Emergy Synthesis of Intensive Eucalyptus Cultivation in São Paolo, Brazil

T.L. Romanelli, M.J. Cohen, M. Milan, and M.T. Brown

Abstract: We used environmental accounting to evaluate high-intensity clonal eucalyptus production in São Paolo, Brazil, converting inputs (environmental, material, and labor) to emergy units so ecological efficiency could be compared on a common basis. Input data were compiled under three pH management scenarios (lime, ash, and sludge). The dominant emergy input is environmental work (transpired water, ~58% of total emergy), followed by diesel (~15%); most purchased emergy is invested during harvest (41.8% of 7-year production totals). Where recycled materials are used for pH amendment (ash or sludge instead of lime), we observe marked improvements in ecological efficiency; lime (raw) yielded the highest unit emergy value (UEV = emergy per unit energy in the product = 9.6E + 03 sej J^{-1}), whereas using sludge and ash (recycled) reduced the UEV to 8.9E + 03 and 8.8E + 03 sej J^{-1}, respectively. The emergy yield ratio was similarly affected, suggesting better ecological return on energy invested. Sensitivity of resource use to other operational modifications (e.g., decreased diesel, labor, or agrochemicals) was small (<3% change). Emergy synthesis permits comparison of sustainability among forest production systems globally. This eucalyptus scheme shows the highest ecological efficiency of analyzed pulp production operations (UEV range = 1.1 to 3.6E + 04 sej J^{-1}) despite high operational intensity. FOR. SCI. 54(2):228–241.

Keywords: environmental accounting, pulpwood, emergy, sustainability, biomass production

THE FORESTRY SECTOR IN BRAZIL is tremendously important both nationally, where it accounts for 4% of GNP and 8% of total exports (Garlipp 2001), and globally, where Brazilian planted forests represent 3% of the world total of 187 million ha and Brazilian forest biomass comprises 18% of the world's 500 billion m^3 (FAO 1999). Commercial forests in Brazil focus primarily on *Pinus* spp. (1.8 million ha) and *Eucalyptus* spp. (3.0 million ha), generating $3 billion in taxes and employing 2 million workers, directly and indirectly. More broadly, planted forests represent a biomass alternative to the exploitation of natural forests (Garlipp 2001). Among other uses, Brazilian eucalyptus plantations are the main source of fiber for the pulp industry, with an existing pulp production capacity of 7.5 million tons per year (Diaz-Balteiro and Rodriguez 2006). The scope and growth of the industry make assessment of operational sustainability important; when we consider the natural resource alternatives to global pulp supply in plantation forests, assessment of sustainability becomes essential.

Silviculture systems are economic and thermodynamic units, subject simultaneously to constraints of profit and thermodynamics. They are also embedded within a global social system in which public and private benefits are frequently at odds. To evaluate their sustainability using measurement techniques that focus on one set of constraints only will fail to address the profound ways in which these constraints are coupled and also fail to enumerate the critical trade-offs between public and private benefits. For planning and assessment of silvicultural operations, both economic and noneconomic factors must be considered, necessitating a systems view (Tellarini and Caporali 2000). Studies approaching economically optimal management and environment (Diaz-Balteiro and Rodriguez 2006) and improvement of environmental conditions of managed forest (Raniusa et al. 2005) have been carried out. In addition, efforts to link economics and ecology have resulted in a proliferation of concepts that quantify eco-efficiency, or the delivery of goods and services that satisfy human demands at a competitive price while decreasing environmental impact for the life cycle of a product (DeSimone and Popoff 1997). In general, there is a widening agreement that short-term economic prosperity and sustainable development are frequently inconsistent objectives (Bastianoni et al. 2001). Indeed, development has been fundamentally predicated on use of nonrenewable resources because of economic drivers of decision making (Hall 2004), often at the expense of the other facets of system health (social structures and environmental condition) (Bruntland Commission Report 1987).

The trade-off between natural resource consumption and economic profitability has stimulated a search for profits via environmental improvement (Shireman 1999); that is, there has increasingly been recognition that long-term economic viability and environmental protection are compatible. For

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example, international standards for sustainability such as ISO 14,000 and Forest Stewardship Council certification have emerged as a means for producers to demonstrate their commitment to sound environmental performance by their adoption of sustainable management practices. As the demand among consumers has grown, indicators and measurement systems for sustainability have become vital tools (Esty and Chertow 1997). Most tools for quantifying sustainability for comparison of process and operational alternatives involve performance indicators based in energy and mass flows (DeSimone and Popoff 1997). We use the energy and material basis of production as the frame within which sustainability is evaluated, with some important modifications, outlined below.

Energy, measured in units of heat, or molecular motion, is usually referred to as the ability to do work, based on the physical principle that work requires energy input. Heat energy is a good measure of the ability to raise water temperature. However, it is not a good measure of more complex work processes. Processes outside of the window defined by heat engine technology do not use energies that lend themselves to thermodynamic heat transfers. Not all energy, matter, and information flows are the same and their heat equivalent is a poor measure of their *quality*.

H.T. Odum introduced the concept of emergy (spelled with an "m") to properly account for the quality of matter, energy, and information flows within systems, including their degradation due to second law losses during transformation processes (Odum 1988). Emergy accounts for the environmental work supporting a process directly as well as indirectly through a chain of energy and matter transformations in both space and time (Odum 1996; Brown and Ulgiati, 2004); in short, evaluating all flows into and out of a system (a process called emergy synthesis) permits analysts to evaluate whole-system resource requirements of a particular production scheme, including both direct and indirect inputs. By definition, emergy is the amount of available energy (or exergy) of one type (usually solar) that is directly or indirectly required to provide a given flow or storage of energy or matter. For example, the organic matter in forest soil represents the convergence of direct solar energy and indirect solar energy (rain and winds) driving the work processes of the forest over many years that has resulted in layer on layer of detritus that decomposes and humifies into soil organic matter. The units of solar emergy are solar emjoules (abbreviated sej) to distinguish them from actual energy joules (abbreviated J). When the emergy required to make something is expressed as a ratio to the available energy of the product, the resulting ratio is the (solar) unit emergy value (UEV) expressed in solar emergy joules per unit (sej unit^{-1}) of flow; emergy per unit energy (sej J^{-1}) is often called transformity, and emergy per mass or volume (sej g^{-1}, sej m^{-3}) is the specific emergy (Odum 1996). In many respects, the UEV value for a product is a thermodynamically explicit measure of eco-efficiency because it relates a given good or service to the environmental work required for its production. Thus, when one is comparing two alternatives to produce the same product (e.g., pulpwood), the alternative with the lower UEV is the more sustainable option.

Studying the emergy required for reforestation options, Odum et al. (2000) evaluated the accumulated structure of forests using above- and belowground total organic matter as a measure of natural capital. Six alternatives were evaluated over time to compute the comparative efficiencies of reforestation. All yielded net public benefit (benefit/cost ranged from 2.6 to 24.7:1), and UEVs ranged from 3.2 to 10.8E04 sej J^{-1}. Whereas the optimal alterative naturally depends on goals, local conditions, and inputs available, that study demonstrated generally that efforts to accelerate forest succession through management are justified. Several wood biomass production processes, with cycles varying from 4 to 140 years, were compared by Doherty (1995). He determined the emergy required for *Eucalyptus* spp. + *Melaleuca* spp. production in Florida (United States), reporting a UEV of 2.7E04 sej J^{-1} for harvested wood that serves as a useful benchmark for this study; more broadly, UEVs for pulp production globally (across species) varied 3-fold from 1.1 to 3.6E04 sej J^{-1}.

Although there are numerous studies comparing general stand management methods (rotation times, reforestation alternatives, and multiple-use management) (Doherty 1995, Odum et al. 2000, Tilley and Swank 2003), the operational processes for intensive forest management are relatively standardized in our study area. Thus, there is a greater need for studies of commercial forestry that compare energy and material flow requirements of operational techniques to maximize sustainability within the confines of existing feasible alternatives (that is, cognizant of the simultaneous profit objective). Field efficiency, maintenance schedules, and, more generally, sensitivity of production systems to subtle operational changes are usually evaluated in economic costs and benefits, but rarely for their comparative sustainability.

In this study we evaluate eucalyptus production in São Paolo, Brazil, using emergy synthesis to explore primary constraints on sustainability and efficiency. We explore the sensitivity of results to three alternative agricultural inputs used to adjust soil pH (limestone, ash, and sludge), and delineate operational resource requirements by type (renewable, nonrenewable, and purchased) and phase (e.g., planting, fertilizing, and harvesting).

Materials and Methods

Emergy Synthesis

For each system (seedlings and eucalyptus wood) under evaluation in this study, we followed environmental accounting protocols previously outlined (Odum 1996, Brown and Ulgiati 1997, Doherty et al. 2002), which start with development of an energy systems diagram that summarizes the resource basis of the operation. This diagram is used to identify key inputs to each system. From the diagram, we compiled a list of direct and indirect inputs necessary for production; these flows are allocated to renewable, nonrenewable, and purchased (Figure 1) at this stage.

This list forms the basis of an environmental accounting table, with each input listed along with the physical flow and the reported units. To meaningfully compare resources

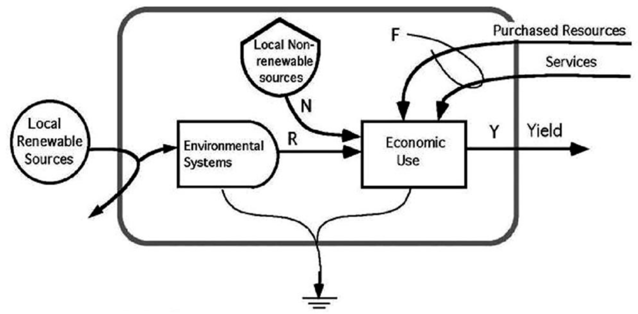

Figure 1. Systems diagram showing aggregated resource flows for environmental production. Emergy flows along thick lines; thin lines to the heat sink represent the loss of available energy/exergy that occurs with all transformations. R, renewable; N, nonrenewable; F, purchased.

of different kinds, we convert physical units (g, J) by UEVs (sej unit^{-1}) tabulated from the existing literature to estimate emergy (sej). All tables include the source of both the biophysical flow (e.g., mass of fertilizer used per hectare per year) and the UEV assigned to that flow (e.g., sej g^{-1} for that fertilizer). In all tables, UEVs are corrected for the new global emergy baseline (Odum 2000). Key outputs of an emergy synthesis include computing UEVs for the products (sej J^{-1} or sej g^{-1}, depending on the product) and a systems-level metric for comparative assessment among competing systems based on the manner in which emergy is partitioned within a given system (Figure 1). From these flow partitions, we compute the emergy yield ratio (EYR), which is the ratio of emergy yield from a process to the emergy costs:

$$\mathrm{EYR} = (R + N + F)/F, \qquad (1)$$

where R (renewable), N (local nonrenewable), and F (purchased) are partitions in the overall emergy budget of the production process. EYR is a measure of how much a process contributes to the larger scale system, and a system-level metric of energy return on investment (Hall et al. 2003).

Emergy Synthesis for Eucalyptus Nursery

An emergy evaluation was conducted for clone nursery production using data from Stape and Balloni (1988), Lopes (2004), and Oliveira (2005) to improve our estimation of the emergy embodied in this important flow. In previous work (Doherty 1995), the price of seedlings or cuttings was multiplied by the emergy/money ratio (EMR) (sej \$$^{-1}$) to impute emergy to the money flow. Although this may give an approximate value, a more detailed analysis of the nursery production process was deemed necessary. In our evaluation, we account for the actual physical inputs (labor, fuels, and equipment). However, emergy in the initial cuttings, which are from genetically improved stock, is assumed to be proportional to the regional average emergy associated with money; that is, the money paid for clone stock buys emergy at a certain rate (the EMR), which for Brazil is 1.0E + 13 sej \$$^{-1}$ (Sweeney et al. 2006). UEVs are from recent sources where possible; all have been updated to the new emergy baseline (Odum et al. 2000). The UEV computed in this analysis is used as an input for eucalyptus wood production.

Emergy Synthesis of Eucalyptus Production

Our analysis of eucalyptus production cycles comes from the region of Itatinga in São Paulo state, Brazil (Figure 2). We focus on production systems on existing plantation lands because implantation on new lands in Brazil is significantly constrained by land limitation. To determine material flow and input requirements per hectare in the production system, data on production system operational details were obtained for a 1,700-ha plantation owned and managed by the Suzano Celulose e Papel company (J. Luiz Gava and A. Di Ciero, pers. comm., 2004) which operates 300,000 ha of plantation throughout Brazil; company internal reports from 2004 were the bases of our analysis. Data are for operations through a single rotation, excluding transportation of harvested biomass to utilization facilities. These data were checked through field measurements and personal communication with the foresters. Harvesting is done on 6- to 8-year rotations with relatively uniform average yields regionally (~41.5 m^3 ha^{-1} yr^{-1}; range 19.0 to 70.0 m^3 ha^{-1} yr^{-1}); this average yield over a 7-year rotation was assumed throughout our analysis. Biomass from these systems is harvested for pulp/cellulose but could alternatively be used for energy; throughout, we provide UEVs for both mass (sej g^{-1}) and energy (sej J^{-1}) to reflect these potential dual uses. We note, however, that for the particular operation we have only considered the energy content of the pulpwood (limbs and bark have been ignored); thus, the UEV per unit energy (sej J^{-1}) is probably an overestimate. The operation examined here uses two mechanized harvesters operating continuously to fell the trees; eight laborers per harvester per shift operate the machinery and manually delimb and crosscut the trees into logs with chainsaws. Two forwarders transport the logs to roadside; costs of transport to a subsequent utilization facility are not included.

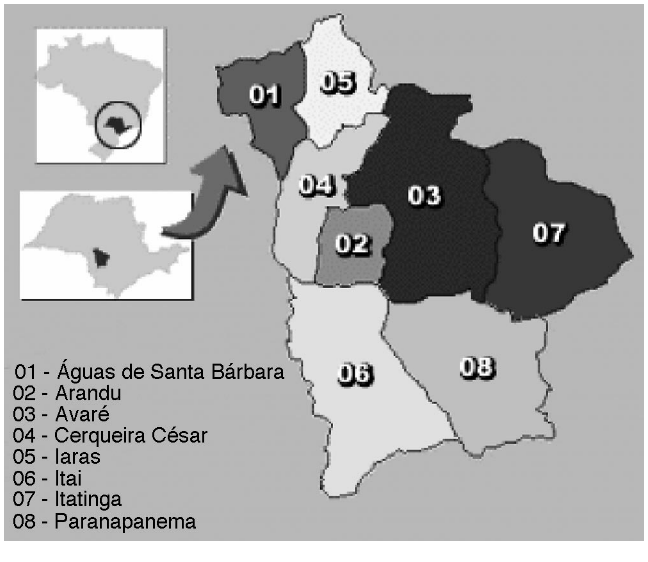

Figure 2. Map of the region of Itatinga, São Paulo State, Brazil.

Plantation stand management operations include soil pH control (via application of lime, ash, or sludge), planting, three fertilizer applications (3rd month, 8th month, and 2nd year), various pest control efforts, irrigation (one time, early in the production cycle), and harvesting. Operations and timing in the Itatinga production system are shown along with biophysical inputs in Table 1. Each portion operation has its own inputs of fuel, labor, and machinery; we compiled application rates for each input (Table 1) as well as indirect requirements for each operation.

Operational Work Capacity

The work capacity (area worked per unit time) captures operational efficiency with respect to stand characteristics (shape and slope), machinery (maneuverability and maintenance), and labor (work rate). For all operations, except harvesting, the operational work capacity is calculated with respect to the tractor-implement characteristics (speed and width) and field efficiency conditions (Equation 2). Field efficiency is the ratio of machine productivity under field conditions to the theoretical maximum productivity, based on the operating width of the machine. Field efficiency declines with poor operator training, suboptimal stand geometric characteristics, and inefficient labor management. Field efficiency is not constant for a particular machine but varies with the size and shape of the field, pattern of field operation, crop yield, moisture, and crop conditions. Travel to and from a stand, major repairs, preventive maintenance, and daily service activities are not included in the computation of field efficiency.

$$\mathrm{Oc} = (S * W)/10) * \mathrm{FE} \qquad (2)$$

where Oc is the operational work capacity ($\mathrm{ha\ h^{-1}}$), S is the machinery operation speed ($\mathrm{km\ h^{-1}}$), W is the machinery working width (m), and FE is the field efficiency (decimal).

For harvesting, attributes of the stand to be harvested such as productivity since previous harvest should be taken into account (Equation 3) because harvesting is limited by processing capacity.

$$\mathrm{Oc_H} = \mathrm{PC_H}/\mathrm{Yield}, \qquad (3)$$

where $\mathrm{Oc_H}$ is the operational harvest work capacity ($\mathrm{ha\ h^{-1}}$), $\mathrm{PC_h}$ is the harvester processing capacity ($\mathrm{m^3\ h^{-1}}$), and Yield is the forest yield ($\mathrm{m^3\ ha^{-1}}$).

Fuel Consumption

Equations 2 and 3 allow inputs to be computed on an area basis. Fuel consumption was determined by the relation of hourly consumption and operational work capacity,

$$\mathrm{C_{OP}} = (\mathrm{C_{HT}}/\mathrm{Oc}) + (\mathrm{C_{HS}}/(\mathrm{Oc} * \mathrm{S_{\#}})), \qquad (4)$$

where $\mathrm{C_{OP}}$ is the fuel requirements of a particular operation ($\mathrm{L\ ha^{-1}}$), $\mathrm{C_{HT}}$ is hourly fuel consumption of tractors ($\mathrm{L\ h^{-1}}$), $\mathrm{C_{HS}}$ is hourly fuel consumption of support machinery ($\mathrm{L\ h^{-1}}$), Oc is the operational work capacity ($\mathrm{ha\ h^{-1}}$), and $\mathrm{S_{\#}}$ is the number of tractors supported.

Machinery Depreciation

Similarly, machinery depreciation was computed based on the mass and useful life of each machine; for the depreciation rate (mass per time) to be related to production on a per area basis, we used Equation 5. For self-propelled machines such as some sprayers and harvesters, implements should not be considered.

$$\mathrm{MD} = \frac{\mathrm{M_t}/\mathrm{UL_t} + \mathrm{M_i}/\mathrm{UL_i}}{\mathrm{Oc}} + \frac{\mathrm{M_s}/\mathrm{UL_s}}{\mathrm{Oc} * \mathrm{S_{\#}}}, \qquad (5)$$

where MD is machinery depreciation ($\mathrm{kg\ ha^{-1}}$), M is machinery mass (t, tractor; i, implement; s, support machinery) (kg), UL is useful life of machinery (t, tractor; i, implement;

Table 1. Material flow for eucalyptus production operations under management of Suzano Celulose e Papel*

Operation	Diesel ($\mathrm{ha^{-1}}$)	Machinery depreciation ($\mathrm{kg\ ha^{-1}}$)	Labor ($\mathrm{hr\ ha^{-1}}$)	Other physical inputs		
					Quantity	Unit
Limestone application	13.54	0.39	1.04	Limestone	1,000.0	$\mathrm{kg\ ha^{-1}}$
Subsoiling + fertilizer + herbicide	33.35	0.76	2.85	Scout	1.0	$\mathrm{l\ ha^{-1}}$
				06–30–10	260.0	$\mathrm{kg\ ha^{-1}}$
Furrowing	20.68	0.77	0.98			
Planting	1.87	0.28	10.29	Seedling	1,790.0	$\mathrm{unit\ ha^{-1}}$
Irrigation	60.66	0.95	14.29	Water	5,556.0	$\mathrm{l\ ha^{-1}}$
Herbicide spraying	18.28	0.50	1.96	Scout	3.0	$\mathrm{l\ ha^{-1}}$
Fertilizer application (8th month)	11.23	0.31	1.06	14–00–15	150.0	$\mathrm{kg\ ha^{-1}}$
Herbicide spraying	4.72	0.10	0.44	Scout	1.8	$\mathrm{l\ ha^{-1}}$
Fertilizer application (1st year)	12.34	0.42	1.06	KCl	150.0	$\mathrm{kg\ ha^{-1}}$
Herbicide spraying	1.00	0.05	0.33	Scout	1.8	$\mathrm{l\ ha^{-1}}$
Fertilizer application (2nd year)	12.34	0.42	1.06	14–00–15	250.0	$\mathrm{kg\ ha^{-1}}$
Harvest†	588.31	12.63	169.09	Lubricant oil‡	22.8	$\mathrm{l\ ha^{-1}}$
Ant prevention	0.00	0.00	16.67	Insecticide	1.0	$\mathrm{kg\ ha^{-1}}$
Replanting	5.17	0.16	10.29	Seedling	55.0	$\mathrm{unit\ ha^{-1}}$
Total	783.50	17.73	231.42	—	—	—

* Information from Jose Luiz Gava and Alexandre Di Ciero, pers. comm., 2004.

† Harvesting requires 49 workers in three 8-hour shifts; each shift includes 2 harvesters and forwarders. Two support trucks per harvester are for repair and fuel. Each harvester processes 16 $\mathrm{m^3\ h^{-1}}$; with a yield of 290.5 $\mathrm{m^3\ ha^{-1}}$, Oc is 0.055 $\mathrm{ha\ h^{-1}}$.

‡ Includes 0.41 $\mathrm{L\ h^{-1}}$ of hydraulic oil (SAE 15W50) and 0.84 $\mathrm{L\ h^{-1}}$ of lubricant oil.

s, support machinery) (h), Oc is the operational work capacity (ha h^{-1}), and $S_{\#}$ is number of tractors supported by a given support machine. Machinery depreciation was estimated based on a useful life of 12,000 hours for tractors and 30,000 hours for Timberjack harvesters.

Labor

Labor requirements were determined based on the number of workers involved in the operation and the operational work capacity:

$$L = (W_{\mathrm{TI}}/\mathrm{Oc}) + (W_{\mathrm{S}}/(\mathrm{Oc} * \mathrm{S}_{\#})), \tag{6}$$

where L is the labor requirement of production (person-h ha^{-1}), W is number of workers involved in the operation (count of personnel) in the tractor-implement (TI) or support machinery (S), Oc is the operational work capacity (ha h^{-1}), and $S_{\#}$ is number of tractors supported by a given support machine.

Agricultural Inputs for pH Management

As part of the environmental accounting process, we compared three types of soil amendments for pH regulation: lime (the conventional material used to raise soil pH), ash, and sludge. Our goal was to determine whether there are meaningful differences in overall resource requirements between these three alternatives, two of which are recycled products. We note here that, although ash and sludge have considerable N, P_2O_5, and K_2O content, fertilization rates were held constant for all three scenarios. Dry matter (DM) application rates were 7,700 kg DM ha^{-1} for sludge and 3,000 kg DM ha^{-1} for ash. The costs of transport of the amendment to the production site are computed based on emergy transportation costs of 2.4E + 11 sej ton^{-1} km^{-1}; we assume 100 km transport in all cases.

From the perspective of sustainability analysis, it is essential to note that we have not embedded this analysis in the larger scale system, wherein sludge and ash represent waste products that would require emergy for disposal and wherein this emergy is obviated by use for soil pH management. That is, where the amendments are recycled from wastes, the emergy of their input may be neglected, and the only costs attributed to the production system are those associated with the transport of the material. We explore the implications of this assumption by comparing the UEV and EYR values computed for the base case (pH management using 1,000 kg limestone ha^{-1}), with those computed for the ash and sludge amendments with and without their emergy included. For the first case ("Raw"), we include the emergy in the sludge or ash in the total emergy use; in the second case ("Recycled") we neglect the emergy in the amendment and only tabulate the transportation costs.

Input Sensitivity Analysis

To better understand UEV sensitivity to changes in stand operations we examined the response of emergy indices to input variability. The arbitrary changes in operations are compared relative to the original scenario, which was for measured inputs of labor, materials, and machinery, using lime for pH control. We compared this scenario with operations modifications, all of which are considered improvements in operational efficiency:

- +Oc scenario wherein field (Oc) and harvest (Oc_H) efficiency increases by 10%.
- +Fuel Economy scenario wherein machinery fuel economy increases by 10%.
- +Life scenario wherein the useful life for machinery increases by 10%.
- −Labor scenario wherein human labor required per hectare decreases by 10%.
- −Input scenario wherein pH stabilizing and agrochemical inputs are decreased by 10%.

The +Oc (operation capacity) scenario could occur when the tractor-implement and harvester operates over 10% more area in the same time. For this to be possible, it would be necessary that any or all of the following changes happen: the implement width increases, work speed increases, stand shape is made more conducive to harvest, or field maneuvers be better planned. All are part of either the Oc (Equation 2) or Oc_H (Equation 3); we examine the scenario where both increase by 10%.

The +Fuel Economy scenario evaluates the effects on emergy use with increased work output per unit fuel input. The +Life scenario measures the effects of improved machinery maintenance and/or improved intrinsic durability. The −Labor scenario explores system sensitivity to changes in human labor inputs. Finally, in the −Input alternative we explore the effects of reducing ALL inputs except for only seedlings and evapotranspiration. Changes necessary for this to be feasible might include training and an information system, which were not taken into account. This hypothetical alternative scenario effectively measures the influence of purchased inputs on total emergy use and highlights the effect of less energy-intense solutions for agriculture and forestry, such as genetic breeding and no-till production.

Results

Material Flows

Material flows for each operational stage are summarized in Table 1, including physical flows (e.g., water or pesticide in the cases of irrigation and pest control efforts, respectively) and indirect flows necessary for their use (e.g., diesel for spreaders, machinery depreciation, and labor). Indirect flows are common across operational stages, and are summed over a 7-year rotation. These material flows were used as the basis for diagrams of seedling and wood production (Figures 3 and 4, respectively).

Emergy Evaluation for Clone Production

The propagule production system requires sunlight, water, and cuttings, which are matched by purchased flows of resources to improve survival and space efficiency. These include purchased flows (electricity, fuels, plastics, pesticides, machinery, and labor) and assets (existing nursery structures). Each flow is quantified in a standard environmental accounting table (Table 2), along with detailed notes

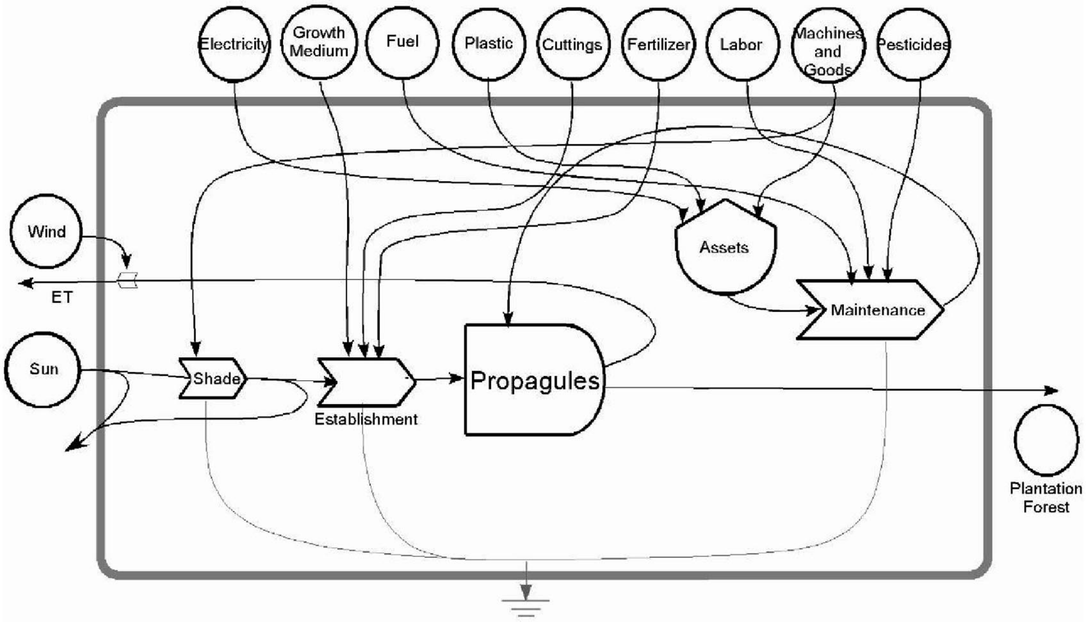

Figure 3. Systems diagram of the production system of Eucalyptus propagules.

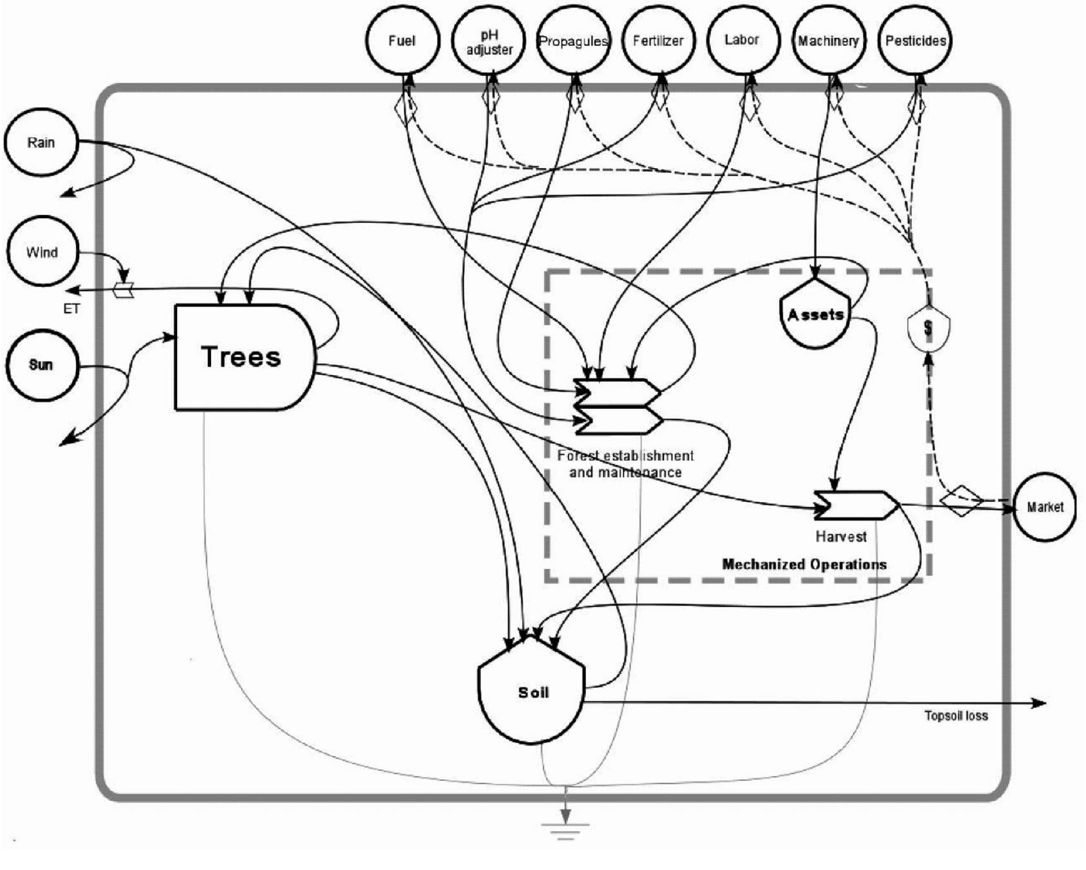

Figure 4. Systems diagram for Eucalyptus production system.

on the source of the physical flow and UEV. Because of the small quantities applied to produce each clone, all determinations were done on the basis of production for 1,000 individuals. Average annual production of the nursery was about 1.4 million seedlings (Lopes 2004). The rotation time between planting cuttings and exporting propagules (90 days) means that annualized flow metrics (sej yr^{-1}) are not computed.

The seven main inputs to the clone propagation system (Pareto chart in Figure 5) are responsible for 97.5% of the total emergy flow; these are plastic (moisture control, trays, and seedling containers), labor, clone cuttings, growth medium, depreciation of the steel table on which the seeds are germinated, shade screen, and time-release fertilizer (Osmocote). Notably, the flows of environmental inputs (sunlight and wind) are small compared with purchased flows;

Table 2. Emergy synthesis for eucalyptus propagules (n = 1,000, 90 day cycle)

Note	Input	Unit	Quantity	UEV (sej unit^{-1})	Emergy flow (E8 sej)
1	Sunlight	J	2.97E + 09	1	29
2	Evapotranspiration (ET)	J	1.84E + 03	3.1E + 04	1
3	Cuttings	US$	2.27	1.0E + 13	227,400
4	Osmocote fertilizer	g	2,200	3.0E + 09	65,464
4	Super-phosphate fertilizer	g	500	2.4E + 09	11,761
4	$(NH_3)_2SO_4$	g	500	1.6E + 09	7,728
4	KCl fertilizer	g	250	1.5E + 09	3,821
5	Captan 50 PM	g	4.1	2.5E + 10	1,030
5	Bentale 500	g	0.3	2.5E + 10	70
5	Dithane M-45	g	1.2	2.5E + 10	300
5	Decis	g	0.2	2.5E + 10	42
6	Diesel	l	0.3	3.9E + 12	11,555
7	Steel table	g	3,200	4.1E + 09	132,160
7	Shade screen	g	1,400	5.9E + 09	81,900
7	Plastic	g	8,300	5.9E + 09	485,550
8	Electricity	J	2.52E + 05	1.7E + 05	446
9	Growth medium	g	21,000	4.2E + 08	87,150
10	Labor	J	1.07E + 07	4.5E + 06	485,490
11	Tractor + trailer	g	7.7	6.7E + 09	514
11	Truck	g	7	6.7E + 09	469
11	Pump/irrigation	g	40.1	6.7E + 09	2,685
Total emergy inputs to produce 1,000 propagules					1.6E14 sej
Total emergy inputs to produce 1 propagule					1.6E11 sej

1. Sunlight = (808.05 cal cm^{-2} day^{-1}) ∗ (4.18 J cal^{-1}) ∗ (1E4 cm^2 m^{-2}) ∗ (90 days) ∗ (0.98 m^2 1,000 seedlings^{-1}) = (2.97E9 J). UEV for solar energy = 1 sej J^{-1} (Odum 1996).
2. UEV for ET = 3.1E + 04 sej J^{-1} (Brown and Bardi 2001, after Doherty 1995). ET = (4 mg m^{-2} s^{-1}) ∗ (0.012 m^2 seedling^{-1}) ∗ (7,776,000 s 90 days^{-1}) ∗ (1 kg 1E-06 mg^{-1}) ∗ (1,000 seedlings) ∗ (4.94E + 03 J kg^{-1}) = 1.84E + 03 J.
3. Emergy of cuttings determined by the emergy money ratio = (US$ 0.227 g^{-1}) ∗ (10 g 1,000^{-1} seedling^{-1}) = (2.27 US$ cutting^1). Emergy money ratio for Brazil is 1.0E + 13 sej US$$^{-1}$ (Sweeney et al. 2006).
4. UEV for fertilizers (Odum 1996): K_2O = 2.9E + 09 sej g^{-1} K, P_2O_5 = 3.0E + 10 sej g^{-1} P, N = 7.7E + 09 sej g^{-1} N. KCl has 63% K_2O, which has 83% K (KCl = 52% K), superphosphate has 18% P_2O_5, which has 43.7% P (superphosphate = 7.9% P), ammonium sulfate (20% N), and Osmocote (10–15–10) has 10% N, 15% P_2O_5 (43.7% P), and 10% K_2O (83% K).
5. Based on the UEV of pesticides = 2.5E + 10 sej g^{-1} (Brandt-Williams 2001).
6. UEV for fuel = (1.32E + 08 J gal^{-1}) ∗ (1 gal 3.8 l^{-1}) ∗ (1.1E + 05 sej J^{-1}) = 3.9E + 07 sej l^{-1} (Odum 1996).
7. UEV for steel = 4.13E + 09 sej g^{-1}; UEV for plastic = 5.9E + 09 sej g^{-1} (from Brown and Buranakarn 2003).
8. Electricity demanded = (2.2 kW) ∗ (2 h day^{-1}) ∗ (227 days yr^{-1}) (1.4E^{-7} yr seedlings^{-1}) ∗ (1,000 seedlings) ∗ (3.6E6 J kWh^{-1}) = 0.07 kWh for 1,000 seedlings. UEV for electricity = 1.7E + 05 sej J^{-1} (Brown and Buranakan 2003).
9. Growth medium is composed of 35% vermiculite, 35% pine bark, and 30% coconut fiber. UEVs are vermiculite = 1.68E + 09 sej g^{-1}, pine bark = 1.68E + 08 sej g^{-1}, and coconut fiber = 1.7E + 08 sej g^{-1} (Odum 1996).
10. UEV for labor = 4.5E + 06 sej J^{-1} (by Brandt-Williams 2001). Emergy per hour of human labor = (8.2 h) ∗ (2,500 kcal day^{-1}) ∗ (day 8 h^{-1}) ∗ (4,186 J kcal^{-1}) ∗ (4.5E6 sej J^{-1}) = 5.9E12 sej man-h^{-1}.
11. UEV for machinery depreciation = (6.7E + 09 sej g^{-1}) (from Brown and Bardi 2001, after Doherty 1995). (6.7E + 09 sej g^{-1}) ∗ (1,000 g kg^{-1}) = 6.7E12 sej kg^{-1}.

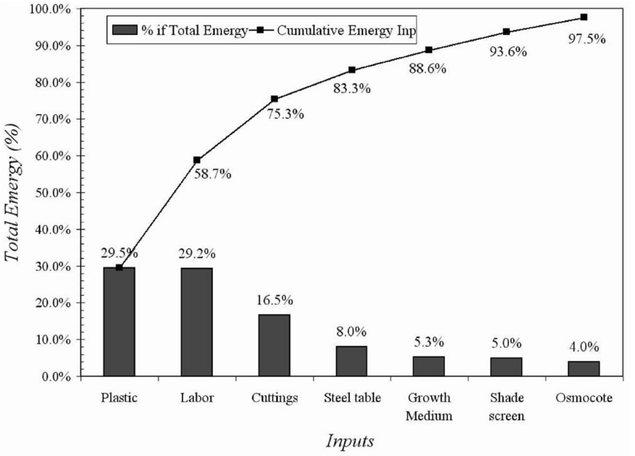

Figure 5. Pareto chart for emergy demand of inputs of the propagule production system.

this situation is typical in high-intensity nursery operations. The final UEV (1.7E + 11 sej clone^{-1}) is used as an input to subsequent evaluations of eucalyptus forest operations.

Emergy Evaluation for Eucalyptus Production

Figure 4 summarizes the resource basis of eucalyptus production, including renewable environmental inputs (rainfall, wind, and sunlight), natural stocks (soil loss), economic stocks (operation machinery), and purchased flows (fuels, pH management materials, propagules, fertilizer and pesticides, new machinery, and labor). Physical flows and UEVs for each input are synthesized in Table 3. Because the rotation cycle is 7 years from planting to harvesting, we report output data on both a total basis (after 7 years) and as an annualized flow.

Yields of pulpwood are reported in m^3 and J (outputs section of Table 3). The study system was assumed to yield 290.5 m^3 of pulpwood (41.5 m^3 ha^{-1} yr^{-1}), representing 2.2E + 12 J of energy (pulpwood only) per hectare.

To evaluate the resource basis of this level of production, we start by summarizing the inputs for the case of using lime for pH management. As with the seedlings, a small number of the inputs represent most of the resource basis. In this case, the top four inputs comprise almost 90% of the

Table 3. Emergy evaluation of eucalyptus plantation (7-year cycle); yields are for pulpwood only

					Solar emergy flow	
Note	Item	Quantity (unit ha^{-1})	Unit	UEV (sej $unit^{-1}$)	Per rotation (E12 sej ha^{-1})	Per year (E12 sej ha^{-1} yr^{-1})
	Environmental inputs					
1	Actual evapotranspiration	3.85E + 11	J	3.1E + 04	11,776	1,682
2	Topsoil loss	70,000	g	7.2E + 08	50	7
	Purchased inputs					
3	Diesel oil	783.5	l	3.9E + 12	3,018	431
4	Machinery	17,700	g	6.7E + 09	119	17
4	Labor	3.03E + 08	J	4.5E + 06	1,362	195
6	Fertilizer (06–30–10)	2.60E + 05	g	4.6E + 09	1,203	172
6	Fertilizer (14–00–15)	4.00E + 05	g	1.5E + 09	578	83
7	Formicide	1,000	g	2.5E + 10	25	4
8	KCl	1.50E + 05	g	1.5E + 09	229	33
3	Lubricant oil	22.8	l	3.9E + 12	88	13
7	Scout	7.6	l	2.5E + 13	189	27
9	Propagules	1,845	unit	1.6E + 11	295	42
10	Water	5.56E + 03	l	1.3E + 09	7	1
11	Limestone	1.00E + 06	g	1.7E + 09	1,680	240
	Transport to site	100	ton-km	2.4E + 11	24	3
	Total inputs				**20,642**	**2,948**
	Outputs					
12	Harvested pulpwood*	290.5	m^3	7.1E + 13	20,642	2,948
13	Harvested pulpwood†	2.16E + 12	J	9.6E + 03	20,642	2,948
	EYR	2.34				

* Assuming use of wood as biomass for pulp and cellulose mills.

† Assuming use of pulpwood as biomass for energy; these data do not include energy in nonpulp products (bark and limbs), which might be used when energy is the principal output.

1. UEV for evapotranspiration = 3.1E4 sej J^{-1} from Brown and Bardi 2001 (after Doherty 1995). Evapotranspiration = (7,796 mm ha^{-1}) $*$ (1E4 L mm^{-1} ha) $*$ (1 kg L^{-1}) $*$ (4.9E + 03 J kg^{-1}).
2. Topsoil loss based on the organic matter content = (5.4E + 04 kcal kg^{-1} organic matter [OM]) $*$ (1.28% OM) $*$ (4.17E + 03 J $Kcal^{-1}$) $*$ (2.4E + 05 sej J^{-1} by Cohen et al. 2006) = 7.2E11 sej kg^{-1}.
3. Diesel UEV and emergy content (Odum 1996) = (1.32E8 J gal^{-1}) $*$ (1 gal 3.8 l^{-1}) $*$ (1.1E5 sej J^{-1}) = 3.85E7 sej l^{-1}.
4. UEV for machinery depreciation = (6.7E9 sej g^{-1}) by Brown and Bardi 2001 (after Doherty 1995). Per kg = (6.7E9 sej g^{-1}) $*$ (1,000 g kg^{-1}) = 6.70E12 sej kg^{-1}.
5. UEV for labor 4.5E6 sej J^{-1} by Brandt-Williams (2001). Energy of human labor = (231.8 h) $*$ (2,500 kcal day^{-1}) $*$ (day 8 h^{-1}) $*$ (4,186 J $kcal^{-1}$) = 3.03E8 J.
6. UEVs: K_2O = 2.92E9 sej g^{-1} K (Odum 1996) $*$ 83%K K_2O^{-1}, P_2O_5 = 2.99E10 sej g^{-1} P (Odum 1996) $*$ 43.7% P $P_2O_5{}^{-1}$, N = 7.7E9 sej g^{-1} N (Odum 1996). 06–30–10 has 6% N, 30% P_2O_5, and 10% K_2O and 14–00–15 has 14% N and 15% K_2O.
7. Based on the UEV of pesticides 2.49E10 sej g^{-1} $*$ 1,000 g kg^{-1} (Brandt-Williams 2001).
8. UEV: K_2O = 2.92E9 sej g^{-1} K (Odum 1996) $*$ 1,000 g kg^{-1}, KCl $*$ 63% K_2O KCl^{-1} $*$ 83% K-K_2O^{-1}.
9. From Table 2.
10. Chemical potential energy of water (4.94E3 J kg^{-1}) multiplied by the UEV of irrigation (4.28E5 sej J^{-1}) (Brown and Bardi 2001 after Doherty 1995) = 1.26E9 sej kg^{-1} = 1.26E9 sej l^{-1} H_2O.
11. UEV of lime (1.68E10 sej g^{-1}) from Odum (1996).
12. Harvested pulpwood = (41.5 m^3 ha^{-1} yr^{-1}) $*$ (7 yr) = 290.5 m^3 ha^{-1}.
13. Energy content of harvested pulpwood = (290.5 m^3) $*$ (495 kg m^{-3}) $*$ (1.5E7 J kg^{-1}) = 2.16E12 J. Energy content by Meada and Pimentel (2006) (after Hakkila and Parikka 2002).

total inputs. For all scenarios, the primary input to the process on both a full rotation and annual basis is transpired water (57–62% of total use) delivered primarily from rainfall; limited irrigation is observed in some sites. Diesel (14–16%), fertilizers (8–9%), pH control (1–13%), and labor (6–7%) follow. Of the total fraction of emergy that is purchased (F in Figure 1), agricultural inputs (fertilizers, lime, seedlings, and pesticides) and diesel were the largest fractions at 43.7 and 37.6%, respectively (Table 4). Labor, another purchased input, represents 17% of the total use, which contrasts strongly with the seedling production system, where labor represents almost 30% of total use. Final output indices, which relate the resource basis for production with physical yields, are reported in Table 3. The UEV was 9.6E + 03 sej J^{-1}, and the EYR was 2.34 for the base case in which lime is used for pH control.

Detailed Analysis of Operations

In an effort to understand operational requirements for each phase of stand management, we decompartmentalized the production system into operational stages (e.g., harvest, pH management, and fertilization) and report the emergy required in the form of inputs (agrochemicals and lime), diesel, and labor for each (Table 4). Each line in this table is the percentage of total purchased inputs (F in Figure 1) for each entry; we omit the contribution of machinery depreciation here, which represents only 1.5% of total purchased emergy use. Harvesting requires most of the purchased emergy inputs (operational work capacity is 0.55 ha hr^{-1}), almost all in the form of diesel and labor; pH management was next. This finding suggests that, from the perspective of increasing ecological efficiency, the primary

Table 4. Percentage of purchased emergy inputs (F) per operations and classes*

	Emergy demand per class (%)			
Operations	Input†	Diesel‡	Labor‡	Total
Harvest	1.1	28.2	12.4	42.7
Limestone application	20.9	0.6	0.1	21.7
Subsoiling + fertilizer + herbicide	7.9	1.6	0.2	9.8
Fertilizer application (2nd year)	4.5	0.6	0.1	5.2
Irrigation	0.1	2.9	1.0	4.1
Fertilizer application (3rd month)	2.9	0.5	0.1	3.5
Fertilizer application (8th month)	2.7	0.6	0.1	3.4
Other (7 operations)	3.6	2.5	3.0	9.7
Total	43.7	37.6	17.0	98.5

* Except machinery depreciation ~1.5% of total.

† Direct inputs of materials for each operation (e.g., lime, fertilizer, water, and lubricants).

‡ Indirect inputs for each operation.

focus should be on harvesting efficiency and pH management. Most of the emergy for lime application is in the lime itself, whereas for irrigation, the primary resource was not water but the diesel required to distribute the water. Further, the roles of fertilization (12.1% of total purchased emergy over three applications) and herbicide application (2.5% of total purchased emergy; included in "Other" in Table 4) over the entire rotation are comparatively small from an ecological efficiency perspective. In total, the indirect inputs (diesel and labor) make up almost 55% of the total purchased emergy, reinforcing the need to look at both direct material requirements for production and indirect requirements.

Scenarios for Managing pH

Selection of pH control amendment and assumptions about how emergy is allocated in the system exert significant control over the results. Because we assumed no increases in fuel consumption, labor, and machinery depreciation with different applications, observed differences among pH management scenarios (Raw) are due to the amount and UEV of ash and sludge applied (Table 5). Assumptions about additional fuel and labor requirements are likely to be incorrect but are justified because the overall fuel and labor requirements are comparatively small (Table 4).

Resource requirements under the two alternative pH management scenarios are higher than those with limestone (Table 5) when the assumption is made to include the emergy in the amendment in the calculations (i.e., in addition to the transportation costs). In all cases, the transportation costs (assuming 100 km transport distance) are negligible. The emergy contained in the lime (1.7E + 16 sej) is nearly half that required for similar pH regulation when using ash, and approximately one-quarter of the emergy required for the same service using sludge. Synthesis indices for each scenario suggest that the resource basis for production is substantially higher with both ash (UEV = 1.0E4 sej J^{-1}) and sludge (UEV = 1.2E4 sej J^{-1}), which correspond to ecological efficiency declines of 5.6 and 22.7%, respectively. Decreases in the EYR (less yield per unit investment) parallel this general conclusion.

When we neglect the emergy cost of the inputs (because they were created for another reason and are energetically free except for transportation), the UEV for pulpwood drops to 8.8E + 03 and 8.9E + 03 for the ash and sludge amendments, respectively; transportation costs assuming 100 km of travel are included in this Recycled scenario. The EYR shows parallel changes (2.65, 2.62, and 2.34 for ash, sludge, and lime), with greater yield per unit investment for both pH control scenarios using recycled products. This result underscores the sensitivity of UEVs to assumptions

Table 5. Alternatives for soil pH control

	Scenario				
System parameter	Lime	Ash (Raw)	Ash (Recycled)	Sludge (Raw)	Sludge (Recycled)
Input mass of pH amendment (kg ha^{-1} rotation^{-1})	1,000	3,000	3,000	7,700	7,700
Input emergy of pH amendment (sej ha^{-1} rotation^{-1})	1.7E + 15	2.7E + 15*	0†	6.2E + 15‡	0†
Transport emergy of pH amendment (sej ha^{-1} rotation^{-1})§	2.4E + 13	7.2E + 13	7.2E + 13	1.8E + 14	1.8E + 14
Output UEV (sej J^{-1})	9.6E + 03	1.0E + 04	8.8E + 03	1.2E + 04	8.9E + 03
EYR	2.34	2.19	2.65	1.88	2.62

* Based on 33.6% organic matter (OM) content = (3.0E + 06 g ha^{-1}) $*$ (0.3363 g OM g^{-1}) $*$ (5.4 kcal g^{-1}) $*$ (4,186 J kcal^{-1}) $*$ (1.2E5 sej J^{-1}) (Odum 1996) = 2.7E + 15 sej kg^{-1} .Ash composition by Benedetti (1994).

† When ash of sludge is recycled, the emergy costs may be assumed to be 0 (because the material is produced for other purposes). In that case, the emergy allocated to pulpwood production is only the marginal cost of transportation.

‡ Based on 29.6% OM content = (7.7E + 06 g ha^{-1}) $*$ (0.296 g OM g^{-1}) $*$ (5.4 kcal g^{-1}) $*$ (4,186 J kcal^{-1}) $*$ (1.2E5 sej J^{-1}) (Odum 1996) = 6.2E + 15 sej kg^{-1}. Sludge composition by Oliveira (2000).

§ Assume 100 km transport distance and 2.4E11 sej ton^{-1} km^{-1} (Federici et al. 2003).

about the system and the potential benefits of interindustry material recycling.

Sensitivity Analysis

Sensitivity of total resource requirements to feasible operation changes are summarized in Table 6 relative to the base case detailed in Table 3. In each scenario, relative changes in total resource requirements are small (<3%), suggesting that the system is relatively insensitive to minor improvements in management. The most improved scenario was decreasing agrochemical inputs, followed by increasing operation capacity. Although no scenario showed marked variation, considering the area over which operations occur, regional emergy savings could be significant. Furthermore, scenarios are at least partially independent, so the relative change with two or more modifications would be approximately the product of their marginal effects.

Discussion

This work has focused on detailed environmental accounting of a particular pulpwood production system that is highly intensive. In many respects, this operation is at one end of the intensity spectrum delineated in Odum et al. (2000); at the other end are generally passive forestry operations with reduced demand of purchased goods and services, but also, generally, reduced yields. Our study is primarily useful, therefore, in delineating resource use and sustainability implications at one end of this spectrum. We explore this context further below by referencing our results to previous studies but start by discussing the ways in which this work has refined evaluations of forest production.

Emergy Evaluation of Propagule Production

In previous studies, estimation of emergy flow in seedlings/cuttings was done using money paid; our study considered the emergy required for production in considerably more detail, obviating the need for this simplifying assumption. Our attention to the actual resource requirements for clone production not only revealed the importance of labor in the process, but underscored the degree to which purchased inputs overwhelm inputs from the environment (EYR ~ 1.0). We did estimate the emergy in the cuttings using the money paid for them; this was done because the emergy requirements for production of clone vegetative propagules have not been thoroughly evaluated. Moreover, our expectation is that, when that analysis is done, purchased goods and services will dominate the emergy usage.

Table 6. Sensitivity of emergy requirements to alternative management (base data = 100)

Scenario	Comparison to base data
Base	100.0
+Oc	98.0
+Fuel Economy	99.0
+Life	99.8
−Labor	99.3
−Input	98.0

We observe that plastic (29% of total emergy) and steel (8%) dominate the emergy required for production; if efforts are made to improve ecological efficiencies of propagule production, alternative materials (e.g., wood and natural fibers cloths, both of which have lower UEVs) may be helpful. Labor (29% of total emergy) is also high, but efforts to reduce this input are likely to be less desirable because of potential impacts to working conditions. Further, economic process optimization has probably led to a condition of minimal labor inputs, suggesting that reducing labor inputs further may necessitate additional physical inputs (e.g., more agrochemical inputs or more infrastructure).

The emergy required for a single eucalyptus propagule was 1.7E + 11 sej. In comparison, Doherty (1995) reports a value of 2.4E + 12 sej per seedling for eucalyptus production in Florida, determined on the basis of the money paid and the EMR. The difference between values (~1,400%) further underscores refinements of a more detailed analysis of resource requirements, even though we cannot discern what fraction of the difference is due to the EMR assumption versus actual differences in production.

National Context

Many of the indices presented in this work are most informative in comparison with similar metrics for the larger system within which they are embedded, wherein there is a well-established set of benchmarks for them (Brown and Ulgiati 1997). Specifically, Brazil has an EMR of 1.0E + 13 sej $\$^{-1}$ (for 2000) (Sweeney et al. 2006); this broad index gives an estimate of the resources embodied in a unit of economic product. The EMR for this product (pulpwood) is 4.7E + 12 sej $\$^{-1}$ assuming a mean price of 15 US\$ m^{-3} (data for 2003 from Goodnow 2006). This number is lower than the national EMR, which is highly unusual for raw resources. Typically, raw resources present a net benefit to the consumer (emergy paid versus emergy received), whereas highly processed goods are a net emergy cost. That we observe a raw product EMR lower than the national average underscores the intensity of the plantation operation under consideration. The EMR for propagules was 1.2E + 12 sej $\$^{-1}$, assuming a unit price of 0.14 US\$ seedling^{-1} (J.L. Stape, pers. comm., 2004), nearly 1 order of magnitude less than the national EMR.

Analysis of Operations and pH Management

One of the central conclusions of this work is that the indirect input requirements for operations (diesel and labor in particular) are large (55% of total purchased emergy) in comparison with the products that are direct inputs (fertilizers and pesticides). Further, most of the resource use is during harvest (42% of total purchased emergy), suggesting that efforts to improve efficiency should be focused there. However, we note that it is difficult to appreciably reduce fuel consumption at harvest because engine efficiency is relatively fixed, as least in the short term. The large amount of diesel demanded during harvest is due to high hourly consumption and low fieldwork capacity. As we observe below, improvements in this area will most likely come from increases in operational harvest work capacity (Oc_H).

The largest direct input in the base case was lime for pH control (21%), followed by the suite of fertilizers used throughout the rotation (10%). Among the fertilizers, phosphorus is the most emergy-intense material, followed by nitrogen and potash. However, this relatively small fraction of the total purchased emergy that is in the form of fertilizers suggests that ecological efficiency is not greatly influenced by application rates and that the primary driver of recommended application rates should be considerations of downstream water quality.

Management of pH is a more complex problem. We showed that lime provided the service of pH regulation with the least resource input when we assumed that the emergy in the alternative amendments was included in the system budget. Use of waste products such as ash and sludge is, however, advocated on the basis of considerations of a larger system context. In particular, sludge and ash pH amendments represent by-products of industrial metabolism (i.e., waste); analyses at the next larger scale, which includes regional coproduction of both pulpwood and ash and/or sludge are expected to show substantial benefits of their use, both by offsetting resource requirements of providing lime and also otherwise disposing of the waste. UEVs observed in a more realistic parallel analysis in which we assume that the emergy in each of the alternative amendments is zero (though retaining transportation costs) were markedly lower (~8%) than those for the lime scenario (8.8E + 03, 8.9E + 03, and 9.6E + 03 for ash, sludge, and lime, respectively). We justify this assumption of zero emergy in the material based on Odum (1996), who discusses the critical need for multiscale and multiuse analyses in public policy development. Specifically, if a product is a waste flow that can be diverted for productive use, then it is appropriate to omit its emergy from quantitative analyses of resources required. Sensitivity to this assumption is clear, which is our rationale for providing both analyses.

Sensitivity Analysis

The sensitivity analysis results suggest that the system as studied is dominated by attributes that are not directly sensitive to management. Evapotranspiration accounts for more than half the total emergy, and 10% improvements in purchased inputs or work outputs appear to make small differences in overall measures of ecological efficiency.

The greatest improvement in performance was observed by increasing the operational work capacity (+Oc scenario), which would involve increasing this parameter without increasing the consumption of other inputs. To realize this level of improvement, labor and fuel inputs per unit area would have to decrease. Because the dominant purchased input is diesel, the reduced input scenario (−Input) has a response almost identical in magnitude to changes in Oc.

Several mechanisms might make 10% improvements in Oc realistic. For example, Oc can be improved by arranging stand shape to minimize maneuvering time. Further, improved maintenance of machinery or even machinery logistics (e.g., oil and diesel delivery in the field) could yield efficiency gains. Precision farming optimizations are increasingly widespread in agronomy (Pierce and Nowak 1999) and are at the cutting edge of forest operations.

Other scenarios (increasing the lifespan of machinery, reducing labor requirements, and increasing machinery fuel economy) did not markedly change overall efficiency, principally because they are small components of the total emergy budget under the base condition (Figure 6a). Although this lack of effect would suggest that these are not aspects of the current production system that should receive scrutiny when one is attempting to improve ecological efficiency, any marginal improvement in yield per resource input may be regionally significant when the thousands of hectares over which intensive production is occurring are considered. What the sensitivity analysis does suggest is that ecological efficiency improvements are expected when operational work capacity increases and/or agrochemical inputs are reduced; efforts to decrease labor inputs or increase the lifespan of machinery are expected to have smaller effects. We note here that this analysis considers only the emergy (ecological efficiency) of production and does not integrate considerations of cost. Thus, these results are best interpreted as guidance for government incentive programs rather than business performance.

Comparative Pulpwood Production

The UEV determined for harvested pulpwood biomass on an energy basis was 9.5E + 03 sej J^{-1}. Doherty (1995) reports UEV values for *Eucalyptus* spp. and *Melaleuca* spp. in Florida (United States) of 2.7 E + 04 sej $J^{-1}$for harvested wood. This result suggests that the production costs in total resource units are >65% less in the Brazilian operation than in the comparable operation in the United States. Notably, this finding is due to both differences in yield (20.0 versus 12.4 ton ha^{-1} yr^{-1} for the Brazilian versus the US example, respectively) and differences in purchased inputs (1.2E15 versus 2.4E15 sej ha^{-1} yr^{-1}, respectively). We note that the Brazilian operation is situated in a region that gets nearly twice as much rainfall as the Florida site.

A more general summary of the relevant literature (Doherty 1995; Doherty et al. 2002; Tilley and Swank 2003) across wood production systems is shown in Table 7. UEVs range from 9.5E + 03 sej J^{-1} (this study) to ~9.0E + 04 sej J^{-1} for hardwood production in Puerto Rico and North Carolina. A more meaningful comparison, however, is among only those systems oriented toward pulpwood production. In Table 7, systems in which the primary output is not pulpwood appear in italics; among the others, the Brazilian example explored here has the lowest UEV, though short-rotation willow (*Salix* spp.) production in southern Sweden had similar efficiency. The mean UEV for pulpwood appears to be near 1.8E + 04 sej J^{-1}. Because UEV measures the resources required per unit of similar output (in this case J of energy), the Brazilian system under study here is a clearly desirable choice.

However, operations vary not only in their total resource requirements but also in their relative proportion of resources of different kinds. This difference can be important because society may be willing to accept slightly lower overall efficiency (i.e., higher UEV) if the resource base supporting a given operation is more reliant on local or renewable sources of emergy. This issue is discussed further in the context of producing electricity in Brown and Ulgiati (2002).

The EYR is comparatively high for pulpwood production, revealing the substantial fraction of input emergy from "free" sources (local stocks and renewable flows). Notably, the willow system in southern Sweden and eucalyptus operation in Florida have lower EYR values, which imply lower return on investment. We note here, however, that the EYR values are not directly comparable with energy return on investment (Meada and Pimentel 2006). Despite the relative intensity of this production scheme, the EYR for this operation is comparatively low, even contrasted with that of other tropical plantation forest operations (slash pine EYR = 2.82, siris EYR = 2.32), both of which have substantially longer rotation times.

Figure 7 summarizes multimetric contrasts for the various wood production operations. As shown (Figure 7a), the eucalyptus system we evaluated had the highest annual energy yield (GJ ha^{-1} yr^{-1}), with intermediate emergy input (sej ha^{-1} yr^{-1}). High yield is expected because it is an intensive system. These annualized comparisons are important because decision making among alternatives needs to focus on time as well as yields and inputs. Specifically, Figure 7a reveals the degree to which local conditions (climate and soils) in Brazil increase production compared with eucalyptus in Florida.

Figure 7b shows the contrast between rotation time and the fraction of inputs that are from renewable resources. As the renewable fraction increases, we infer an increase in large-scale sustainability. In general, there is a tradeoff between shortened rotation time and the energy input requirements; as the rotation time increases, the fraction of resources that can be obtained from renewable flows seems to increase, with a maximum at approximately 70%. One measure of integrated sustainability (that is, optimizing both economic and environmental objectives) would be to select those production systems that provide high-energy yields in short periods of time while relying maximally on renewable resources. Thus, points above the curve in Figure 7b would be considered more sustainable, with a quantitative measure of sustainability emerging from the magnitude of the vertical difference between the point and the curve. We observe that the current eucalyptus study (7-year rotation time, 58% renewable) exhibits the largest positive deviation from the fitted curve and clusters with other tropical plantation forest operations. The high-intensity, short-rotation subtropical and temperate operations fall directly on the line, suggesting that they are comparatively unsustainable compared with these tropical systems. We note here that this list of forest production schemes is both sparse and dated; efforts to evaluate multiple pulpwood production schemes globally, at the same level of detail adopted in this work, are needed to more reliably quantify comparative sustainability. Further, other means of producing raw materials for paper need to be evaluated and placed in the same context.

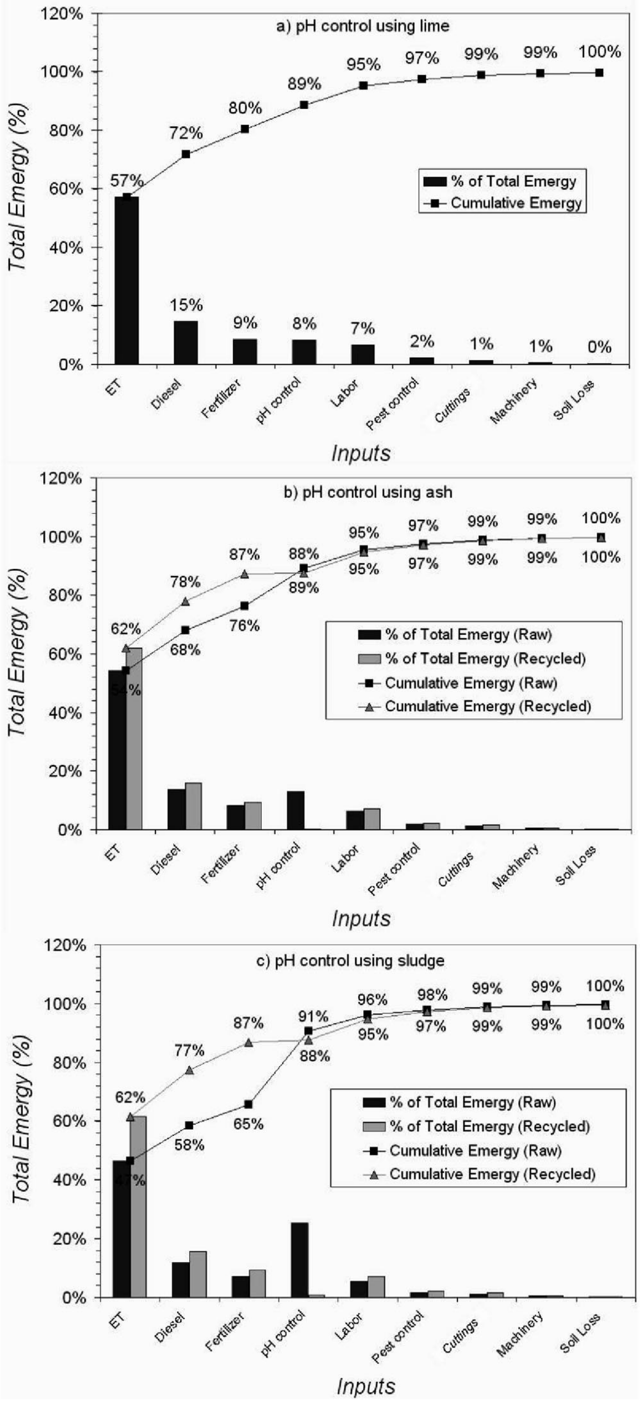

Figure 6. Pareto chart for emergy demand of inputs of the Eucalyptus production system for pH management using (a) lime, (b) ash, and (c) sludge. For the latter two analyses, Pareto curves are shown for the "Raw" and "Recycled" scenarios.

Finally, high yields per unit investment in the current eucalyptus system are reflected in Table 7, which shows that it has the lowest UEV and comparatively low external (purchased) resource requirements (high EYR). The contrast in purchased input requirements between this system and pulpwood production in southern Sweden with similar UEV is clear.

Overall, we conclude that eucalyptus pulpwood operations in this area represent the most ecologically efficient production that has been evaluated to date. Major improvements in ecological efficiency may lie in how pH is managed in local acid tropical soils and, in particular, in what

Table 7. Energy synthesis of different wood biomass production systems (data of harvested biomass)

Production species	Rotation (yr)	UEV (sej J^{-1})	EYR	Location
1. *Eucalyptus* spp. (this study)	7	9.5E+03	2.36	São Paolo, Brazil
2. Willow (*Salix* spp.)*	4	11.3E+03	1.33	Southern Sweden
3. Boreal spruce (*Picea aibes*) and pine (*Pinus silvestris*)†	80	16.9E+03	2.51	Southern Sweden
4. Loblolly pine (*Pinus taeda*)†	30	18.6E+03	2.57	Southern Illinois, United States
5. Siris (*Albizia lebbek*)†	11	19.0E+03	2.32	Puerto Rico
6. *Eucalyptus* spp./*Melaleuca* spp.†	5	27.1E+03	1.38	South Florida, United States
7. Mixed hardwood†	*60*	*33.1E+03*	*3.95*	*Southern Illinois, United States*
8. Slash pine (*Pinus elliottii*)†	25	36.2E+03	2.82	North Florida, United States
9. Secondary tropical rainforest†	*140*	*55.6E+03*	*2.07*	*Papua New Guinea*
10. Mixed hardwood‡	*NA*	*53.0E+03*	*NA*	*Nantahala National Forest, NC, United States*
11. Mahogany (Swietenia macrophylla)§	*15*	*92.4E+03*	*18*	*Puerto Rico*

Production for which pulpwood is not the primary resource output are in italics. NA, not available.
* From Doherty (1995).
‡ From Tilley and Swank (2003) (transport emergy beyond roadside removed).
§ Odum et al. (2000).

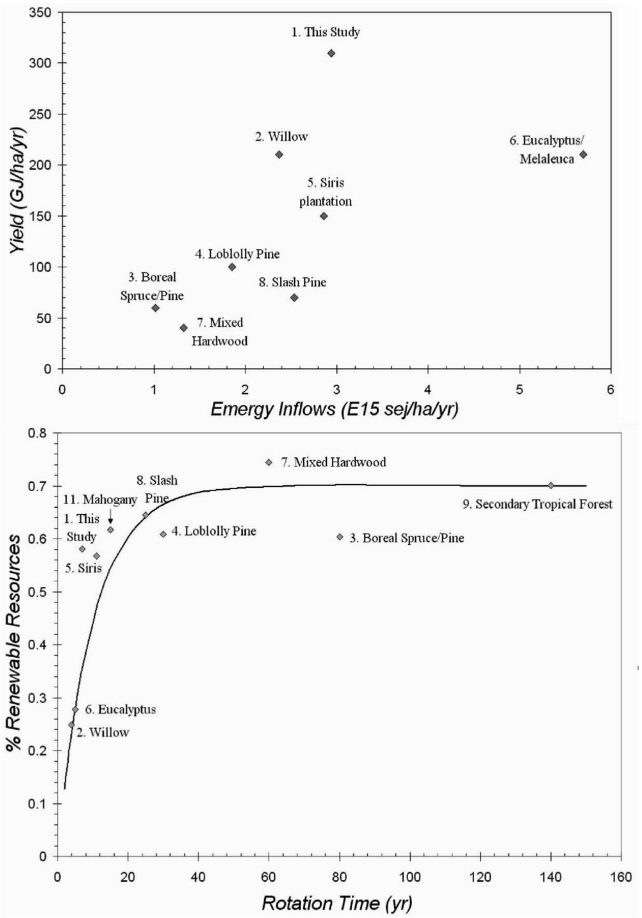

Figure 7. Comparisons among alternative production system (a) energy yield (GJ ha^{-1} yr^{-1}) versus emergy input (sej ha^{-1} yr^{-1}) and (b) % renewable resource versus rotation time (years), with a fitted exponential function (r^2 = 0.73). Numbers at each point correspond with Table 7; data were not available for all studies.

context the materials for pH management are acquired. Because this study reports the lowest UEV for pulpwood that has been computed, there is a need to repeat this study more generally for tropical short-rotation woody crops. Further, efforts to produce similar detailed analyses of particular forest operations will clarify whether the results of our sensitivity analysis hold and what opportunities exist for improving ecological efficiency and ultimately introducing environmental inputs into resource accounting procedures.

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