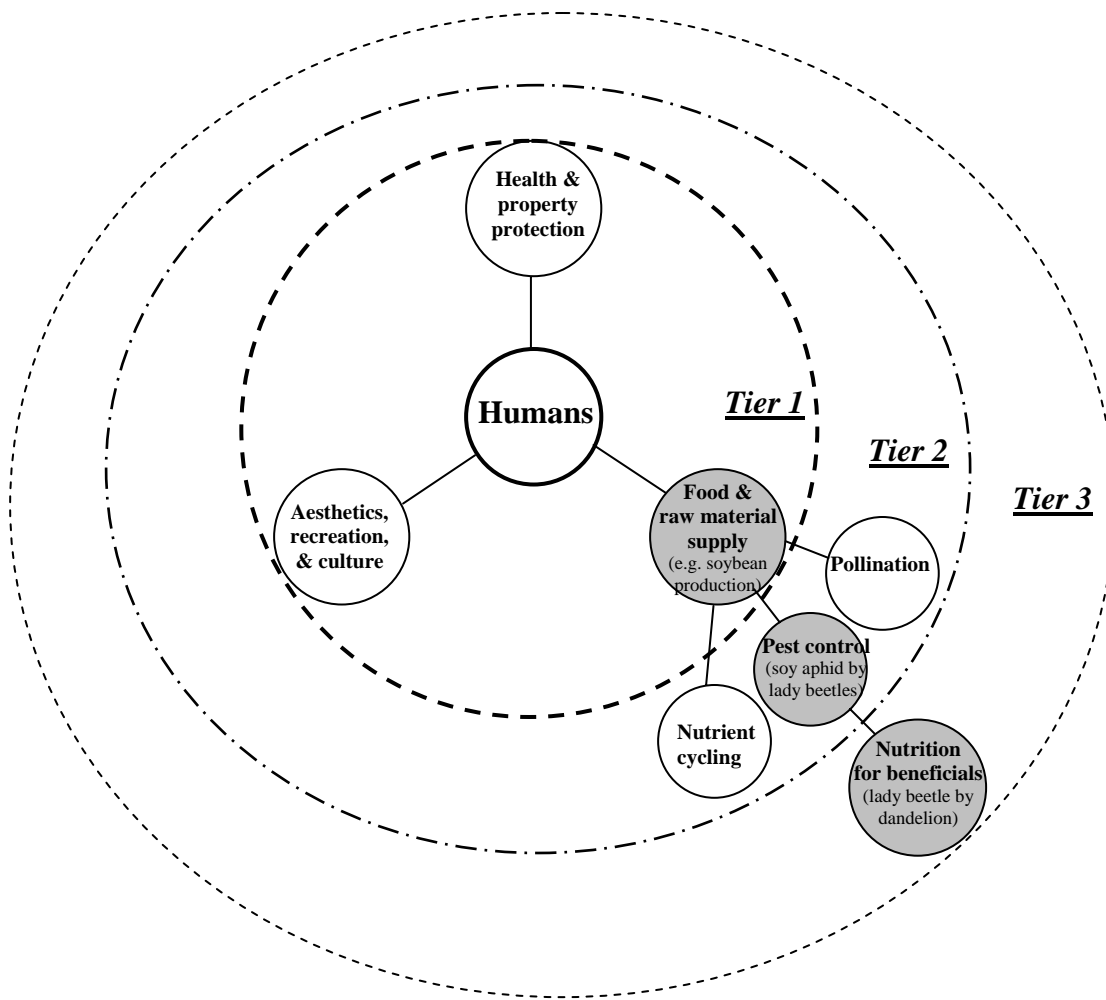


Figure 3. Concentric tiers of ecosystem services as a neural network illustrated with biological pest control of soybean aphid by lady beetles.

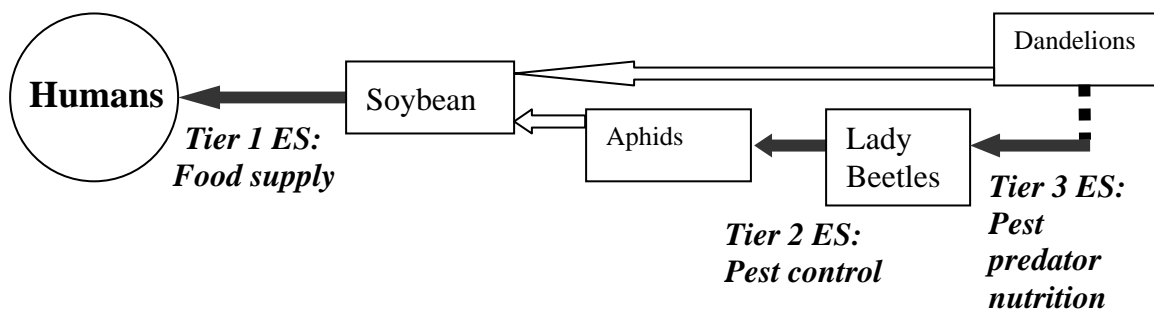


Figure 4. Linkages between the three tiers of ecosystem services (Black arrows represent beneficial services and white arrows represent damaging effects).

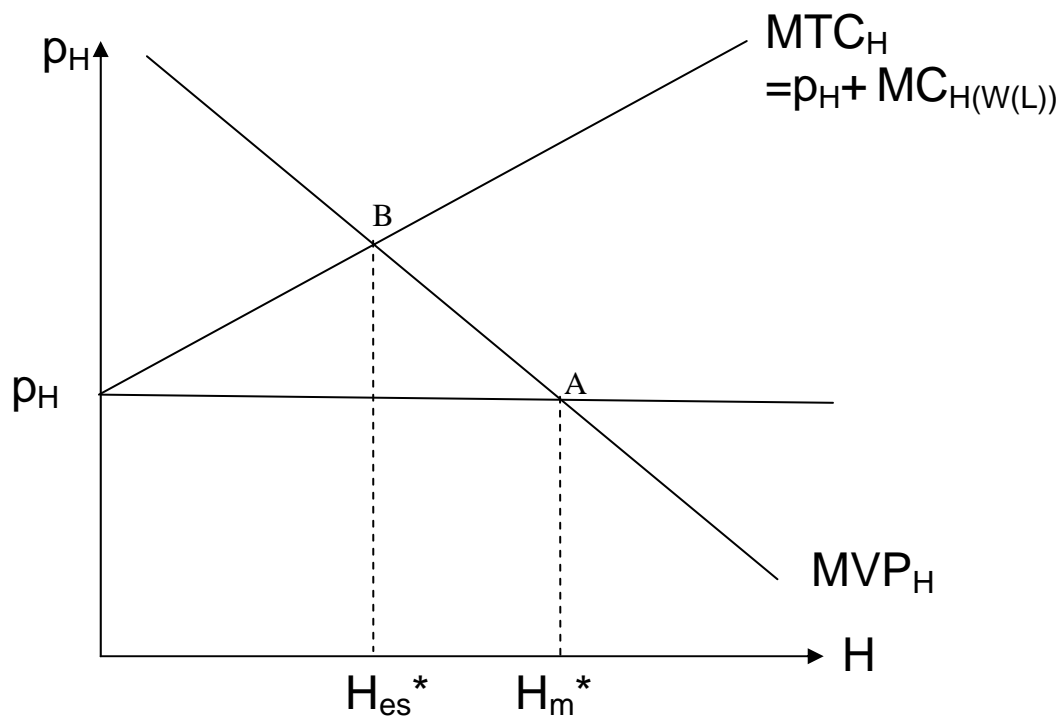


Figure 5. Optimal herbicide rate using only marketed inputs at H_m^* versus accounting for ecosystem services under marginal total input cost (MTC_H) at H_{es}^* .