Emergy Evaluation of Reforestation Alternatives in Puerto Rico

Howard T. Odum, Steven J. Doherty, Frederick N. Scatena, and Pushker A. Kharecha

ABSTRACT. Six alternative ways of reforesting degraded lands in Puerto Rico were evaluated using *emergy* (spelled with an "m"). Emergy and its economic equivalent, *emdollars*, put the contributions of environmental work and human services on a comparable basis. This article shows the emergy method for evaluating forest contributions to public benefit and its use to select alternatives for reforestation. Emdollar values were compared for six scenarios for reforestation of degraded land in Puerto Rico: (1) the natural succession within or adjacent to mature forest; (2) reforestation from the spread of the exotic tree siris *(Albizia lebbek)*; (3) reforestation with plantations of siris and mahogany for harvest; (4) reforestation by leaving plantations unharvested; (5) direct planting of seedlings of many species; and (6) starting patches of forest by massive transfer of topsoil, seed bank, and roots. After energy systems diagrams were made for each reforestation alternative, data were assembled and evaluation tables prepared that estimated the emergy required for: (1) canopy closure and (2) developing species complexity if left unharvested. To explain the method, detailed calculations were included for one of the alternatives, exotic *Albizia lebbek* plantation on 11 yr harvest cycle.

All alternatives generated net public benefit (emdollar yield ratios 4.2 to 24.3). The emdollar value of a closed canopy developed in 10 to 20 yr ranged from 20,000 to 48,000 em$ /ha, whereas the economic costs were $1200 to $9700. For complex forest development in 25 to 60 yr, values ranged from 63,000 to 118,000 em$ /ha, much higher than economic costs of $4000 to $12,000/ha. Highest public benefit per dollar cost came from succession (24.7 em$/$) and exotic colonization (19.1 em$/$). Highest potential monetary returns were from exotic spread (15.1 $/$) and plantations (17.9 and 14.5 $/$). Stand quality after 60 yr, as measured by the transformity (emergy/energy), was largest in mahogany plantation (6.4×10^4 sej/J) and succession forest (3.9×10^4 sej/J). FOR. SCI. 46(4):521–530.

Additional Key Words: Evaluation, emergy, reforestation, Puerto Rico.

THE SURGE OF WORLDWIDE USE OF FORESTS is rapidly removing the forests of the planet, after which lands are used for pastures, plantations, and human settlements. Many uses are not sustainable in the long run, and lands with depleted soils and biodiversity result. Forest restoration and rotations to restore land productivity and carbon-dioxide assimilation are becoming a global priority. Many ways of restoring forests are known including the costly direct planting of trees and the sometimes too-slow natural regeneration.

Whereas market values drive decisions of individuals and businesses, policies and decisions on use of lands and forests need integrated evaluation to select those alternatives that maximize net public benefit. This article uses emergy (spelled with an "m") and emdollars to evaluate on a common basis the real wealth contributed to forests by natural processes *and*

Corresponding author is H.T. Odum, Graduate Research Professor Emeritus of Environmental Engineering Sciences, P.O. Box 116450, University of Florida, Gainesville, FL, 32611-6450—Phone: (352) 378-8172; 392-0847; Fax: (352) 392-3076; E-mail: htoeco@aol.com. Steven Doherty is Assistant Professor, Centre for Sustainable Agriculture (CUL), Swedish University of Agricultural Science (SLU), Box 7047, SE-750 07 Uppsala, Sweden —Phone: 46 18 671493; E-mail: steven.doherty@cul.slu.se. Frederick N. Scatena is Research Hydrologist, International Institute of Tropical Forestry, USDA Forest Service, P.O. Box 25000, Rio Piedras, Puerto Rico, 00928-5000—Phone: (787) 766-5335; E-mail: f_scatena@UPR1.UPR.CLU.EDU. Pushker A. Kharecha, 2208 Meadow Lane Dr., Easton, PA 18040—E-mail: pk44@visto.com.

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by the inputs from the economy. For maximum public benefit, the alternative that restores forest with the most emdollar value relative to economic cost should be chosen. A book summary of environmental accounting with emergy concepts was published previously (Odum 1996).

Forest Contribution and Economic Valuation

Forests are often evaluated by production costs or market values, which are the willingness of humans to pay money for goods and services. However, the contributions of nature's work in forest production and maintenance are not appropriately evaluated with market values. As Figure 1 shows, money is only paid to people for their contributions, and not to the ecosystem. In fact, the market values are inverse to ecosystem contributions. When soils, wood, fruits, clean runoff, and other forest products are abundant, they contribute most, but the market value is small. When the environmental products are scarce, their market value is high.

Many efforts by economists and others have been made in the last two decades to "internalize the externalities," which means modify market valuation to consider ecosystems more. What is done with emergy evaluation is the reverse: to "externalize the internalities," that is, put the contributions of the economy on the same basis as the work of the environment. Referring to Figure 1, the procedure evaluates *E*, the inputs to the forest processes, *F*, the feedbacks from the main economy, and *Y*, forest outputs of economic use and indirect support of the economy.

The benefit and success of each reforestation system needs to be considered in its role as part of a whole cycle of renewal. The best system makes the whole cycle contribute more emergy to the combined system of environment and economy.

Previous Studies

The state of depleted forests and many systems of restoration and reforestation in the tropics were extensively summarized in a monumental review by Wadsworth (1997). His sections on planting, recovery through succession, volunteer forests, natural regeneration, gap planting, rotation, and shifting cultivation include examples from Puerto Rico. Wadsworth found a rich history of reforestation initiatives in Puerto Rico, representative of many tropical areas. Forest cover in Puerto Rico was 36% in 1990.

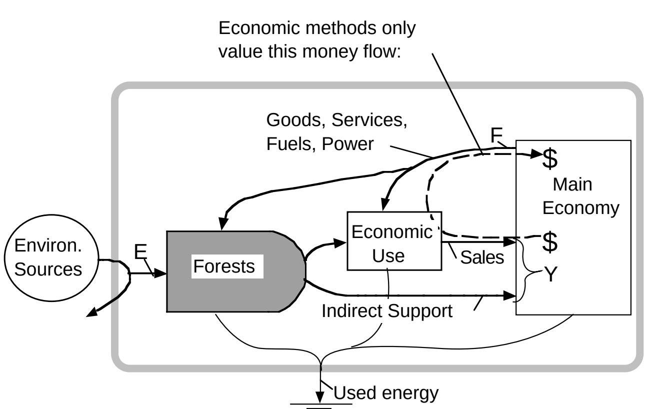


Figure 1. Energy systems diagram of forests and the economy. E = environmental inputs to the forest; F = feedbacks from the economy to forests to process economic use; Y = yields of forest contributions to the economy.

Killian and Fanta (1998) introduced symposium papers on forest degradation and rehabilitation by defining current site potential for comparison with the larger long-range natural site potential. Parrotta et al. (1997) described ways of accelerating natural forest regeneration. Hunter, Hobley, and Smale (1998) showed that the monetary net benefit of restoring degraded land was less than afforesting better land. However, monetary evaluations only include the costs of human service and yields to human use. The inputs from environmental processes and restoration of natural capital are not included.

In our previous studies of net contribution to wood production (Doherty et al. 1994, 1995, Scatena et al. 2000), we used emergy-emdollar measures to evaluate the sustainable inputs to forest growth and harvests. These were averaged over the whole cycle of growth and expressed as annual rates. Evaluations included forests, forest plantations, and parks from New Zealand, Sweden, New Guinea, Southern United States, and elsewhere (Doherty et al. 1994, Doherty 1995, Odum 1984, 1996). Net yield was found to be a function of time of growth and could not be increased by shortening the cycle of harvest and replanting. A comparison of emergy evaluation with other energy analysis approaches was made by Brown and Herendeen (1996).

In this article, we evaluate the emergy accumulated during reforestation, and the averaged annual rate of emergy accumulation. Whereas previous analyses evaluated the harvested yield of forest products, in this study the reforestation yield is taken as the accumulated structure of the whole forest using above- and belowground total organic matter as a measure of the natural capital. Six alternatives were evaluated.

Concepts and Measures

As reviewed by Martinez-Alier (1987), starting in the middle of the last century, investigators have tried to evaluate items of environment and economy with available energy (potential energy, exergy). These did not succeed because energies of different kinds were treated equally. A calorie of sunlight, wind, leaves, wood, coal, hydrogen, animals, and people were all treated as equal. Instead, emergy puts everything that is evaluated in units of one kind of energy required directly and indirectly to produce it. A brief explanation of the emergy concept follows. For detailed discussion and example, see Odum (1996).

Emergy-emdollar evaluation is not new, being applied to agriculture for the President's Science Advisory Committee in 1967 (Odum 1967). As one of several concepts of "embodied energy," it was formally renamed for clarity in 1983 and has been revised and refined in many applications, including evaluations of nations, states, cities, energy sources, technologies, information, materials, history, impacts, and alternative policies.

Emergy

Emergy is based on the *principle of universal energy hierarchy*, which may be a fifth law of energetics (Odum 1976, 1988). Since every transformation process utilizes many joules of available energy of one kind to make a few joules of another, all processes can be arranged in a series web, or an energy hierarchy. Food chains are a familiar example. *Emergy is defined as the energy of one kind required for all the input pathways to operate a network.* The concept is illustrated with Figure 2. The unit of this available energy previously degraded was defined as the *emjoule*. Emergy is a measure of real wealth based on the work of the environment.

In a tree, the energy transformations and transport, from sun to leaves to branches to trunks, generate the high quality structural wood that feeds its service back to support and nourish the limbs and leaves. In our systems diagrams, energy transformation series are drawn from left to right. For example, in Figure 2, abundant sunlight of low quality on the left is transformed in a series of steps into lesser quantities of higher quality in wood and forest uses on the right.

The structures and processes in forests, economic uses, and society are on many scales of time and space. Note the items of three scales illustrated in Figure 2. In order to put the work contributions of the many scales on a common basis, the energy available for work on all scales is evaluated in units of emergy on one scale, solar emjoules (based on one form of energy, solar insolation).

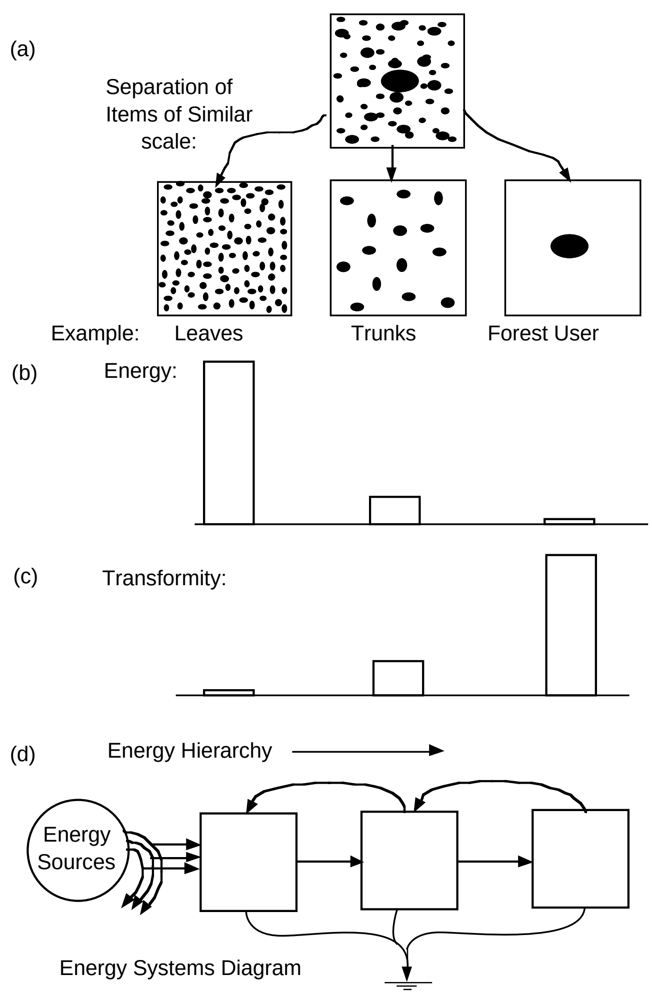


Figure 2. Diagram illustrating the concepts of energy hierarchy. (a) Separation of items of similar scale; (b) flows of energy; (c) transformity of the energy flows; (d) energy systems diagram showing energy flows through units of three scales.

Emergy Flow (Empower)

The rate of flow of emergy per time is defined as *empower*. In this article, emergy flows on pathways are in solar emjoules per year.

Emergy Storage

The solar emergy of storages and structures is the sum of the emergy inputs while the storage was being accumulated. Values of stocks are often calculated as the energy stored multiplied by the solar transformity.

Transformity

In each energy transformation, most of the input potential energy is degraded into "used energy," as required by the second energy law. Energy flow decreases with each step (Figure 2b), but the fewer and fewer joules of output usually have increasingly powerful abilities to feed back as a loop and reinforce the web. Data on the use of energy of one kind to generate a product or service at other levels are used to express all pathways in units of one kind of energy. *Transformity was defined as the joules of available energy of one type that is necessary to generate one joule of available energy of another kind* (Odum 1996). Where solar energy is used as the common denominator, the quantity is the *solar transformity in solar emjoules per joule* (sej/J). By definition, the solar transformity of solar energy reaching the ground is one.

Since all of the energy transformations of the geobiosphere can be arranged in series like that in Figure 2, energy flows of the earth can be regarded as an energy hierarchy. Many joules of available energy at one level are required for a few at the next level. Therefore, transformity indicates position in the energy hierarchy of the geobiosphere. Transformity is also used in this article to indicate the quality of reforestation, with high transformity indicating a higher quality of reforestation.

Emergy evaluation tables often use transformities from previous emergy evaluations (of global processes, energy industries, ecosystems, and so forth). Solar transformities used in this study are summarized in Table 1. New transformities are calculated from emergy evaluation tables. For flows, the total emergy input is divided by the energy of the output. For storages, the total emergy stored is divided by the energy stored.

Thermodynamic Best Transformity

Transformities are a kind of efficiency measure. They measure the total inputs necessary for a unit of output. For any transformation process that operates at maximum production rate, there is a minimum transformity, limited by thermodynamic laws. Most calculated transformities are higher than the minimum because of various inefficiencies that go with newly developed methods, technologies, and waste. The observed higher transformity is used to calculate what is

Table 1. Solar transformities and emergy per mass.*

Note†	Item	Solar transformity (sej/J)	Emergy/mass (sej/g)
1	Sunlight reaching ground	1	—
2	Transpired rain	1.82 E4	
3	Geopotential energy in rain	1.05 E4	
4	Organic matter of soil	7.4 E4	
5	Liquid fuel	6.6 E4	
6	Eroded sediment		1.0 E9
7	Machinery, vehicles		6.7 E9

* Source, Odum (1996). Abbreviations: sej = solar emjoules; J = joule; g = gram. E4 is the computer notation for 10^4. Items #1, 2, 3, and 6 are based on global empower, the sum from the sun, deep heat of the earth, and tide.

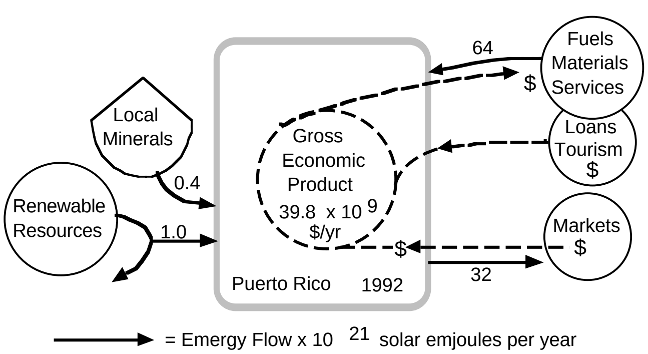
† Notes:

1 Global sunlight reaching the earth's surface defined as 1.
2 Chemical potential energy of fresh water in global rain over land divided by global empower. Rain emergy is used when water is transpired.
3 Geopotential energy of global rain over average land elevation divided by global empower.
4 Empower of forest production divided by energy of the organic matter formed.
5 Motor fuel transformity 1.65 times higher than coal according to work efficiency. Coal transformity the average of several methods (Odum 1996).
6 Earth cycle and erosion rate divided by global empower.
7 Emergy evaluation of steel processing by Bosch (1983).

going into a current process. Sometimes the lowest known value is used to indicate potential gains for being more efficient.

Emdollars

The buying power of money depends on the contributions of real wealth which we measure with emergy. The emdollars are the part of the gross economic product due to an emergy contribution. The emergy evaluation of Puerto Rico by Doherty (1995) is summarized in Figure 3 and provides a ratio between emergy and money (1.64 x 10^{12} solar emjoules per 1992 dollar). *Emergy/money ratio* is the total emergy of a region divided by the gross economic product of that region in a given year. It is a measure of real wealth purchasing power of the money for that economy and that year. In evaluation tables, the emergy flows or storages are divided by the emergy/money ratio to obtain emdollars.



$$\text{Emergy/Money} = \frac{(65.4 \times 10^{21}\ \text{sej/yr})}{(39.8 \times 10^{9}\ \$/\text{yr})} = 1.64 \times 10^{12}\ \text{sej/1992}\ \$$$

Figure 3. Emergy inputs, money circulation, and emergy/money ratio in Puerto Rico in 1992 (Doherty et al. 1994, Doherty 1995).

Valuation Indices

Nine indices were used in the interpretations:

1. *Rate of contribution in em$/ha/yr* indicates speed of restoring real wealth.
2. *Emergy storage in em$/ha* indicates the accumulated value.
3. *Monetary requirement in $/ha* indicates the cost of each alternative.
4. *Market values in $/ha* suggest potential commercial values.
5. *Emdollar/cost ratio in em$/$* indicates public benefit per dollar spent.
6. *Emdollar/market value ratio in em$/$* shows hidden public benefit.
7. *Market value/cost ratio in $/$* suggests commercial advantages.
8. *Emergy yield ratio = emergy of yield/emergy from economy in sej/sej* (Y/F in Figure 1). Yields include products and natural services. This ratio indicates the net public benefit.
9. *Emergy investment ratio = emergy from the economy/emergy of nature* (F/E in Figure 1) measures the intensity of economic development and the impact on the environment. An economically favorable condition is predicted when the emergy investment ratio of an activity is smaller than the average for the surrounding region. A process with low ratio is contributing more free inputs that help economic activities compete. The average investment ratio for Puerto Rico is 46 (Doherty 1995), much higher than the U.S. average of about 7 (Odum 1996).

Methods

The methods used for forest emergy evaluation are listed next using details for a siris plantation, *Albizia lebbek* (Figure 3 and Table 2). They are given in the form of instructions to help those who wish to apply the methods to other forests:

1. Draw an energy systems diagram first. Represent the structure as well as the functions of the systems to help identify the inputs and outputs to be evaluated. Figure 4 is for a siris plantation. Explanations on use of the symbols and their energetic and mathematical meaning are given elsewhere (Odum 1971, 1983, 1994, 1996, Odum et al. 1998, Odum and Odum 1999).
2. Prepare an emergy evaluation table with line items for each input, output, or other flow of special interest. Table 2 evaluates the siris plantation. The first column of the table contains the numbers of the corresponding footnotes, which explain the derivation of the values in the table. The second column lists the items being evaluated and indicates the units. In the third column are the raw data for the items; these are usually expressed as energy, mass, or monetary values. The fourth column contains the emergy per unit of data in the previous column. Transformities and emergy per mass values assembled from other studies

Table 2. Emergy evaluation of of siris (*Albizia lebbek*) in plantation and possible fuelwood harvest in Puerto Rico (modified from Doherty 1995)*—11 yr cycle, 1 ha (Alternative #3, Figure 5).

Note††	Item	Resources used units/ha (J, g, or $)	Solar emergy per unit§ (sej/unit)	Solar emergy stored (E13 sej)	Mean annual solar emergy use (E13 sej/yr)
Environmental sources, 11 yr					
1	Rain, transpired	4.64 E11 J	18,200	846	77
2	Mineral soil	1.78 E7 g	1.0 E9	1,782	162
3	Phosphorus	6,800 g	2.70 E9	20	1.8
Subtotal				2,648	240
Silviculture					
4	Fuels	3.95 E8 J	47,900	21	1.9
5	Tractor	400 g	6.70 E9	3	0.3
6	Weeding labor	1.38 E7 J	4.81 E6	63	5.7
7	Seedling costs	1,313 $	1.64 E12	215	19.5
8	Services	1,540 $	1.64 E12	253	23.0
9	Capital expenses	3,790 $	1.64 E12	622	56.5
Subtotal				1,177	106.6
10	Above ground prod. (114 Tn/ha)	1.89 E12 J	—	3,825	347
Harvesting					
11	Fuels	1.63 E9 J	47,900	86	7.8
12	Tractor	1,206 g	6.7 E9	8.8	0.8
13	Services	1,341 $	1.64 E12	219	20.0
Subtotal			313.8	28.6	
14	Harvested biomass (100 Tn/ha)	1.67 E12 J	—	4,139	376.0

* Since the siris plantation used in this evaluation was only 4.5 yr old (Parrotta 1993a), rotation period was taken as the lower end of optimal rotation length for similar rain-fed plantations in India, reported as 11–14 yr (Parrotta 1987). Biomass accumulation rates are based on 4.5 yr of growth.

† Abbreviations: Tn = Metric ton (10^6 grams); others as noted in Table 1.

†† Notes:

1 Evapotranspired rain = 1710 mm/yr (Scatena et al. 2000) (15 yr to canopy forest) (50%; est. used during growth cycle) (1.71 m/yr) (1 E4 m^2/ha) (1,000 kg/m^3) (4.94 E3 J/kg) (0.5)(11) = 4.64 E11 J/ha.

2 Geologic contribution evaluated at the rate of soil erosion as 1.62 E6 g/ha/yr (Scatena et al. 2000); (1.62 E6 g/ha/yr) (11 yr) = 1.78 E7 g. Solar emergy per mass from world cycle (Odum 1996): 1.0. E9 sej/g).

3 Phosphorus (from weathering and rain): 6.80 E3 g/ha/yr (Parrotta 1987). Solar transformity from phosphate formation in Florida (Odum 1996).

4–9 Silviculture estimates using willow plantation inputs (Doherty 1995, unless otherwise cited).

4 Fuels: (112 l/ha; stand establ. + 10 l/ha; planting = (122 l/ha) (3.56 E7 J/l)/(11.0 yr rotation) = 3.95 E8 J/ha/yr.

5 Tractors: 10 hr/ha; stand establ. + 1 hr/ha; planting = (11 hr/ha)/(15,000 hr; useful lifetime) (6,000 kg; tractor wt) (1,000 g/kg) = 4400 g/ha/rotation/(11.0 yr rotation) = 400 g/ha/yr.

6 Weeding (manual labor): plots were manually weeded every 2 months for first year (Parrotta 1993b): (0.50 hr)/(10 ×10 m plot) (1.0E4 m^2/ha) (6 times/yr) = 300 hr/ha; (300 hr/ha) (2500 kcal/day/24 hr/day) (4186 J/kcal) = 1.3 E8 J/ha.

7 Seedling costs: (75 $/1,000 ind.; price of willow seedlings) (17,500 ind./ha; ave. of 2×2m, 1×1m, 0.5×0.5m density plots (Parrotta 1993a) = 1312.5 $/ha; 1312.5 $/ha/(11.0 yr rotation) = 119.3 $/ha/yr.

8 Services estimated from fuel: (122 l fuel/ha; stand establ., planting) (0.2642 gal/l) (1.23 $/gal; U.S. ave. gas price, July 1995) = 39.65 $/ha; (300 hr/ha; manual labor, item 6) (5.00 $/hr) = 1500.00 $/ha; 1539.65 $/ha/(11.0 yr rotation) = 139.97 $/ha/yr. Where transformities include services they do not appear as separate line items.

9 Capital expenses: ave. land price for areas surrounding Luquillo Experimental Forest 2,898 $/ha (Scatena et al. 2,000) plus property tax: (2,898 $/ha) (28.00 $/1,000 $ assessed land value) (11 yr) = 892 $/ha.

10 Aboveground production (Parrotta 1993a): 46.6 Tns/ha aboveground biomass (incl. understory) after 4.5 yr (46.6 Tn/ha)/4.5 yr = 10.4 Tn/yr; (10.4 Tn/yr) (1.67 E10 J/Tn) (11yr) = (1.89 E12 J/ha/yr).

11–13 Harvest/ Tn estimates using willow plantation inputs (Doherty 1995, unless otherwise cited).

11 Fuels: (5 l/Tn) (3.56 E7 J/liter) = 1.78 E8 J/Tn multiplied by (9.13 Tns/ha/yr; ave. harvest, Y_2 below) = 1.63 E9 J/ha/yr.

12 Tractor: (0.33 hr/Tn) (15000 hr; useful lifetime) (6,000 kg; tractor wt.) (1,000 g/kg) = 132 g/ton multiplied by (9.13 ton/ha/yr harvest) = 1206 g/ha/yr.

13 Services: (13.40 $/ton) (9.1 ton/ha/yr) (11 yr) = 1341 $/ha.

14 Harvested biomass: 4110 g/m^2; branches, stems (w/o leaves, understory) (Parrotta 1993a); (4.110 g/m^2) (1.0E4 m^2/ha)/(1.0 E6 g/Tn)/4.5 yr = 9.13 tons/ha/yr; (9.13 ton/ha/yr) (1.67 E10 J/ton) (11 yr) = 1.67 E12 J/ha/yr.

(Table 1) are used in column 4. Multiplying the values in column 3 by those in column 4 yields the emergy values entered in column 5. In some tables the fifth column contains annual rates (empower), whereas in this article the numbers are emergy accumulations (emergy stored) for the years of growth. The accumulated totals include some "once only" items such as planting seedlings plus some annual values like land tax. In column 6 the average rate of emergy accumulation was obtained by dividing by the number of years required. In this article, emergy evaluations were made for each alternative at two stages: (1) the time of canopy closure, and (2) the time when a more complex forest develops with higher biodiversity.

3. Assemble subtotals and other data for calculating indices (example, Table 3). Estimate the emdollar values of inputs

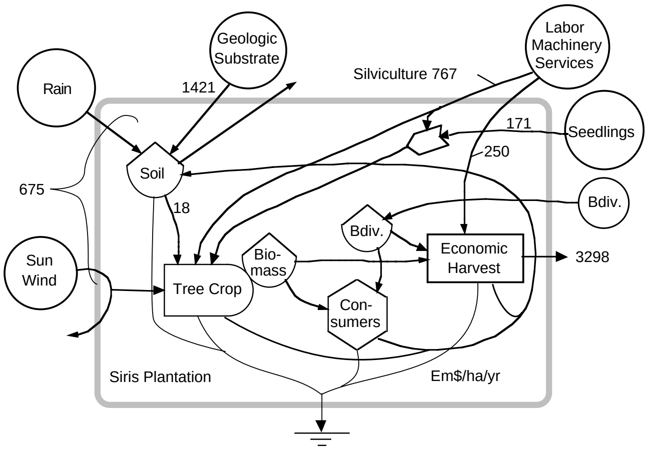


Figure 4. Energy systems diagram of exotic siris plantation in rainforest climate of eastern Puerto Rico. Values are the inputs in emdollars per hectare per year averaged over 11 yr required for canopy closure (see Table 2). Abbreviations: Bio = biomass; Bdiv = species biodiversity.

and yields by dividing the emergy values by the appropriate emergy/money ratio for that economy. The emergy/money ratio used in this article was for Puerto Rico in 1992 (1.64×10^{12} sej/1992$ from Figure 3). Sum the monetary costs of the alternatives. Estimate the market values of the forest stand and the harvest yield, if any.

4. Prepare a summary of stand characteristics (Table 3). Use the various subtotals (from Tables 2 and 3) to calculate indices for interpretation and comparison of forest alternatives.

Reforestation Examples Evaluated from Puerto Rico

Six categories of reforestation were compared in this study: (1) Natural succession, seeded from adjacent high diversity forest. A high diversity forest is one of high species variety and complexity, usually achieved by ecological succession where many species are available nearby for seeding. Such forest rebuilds soils and protects watersheds. (2) Colonization by siris (*Albizia lebbek* [L.] Benth). (3) Plantations of siris and mahogany managed in harvest cycle. Plantation forest is a forest of one or two species planted to yield an economic product. Where the product is wood, it is usually cut and replanted for another growth cycle. (4) Unharvested siris plantation as foster ecosystem. (5) Variety planting (planting of many species). (6) Patch start (transfer patches of higher diversity forest). Explanations follow.

1. *Natural Succession from Adjacent High Diversity Forest* (Figure 5a). A small part of the normal forest goes into reproduction and restoration of trees as they fall or are more extensively brought down by recurring catastrophes, such as storms and landslides. This restoration occurs on many scales as small or large patches are formed and restored with seed, coppicing, regrowth, and repair. The emergy required is that from the inputs supplied by an equal area of adjacent mature forest and that required from the economy for land management and tax.

2. *Spontaneous Colonization by an Exotic* (Figure 5b). As Puerto Rican lands formerly in agriculture were abandoned, there was a dramatic colonization by exotic, leguminous trees at little cost to the human economy (Chinea-Rivera 1992). Siris (*Albizia lebbek* [L.] Benth.) is a fast-growing, deciduous pioneer species, which covered much of Puerto Rico's former agricultural lands in a few years and is used widely throughout the world as a source of fuelwood. It was one of many exotics tested for plantation potentials and is currently grown experimentally in Puerto Rico as a possible means of rehabilitating degraded lands (Parrotta 1987, Chinea-Rivera 1992, Parrotta et al. 1997). To evaluate the exotic siris, data for a low stand density plantation (Parrotta 1987) were used. Some numbers were taken from Chinea-Rivera (1992) for the related species *Albizia procera* (Roxb.) Benth., also colonizing in low altitude areas of Puerto Rico.

   After an exotic tree has become prevalent in a stand, it may be followed later by a complex of other species with high biodiversity coming up under the initial canopy of the exotic colonization (Lugo 1992a,b, 1997). Thereafter, the exotic can become the regular successional stage in the alternation between agriculture (or plantation) and complex forest.

3. *Reforestation with Plantations* (Figure 5c) is represented with two examples in this article. One is siris on an 11 yr harvest cycle, the example introduced in Methods (Figure 4, Table 2). Also evaluated is the line planting of mahogany in Puerto Rico to convert secondary succession in various states to plantation production with the help of thinning and final harvest at 60 yr (Weaver 1989).

4. *Unharvested Foster Plantation* (Figure 5d). The diagram represents the more complex forest system that develops after siris plantation is left unharvested (Chinea-Rivera 1992, Parrotta 1993b). An understory with diverse native vegetation, insects, microbes, and other organisms helps stabilize the microclimate, soils, nutrients, animals, and so on. Other crown tree species that adapted to slow growth and in shade are eventually seeded by ground animals, birds, and bats. In time, the foster plantation gradually becomes a diverse forest if the sources of biodiversity are available.

5. *Planting a Variety of Trees* (Figure 5e). Direct reforestation by planting a variety of trees is the simple approach aimed at directly restoring complexity and diversity. However, this approach requires considerable nursery and planting costs, and is usually restricted to those tree species easily raised and available in quantity.

6. *Starting Patches of Complex Forest* (Figure 5f). How does one reestablish the complex forest in areas a long way from seed sources and animal dispersing mechanisms of existing diverse forests? One approach is to establish patches of complex forest complete with

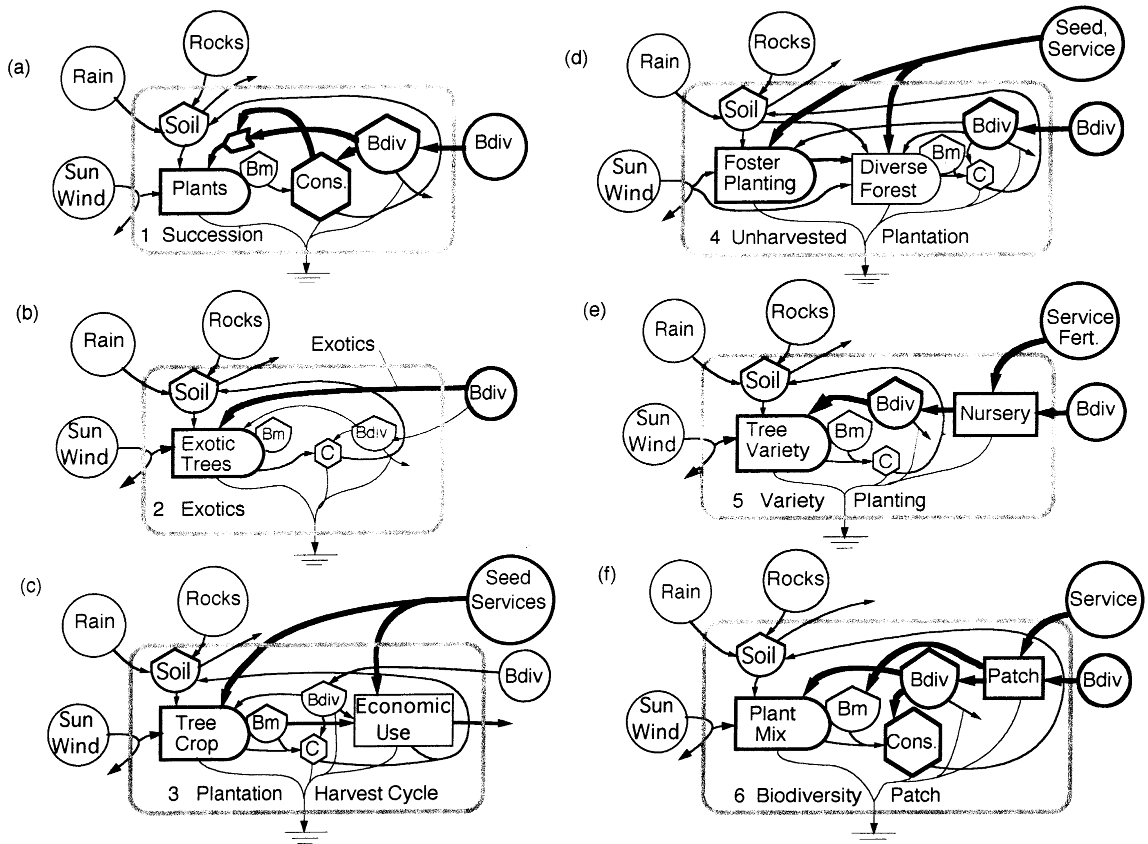


Figure 5. Aggregated energy systems diagrams comparing the six reforestation examples evaluated in this article. Pathways that start the reforestation are drawn with heavy lines. Bdiv = biodiversity; Bm = biomass; C = cons. = consumers.

litter, microbes, invertebrates, and as many plant species as can be transplanted. Then that patch could grow outward with its own mechanisms of seed dispersal. An attempt to transfer a wetland nucleus by earth moving machinery in a phosphate mining operation of Occidental Chemical Corporation, near White Springs, Florida, was not very successful because of the destruction, homogenizing, and difficulty of establishing appropriate soil moisture conditions (Brown and Odum 1985).

Results

Table 3 summarizes the results of evaluating six reforestation alternatives, expressing emergy values as emdollars to compare with monetary values and costs. Table 4 compares indices for the canopy closure stage. Table 5 compares indices for the longer times to achieve species complexity. Line numbers refer to Tables 4 and 5.

Emdollar Values

Stored emdollar values (lines 2 and 12) and rates of restoration (lines 3 and 13) are high where there were large inputs from nature (succession) or the economy (patch) or both (mahogany). The annual rate of generating emergy value by natural succession was 2.6 times faster than the slowest alternatives, the exotic invasion (items 3 and 13). Time was a factor in efficiency of reforestation. Alternatives that required more time used more emergy.

Economic Costs, Emergy Benefit, and Economic Values

Dollar costs are lowest in the spontaneous alternatives (succession and exotic spread) and highest in labor intensive alternatives (plantations, variety planting, and patch transfer). Alternatives requiring more time require more land-related costs. Lines 5 and 15 show that emdollar values are 2.6 to 24.7 times greater than dollar costs, indicating all the alternatives are a net public benefit. The high emdollar values of the spontaneous natural alternatives indicate their worth in watersheds and public parks.

In lines 6 and 16, stumpage estimates of potential dollar values of wood were used to calculate ratios of em$/$ value. At canopy closure, when market values of small trees were small, emdollar values were 3.9 to 11 times greater. The emdollars of real wealth involved in reforestation is much larger than economic value of timber in early stages. Later, when market values were larger, emdollars were 0.7 to 5 times the dollar values. Mahogany has the greatest economic value.

Lines 5 and 16 relate the dollar values at canopy closure to the dollar costs. There is net benefit in dollars only in spontaneous reforestation (succession and exotic spread). However, by the time complexity was developed, all stands had greater market value than cost.

Emergy Yield Ratio (Y/F)

The emergy yield ratios are large and indicate that 4 to 24 times more real wealth going to the economy than is received back from the economy. These values are in the range of

Table 3. Indices summarizing emergy evaluation of 1 ha siris plantation in Table 2.

Note[†]					
Accumulated storages*					
1	Forest in 11 yr	3,825	10^{13} sej	33,553	Em$
2	Harvested yield	4,139	10^{13} sej	36,307	Em$
Annual rates					
3	Environmental sources	240	10^{13} sej/yr	2,105	Em$/yr
4	Silvicultural inputs	107	10^{13} sej/yr	938	Em$/yr
5	All inputs to growth	347	10^{13} sej/yr	3,044	Em$/yr
6	Harvesting inputs	27	10^{13} sej/yr	251	Em$/yr
7	All inputs to yield	376	10^{13} sej/yr	3,298	Em$/yr
8	All from economy	136	10^{13} sej/yr	1,193	Em$/yr
Dollar costs, 1995 $					
9	Forest in 11 yr	$9,657			
10	Harvesting	$4,800			
Dollar value 1995					
11	Stumpage 11 yr	$5,600			
Indices of aboveground product, 11 yr					
12	Solar transformity	20,238	sej/J		
13	Emergy yield ratio	3.2			
14	Emergy investment ratio	0.45			
Indices of harvested biomass, 11 yr					
15	Solar transformity	24,784	sej/J		
16	Emergy yield ratio	2.8			
17	Emergy investment ratio	0.38			
Emergy—economic comparison					
18	Emdollars/dollar cost	Em$/$ cost	3.5		
19	Emdollars/dollar value	Em$/$ value	6.0		
20	Dollar value/dollar cost	$ value/$ cost	0.6		

* 1997 US$ calculated by dividing empower by 1.14×10^{12} sej/1997 $.

† Notes:

1 Sum of environmental and silvicultural items, 1–9 in Table 2.
2 Line 14 in Table 2.
3 Sum of items 1–3 in Table 2.
4 Sum of items 4–9 in Table 2.
5 Sum of environmental and silvicultural items, 1–9 in Table 2.
6 Sum of items 11–13 in Table 2.
7 Line #14 in Table 4 (sum of Items 1–9 and 11–13 in Table 2).
8 Sum of silviculural and harvesting inputs (lines 4 and 6).
9 Costs per hectare from notes 4–9 in Table 2: fuels $40, tractor $1,100, weeding labor $1,500, seedling costs $1,313, initial services $1,540, capital expense $2,979.
10 Costs per hectare for 100 Tn/ha from notes 11–13 in Table 2: fuels $150, tractor $3,300, services $1,340.
11 Stumpage value (100 Tn/ha) ($56/Tn) = $5,600.
12 Solar transformities of aboveground production: (Emergy of line 1)/(energy in line 10 of Table 2): (3825 E13 sej/ha/yr)/(1.89 E12 J/ha/yr) = 20,238 sej/J.
13 Emergy yield ratio of above ground production: Emergy units: (line 5)/(line 4): (347 E13 sej/ha/yr)/(107 E13 sej/ha/yr) = 3.2.
14 Emergy investment ratio of above ground production: Emergy units: (line 4)/(line 3): (107 E13 sej/ha/yr)/(240 E13 sej/ha/yr) = 0.45.
15 Solar transformity of harvested biomass: (Emergy of line 2)/(energy in line 14 of Table 2): (4139 E13 sej/ha)/(1.67 E12 J/ha) = 24,784 sej/J.
16 Emergy yield ratio of harvested biomass: Emergy units: (line 7)/(Line 8): (376 E13 sej/ha/yr)/(107 E13 sej/ha/yr) = 3.6.
17 Emergy investment ratio of harvested biomass: Emergy units: (line 8)/(line 3): (1015 E13 sej/ha/yr)/(2648 E13 sej/ha/yr) = 0.57.
18 Ratio of line 1 to line 9.
19 Ratio of line 1 to line 11.
20 Ratio of line 11 to line 9.

fossil fuels. Forest contributions are much higher than those of typical agriculture because more time for nature's work is allowed relative to the emergy used to start the system

Emergy Investment Ratio (F/E)

The emergy investment ratios (lines 9 and 19) are small (0.05 to 0.33), much smaller than values for agriculture (2 to 50). For these alternatives, the impact of the economy on environment is slight. The low ratio indicates unutilized contributions to the economy that can attract further economic development.

Forest Transformity (sej/J)

Solar transformities (lines 10 and 20) indicate the quality of forests developed, ranged 1.9 to 6.4×10^4 sej/J, similar to products from other forestry operations (Doherty 1995).

Table 4. Comparison of indices at time of canopy closure of each reforestation alternative.

Note	Item	1— Succession	2— Siris spread	3a & 4— Siris plantat.	3b— Mahogany	5— Variety	6— Patch
1	Age in years	10	15	11	15	15	20
2	Em$/ha	40,060	23,286	33,553	35,682	28,359	48,439
3	Em$/ha/yr	4,006	1,554	3,044	1,713	1,890	2,420
4	Costs in $	1,620	1,217	9,657	9,712	7,315	8,480
5	Em$/$ cost	24.7	19.1	3.5	2.6	3.9	5.7
6	Em$/$ value	11.1	3.4	6.0	4.8	4.7	8.8
7	$ Value/$ cost	2.2	5.6	0.6	0.5	0.8	0.6
8	Emergy yield ratio	24.3	20.4	2.8–3.2	10.0	5.2	4.0
9	Emergy invest. ratio	0.09	0.05	0.36–0.6	0.09	0.23	0.33
10	Solar transformity ¥ 10^4 sej/J	3.9	2.0	2.0–2.4	5.5	1.9	4.0

Discussion

Historically, there were many efficient and automatic reforestation cycles that operated on smaller spatial scales, like tree fall replacement, natural regrowth on landslides, shifting agriculture, and tribal forest management. Now, however, older systems of reforestation may not suffice for special soil conditions of abandoned, degraded lands and large areas without the necessary sources of biodiversity for restoration. Because appropriate species are not available for these new conditions, succession is arrested, lands become bare or scrubby, and there are long delays in regeneration of soils and production.

Rapid and automatic reforestation is a critical global need, not only to restore forests and provide fuelwood, but for restoration of soils for agricultural rotation following decades of nonrenewable land exploitation. The fastest restoration of high emergy value may be human-assisted natural succession, where complex high diversity forest is available for seeding. Such managed fallow systems have been protected by indigenous peoples throughout the world for hundreds of years. However, the native set of restoration species that worked previously may not be suitable now. Because agriculture and forestry practices often leave the land in a condition different from that of the earlier natural cycles, exotic tree species in many places of the world are the first to lead off in nature's semispontaneous restoration.

We obtain insight on the managed systems by comparing the emdollars in the reforestation with that of the natural forests that develop unassisted. A good system maximizes the emergy from environment while matching it with emergy from the economy at no greater ratio than for any other economic initiative. Thus, the net benefit may be greatest when purchased inputs are moderate. The variety planting and the mahogany plantation had more emergy from the economy, whereas the more natural processes achieved the closed canopy and diversity stages with less.

The best alternative depends on the goals, local conditions of environment, and inputs available from the economy. When the goal is restoration of a particular forest type, timber resource, special habitat, or historical condition, additional inputs may be necessary and the spontaneous self organization of the forest may not suffice.

The high net emergy in reforestation indicates how much public subsidy in development costs, conservation easements, tax exemptions, or other incentives are justified while maintaining net benefit. Priority can be given to reforestation plans with highest ratio of emdollars developed to dollar cost. *A priori*, other things being equal, the system of rotation that allows more production time can accumulate more free contribution from the environment. However, more time also increases the emergy required from the economy in land control services.

The potential of a site for accumulating emergy value in forest production is that of its natural inputs plus those that can be arranged by outside inputs by land managers. On a larger scale, the emergy of the reforestation should be compared with alternative uses of the economic inputs.

Table 5 evaluates emergy for the assumed times for developing diversity (ranging 25 to 60 yr). There is a twofold range in rates of restoration judging by the values of emergy/ha/yr.

Table 5. Comparisons of indices of reforestation after alternatives developed complex forest.

Note	Item	1— Succession	2— Siris spread	3a & 4— Siris plantat.	3b— Mahogany	5— Variety	6— Patch
11	Age in years	25	50	34	60	30	30
12	Em$/ha	100,152	82,310	68,340	118,579	115,768	63,321
13	Em$/ha/yr	4,006	1,646	1,975	2,006	3,853	2,103
14	Costs in $	4,050	4,040	5,246	9,712	5,393	11,970
15	Em$/$ cost	24.7	20.3	12.0	12.2	21.4	5.3
16	Em$/$ value	5.0	1.3	0.7	0.8	3.6	2.6
17	$ Value/$ cost	5.0	15.1	17.9	14.5	8.3	11.4
18	Emergy yield ratio	24.3	20.4	10.9	14.0	9.6	4.5
19	Emergy invest. ratio	0.05	0.27	0.10	0.09	0.12	0.24
20	Solar transformity ¥ 10^4 sej/J	3.9	2.0	2.2	6.4	1.9	3.6

Summary

Emergy-emdollar evaluations show reforestation systems contribute far more to the public wealth than is recognized by market values. The results suggest the amounts of public subsidy or tax exemptions that are justified in accelerating reforestation to increase the real wealth of the economy. As a general policy, more real wealth is generated by selecting alternatives that maximize emdollars. Net benefits are greatest when it is possible to use the unassisted natural succession or colonization by exotics where initial conditions require it. Emergy evaluation provides quantitative ways to evaluate the indirect as well as direct contributions of forests for whatever use.

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