ABSTRACT

Title of Dissertation: MATERIAL AND EMERGY CYCLING IN NATURAL AND HUMAN-DOMINATED SYSTEMS

Brandon Kyle Winfrey, Doctor of Philosophy, 2012

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In order to address how emergy cycles with material in systems, the following work uses three studies that 1) explores the reasons why emergy should follow cycles, 2) shows how emergy should be allocated to cycling material within a system, and 3) shows how emergy can be simulated dynamically in systems that cycle material. The first study investigated how waste flows from its production process, through some transformation in a treatment system, and into the environment, which must use resources to absorb the waste's residual available energy that went untreated by the treatment system. This study showed that much work was required by the environment to return constituents in waste to background levels. Waste treatment systems for two different wastewater types and three different scenarios of treatment were compared using this new methodology and a novel index. Passive treatment systems performed better with regards to the new index, using less purchased emergy and more renewable emergy. The second study examined how emergy can be allocated to cycles within systems that have internal material flows as a large component (i.e., forest ecosystem and farms). Three study sites were evaluated that cycled phosphorus at similar levels internally. The natural system recycled the same

amount of mass but required less emergy to do so because purchased emergy was not required for the forest to recycled emergy. In the farms, NPP of crops, and thus recycling phosphorus, required substantial purchased inputs. The third study adapted a previous minimodel with two storages of material, one low quality and one higher quality. The low quality material storage was open to material input and output and the overall system was open to energy input and output. Response variables of this model were compared to the previous model and to previous rules for simulating dynamics of emergy cycles within systems. This model showed that a system open to material inputs and outputs could accumulate more material while proportionately less emergy flows in. Consequently, emergy becomes “diluted” by increased material accumulation in systems that are open to material as those closed to material have higher steady state emergy cycling.

Material and Emergy Cycling in Natural and Human-Dominated Systems

by

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Chapter 1. Introduction

Emergy is the amount of available energy of one type used directly and indirectly to make a product or service (Odum, 1996). This amount of available energy of one type embodied in that product or service is a reflection of its quality. When more available energy was used up in energy transformations (i.e., higher emergy), the resulting energy, while lower in energy terms, is higher in emergy terms and thus quality. Quality relates to the ability to do work. Energy that has high quality is able to do more work. That is, a joule of high quality electricity can power a computer, while the same joule, if available in solar form cannot. Many solar joules must be transformed in order to do the same work as the one joule of electricity (i.e., electricity has high emergy, solar energy has low emergy). The ratio of one type of available energy used directly and indirectly to make a joule of another is called the transformity, typically calculated in terms of solar emjoules per joule. For example, the ratio of solar emjoules (sej) used directly and indirectly to make one joule of electricity may be on the order of 10^5 sej/J.

Accounting procedures for emergy have been outlined in Odum (1996). These procedures include "Emergy Algebra" rules that define how a system should be evaluated based on its inputs and outputs. In particular, when evaluating the output emergy of a system, all of the inputs required to make that output are summed and applied to the output. In the situation where multiple products are created, the emergy analyst makes a decision on whether each product is a "split" or a "co-product." A product that is determined to be a split is one that can be created regardless of whether the other product was created (e.g., an automobile can be used for running errands or for commuting to work. The work done by the automobile has different uses, but the work of this product (transportation) is the same for both. The emergy of each pathway would be split based on the respective energy used). In the case of a product being classified as a split, the total emergy inputs are divided between the multiple products (typically in terms of their relative energy flow, or power). A co-product is a product that cannot be avoided when another product is made (e.g., in the production of sheep, wool and meat are co-products because you cannot produce a sheep without wool or without meat). In the case of a co-product, both products receive all of the emergy inputs. It is this special case that emergy is not conserved similarly to energy at the system scale.

The importance of emergy accounting of system inputs and outputs is evident in support of the Maximum Power Principle (Lotka, 1922a, b; Odum, 2007). During development of a system, self-organization creates system designs that prevail when power intake, energy transformations and mechanisms that reinforce production (autocatalysis) are maximized (Odum, 1995). Emergy analysis can be used to evaluate maximum power of systems as emergy is a measure of all of the energy of one type used

in a production process. However, it is less clear whether systems with large internal material or energy cycles and low power intake necessarily compete poorly with those that intake more power, but have smaller internal cycling of material or energy. These systems may compete because they maximize use of mechanisms that reinforce production through recycling high quality energy or material. Odum's rules for environmental accounting can be applied to system inputs and outputs, but it is less clear how to account for flows of emergy that are internal to a system. Indeed, some systems function with important internal cycles of material or energy, and so the emergy of these flows is of interest. This research intends to explain the importance of assigning emergy to cycling flows, make decisions on the allocation of emergy to these flows, and simulate the dynamics of emergy cycling in a system open to material and energy inputs with high internal material cycling.

1.1. Emergy Methodology for Waste Treatment Systems

Waste is the result of society's consumption of agricultural and industrial products being decoupled from natural material cycling loops (Arias and Brown, 2009; Odum, 1994). In most industrialized societies, this waste is physically, biologically, and chemically transformed before becoming an environmental and public health liability. However, for these transformations to conform to the needs of society, valuable natural resources are required. As these resources become scarcer, there is an increased need to rely on energy derived from the environment. Using passive treatment systems to mitigate waste created in industrial and domestic activities utilizes natural energy sources for the benefit of both society and nature.

Emergy analysis, an environmental accounting technique, was used to evaluate the benefits society gains from relying on passive rather than active treatment of waste. This technique employs biophysical measures to represent value rather than solely economic indicators. The total available energy in a product or service is made up of previously transformed energy of various types. The total available energy previously used up directly and indirectly is the emergy. The total energy requirements for creating a product or service are normalized to solar energy equivalents, represented by the solar emjoule. The transformity is the ratio of the amount of solar emjoules used to create a product or service (emergy) to the total available energy (exergy, measured in Joules) in that product or service (Odum, 2007). When a production process yields two or more products simultaneously, an accounting decision is made whether to split emergy inputs between the products based on their respective exergy (split) or to assign all of the emergy inputs to each of the products (co-product) (Odum, 1996). In some studies, waste is considered a co-product (Björklund et al., 2001), in others waste is considered a split (Mu et al., 2011). Environmental accounting that allocates emergy to waste products may not conform to traditional emergy principles.

While waste can have exergy in the form of chemical and/or gravitational potential energy, waste that is released to the environment does not drive a production process or do meaningful work. Consequently, it has been proposed that waste does not carry emergy because, by definition, it has no utility (Ulgiati et al., 2004). Waste with residual exergy that is conveyed to the environment forces ecosystems to reconfigure to absorb the incoming exergy. However, the emergy required by the environment to absorb the waste should be included as an input to the production system (Ulgiati et al., 2004;

Vieira and Domingos, 2004). The emergy required to treat waste prior to disposal to the environment is an additional input to production processes that should be considered upstream of production (Ulgiati et al., 2004; Vieira and Domingos, 2004). Without treatment of waste products, the production process is not complete. Ideally, exergy in waste products would be used in the production process (recycling) or in another process (reuse), but many times waste exergy is treated in treatment plants that require purchased emergy and convey residual exergy into the environment at levels requiring emergy from the environment.

This research evaluates three scenarios of treatment (i.e., No Treatment, Active Treatment, and Passive Treatment) of two types of wastewater (i.e., Acid Mine Drainage and Municipal Wastewater) using traditional emergy analyses. However, a method of emergy evaluation of waste flow is presented. The evaluation of emergy requirements by downstream environments receiving treated waste that still contains available energy above background levels is also evaluated. This evaluation was done to show the importance of evaluating emergy of cycles (waste cycled in the environment to background levels).

1.2. Recycling of Mass and Emergy in Natural and Human-Dominated Systems

Using emergy for evaluating ecological and economic systems is becoming increasingly widespread. The methods for environmental accounting of systems that recycle material are not fully formed. It is important to work towards an understanding of

how emergy is allocated to materials that recycle. Particularly, transformed materials that recycle within systems may not be adequately represented in the emergy methodology.

Some important headway has been made towards developing a conceptual framework for allocating emergy to materials that are recycled. Brown and Buranakarn (2003) introduced new indices for recycled material that could aid in decision-making for selecting construction materials. This study also framed recycling in production processes in a way that separates the emergy required for waste disposal, recycling the material, and the emergy of the material itself (Brown and Buranakarn, 2003). Building on this concept, (Brown, 2005) introduced the idea of "emformation." This principle suggests the evaluator tracks separately the emergy associated with material and the formation of that material. For instance, the emergy of an aluminum can would have the emergy of the aluminum material and the emergy involved in forming the aluminum into a can tracked separately. In recycling the can, the emergy of the aluminum material would be recycled, while the formation emergy ("emformation") would be lost. This was a novel application of emergy concepts, as emergy is not typically thought to be "lost." In another study, Tilley (2011a) builds on the idea of tracking material- and energy-emergy separately while proposing revisions to dynamic emergy accounting methodology for cycling systems. The emformation was tracked separately from the emergy of the material in a dynamic model, EmCycClos, where emformation was "exported" from the system while emergy of the material recycled 100% back to the originating storage. This study expanded on the notions of partial transformities and partial specific emergies, used to describe separate material- and energy-emergy content respectively (Tilley, 2011a).

Revisions to emergy evaluation methods for systems that recycle waste were proposed in Amponsah et al. (2011). This study developed formulae to describe recycling pathways that agreed with emergy algebra rules. They found that a product's emergy (and thus its transformity) changed with the number of times the material was recycled, as well as the extent of recycling (part of material vs. 100% recycled). The authors proposed a correction factor that accounts for the extent of recycling and number of times the product was recycled. The correction factor could be included in emergy evaluation tables of production processes (Amponsah et al., 2011).

Most studies on emergy methodology regarding recycling systems have used managed, human-dominated systems as a basis wherein emergy is allocated to recycling pathways. This study compares managed systems to natural systems that recycle similar material without the use of purchased emergy. Emergy will be allocated to cycles of material in each system and compared using indices that include material and emergy recycle.

1.3. Simulation Models of Recycling Mass and Emergy

In systems cycling materials, the internal flow of material could be orders of magnitude larger than inputs and are often at a higher concentration than background levels. In order to maintain these cycles, energy is required to concentrate the material and then is lost as heat when the material degrades. Within the system, the material does not necessarily fully degrade to background levels, continuing to carry with it embodied energy from the last transformation to another state within the system. Consider phosphorus in a forest: low quality phosphorus from the atmosphere is deposited in forest

soil, taken up by tree roots, and concentrated through root transfer to aboveground biomass (e.g., leaves). The phosphorus has the embodied energy (emergy) of its low quality state in the forest soil and the concentrating process of plant growth using solar energy. This concentrated phosphorus can be deposited back into the soil through litterfall, root exudation and death, or foliar leaching. Because the phosphorus is still concentrated in dead plant biomass, it still has some emergy relative to its background level. To preclude emergy allocation to that internal flow of material is to improperly reflect its quality in the system. Collins (2002) asserted that emergy accounting rules do allow emergy to cycle. In the case of electrical systems where steady state internal currents drive the system, disregarding the internal cycles may leave out important aspects of the systems functioning (Collins, 2002).

In many traditional emergy analyses, steady-state system inputs and outputs are evaluated (Odum, 1996). Sufficient emergy-algebra rules for these analyses exist (Brown and Herendeen, 1996). However, dynamic emergy accounting can show how emergy and transformity changes over time (Odum and Odum, 2000; Tilley and Brown, 2006), which can be an important aspect of valuing products (Odum, 2007). Current emergy accounting rules can be improved for systems with large internal material cycles (Tilley, 2011b).

The literature published on concept of material-emergy accounting is summarized in Tilley (2011b). Because this study builds on these concepts, they will be described here as well.

Similar and related to the energy hierarchy principle (Odum, 1996), Odum (1999) proposed that materials organize hierarchically based on concentrations. By concentrating

a material, available energy is used and degraded, resulting in a transformation process that accumulates emergy. Low quality energy from downstream sub-systems is used in the concentration of materials in fewer, higher quality sub-systems upstream (Odum, 1999). Odum (1999) also stated that material carries with it the emergy of the material at its current state plus the emergy associated with concentrating it. When the material is dispersed, the emergy associated with the material would decrease (Odum, 1999). Tilley (2011b) points out that the notion that emergy can be lost was novel at the time.

One major step in material emergy accounting was the acknowledgment that recycled materials, while lower quality than their previous concentrated state, still have emergy relative to background concentrations (Buranakarn, 1998). Cohen (2002) referred to this concept as "emergy retrograding" and applied it to a simulation model to describe soil genesis. This stock and flow model had two storages, one high quality material and one low quality. Material entered the system at low quality and cycled internally through a concentration process that used a constant flow source of energy (Figure 1.1). Material was dispersed from the low quality storage as an output from the system with no emergy and exported from from the high quality storage with emergy (Cohen, 2002). The material recycle flowing from the high- to low-quality storage carried emergy because it was more concentrated than background levels. The specific emergy of that recycle flow was that of the destination storage and the rule for this decision is called the "network emergy rule" (Cohen, 2002). This study compares the "network emergy rule" on a similar two-storage model developed after recent work by Tilley (2011b) in dynamic emergy accounting of material cycles.

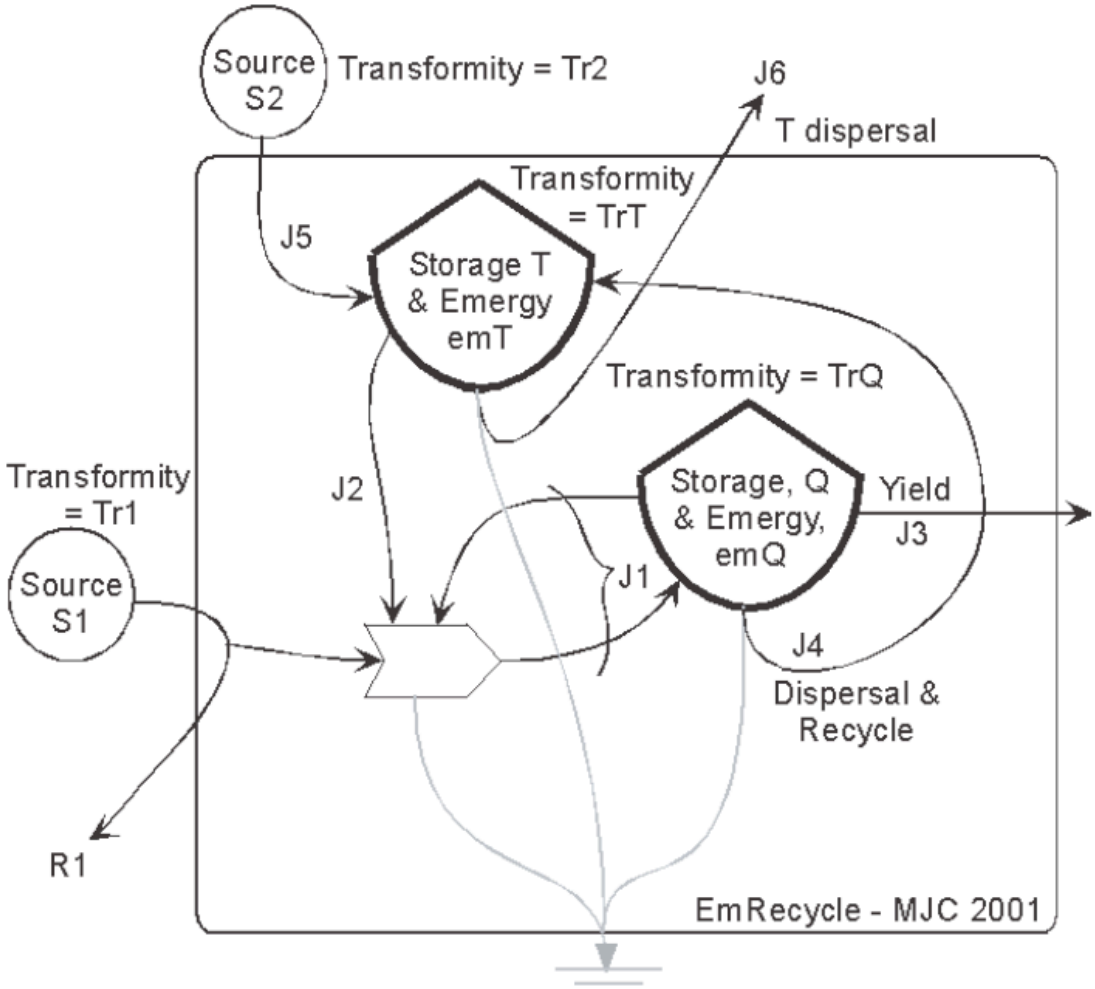


Figure 1.1. Systems diagram of two storage simulation model from Cohen (2002). emT and emQ refer to the emergy of storage T and Q, respectively.

Recently, Tilley (2011b) applied the concept of "emformation" (discussed in Chapter 3 of this dissertation) to dynamic emergy accounting. Although this study was not influenced by Cohen (2002), the models were very similar. Tilley (2011b)'s EmCycClos model contained a closed material cycle (Figure 1.2) while Cohen (2002)'s EmRecycle model included inputs, outputs, and dispersal of material. The goal of the EmCycClos model was to apply the "emformation" concept to dynamic emergy

simulation in order to better understand whether emergy can "degrade" with material dispersal (Tilley, 2011b). Tilley (2011a) revised the simulation modeling rules that artificially stopped emergy accumulation as a result of logic statements in the dynamic emergy accounting rules from Odum and Odum (2000). Instead, emergy was exported on pathways carrying emergy from the storages, their accumulation described by a differential equation that was the balance of emergy inflow and outflow (Tilley, 2011b). This study uses this revised framework for dynamic emergy accounting.

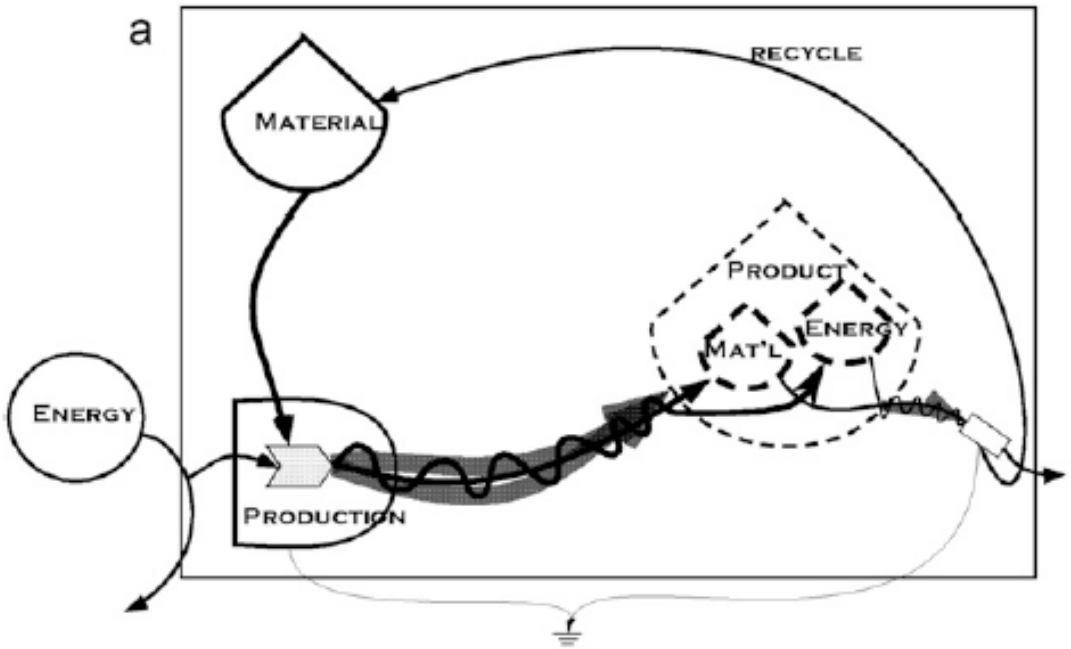


Figure 1.2. EmCycClos simulation model with closed material cycle and throughput energy (Tilley, 2011b).

This study will build upon the EmCycClos model by simulating emergy dynamics of a system open to material inflow and outflow. The dynamics of this materially open system will be compared to both the closed model using current calibration and previous accounting rules for simulating dynamics of cycled emergy.

1.4. Goal

Environmental accounting methods using emergy do not adequately address systems with material cycling as a major component. Until recently, emergy that flows with internal cycles was not evaluated in emergy analyses. This research intends to improve the methodology of the evaluation of cycling emergy.

1.5. Objectives

The concept of emergy evaluation of cycling material is not new, but application of this concept is still rare and requires exploration of its importance. In order to communicate why emergy is associated with material cycles, the first objective is to show that material contains emergy at different gradients relative to a system and its boundaries through the evaluation of waste treatment systems. In addition, an indicator for comparing treatment systems was developed.

Objective 1: Evaluate systems that receive emergy in the form of waste. Evaluate the discharge of emergy from treated waste into the environment above background levels.

Objective 2: Develop a method for calculating the work required by the environment to absorb residual emergy from waste in order to return to background levels.

Objective 3: Develop an indicator that can be used to compare treatment systems that encompasses the most important aspects of performance.

Through these objectives, it can be understood that emergy can be assigned to flows of material or energy that are not explicitly inputs to other production processes thought to have value (i.e., waste emergy reorganizes receiving ecosystems, the product is the absorption of that emergy). The next step is to assign emergy to flows of recycling material in real systems through detailed emergy evaluations.

Objective 4: Complete traditional emergy analyses on three similar systems with varying degrees of human influence- one forest, one agro-ecologically managed farm, and one conventionally managed farm.

Objective 5: Identify and quantify storages and flows of a conservatively cycling material in each system.

Objective 6: Determine appropriate allocation of emergy to material flows. Calculate emergy of these flows.

Objective 7: Develop indices that can be used to compare systems of varying human influence and look for patterns regarding material and emergy cycling.

These objectives lead to a better understanding of how emergy should be allocated to material cycling within systems. Because internal material cycling can be much larger than inputs and outputs, the internal cycling of emergy may be an important

aspect of how a system functions. Comparing systems along a gradient of natural to heavily managed systems should suggest if the accounting for internal emergy cycling does result in meaningful indices or if it follows expected patterns. Allocation of emergy to material cycling in a static system can be further explored by simulating the dynamics of emergy in a minimodel.

Objective 8: Develop a minimodel that simulates two material storages cycling emergy. The model should be open to inputs and outputs of material and energy.

Objective 9: Compare minimodel development to previous minimodels that simulate dynamics of emergy cycling.

Objective 10: Simulate material, energy, and emergy in minimodel and compare results to previous minimodels.

These objectives will improve the understanding of how emergy dynamics can be simulated in systems with important material cycles. The development of a new minimodel that is open to material inputs and outputs is a major contribution to the improvement of simulating the dynamics of emergy and is a prototypical application of emergy.

1.6. Plan of Study

The objectives of this dissertation will be carried out in three separate studies. First, Objectives 1 – 3 will be addressed in the study entitled "Emergy Methodology for Waste Treatment Systems." Model systems and an existing system will be evaluated using traditional emergy methods. However, because no clear methods for the evaluation of waste exist, they will be explored and explained here. Systems treating waste will be evaluated for renewable, non-renewable, and purchased inputs. The treatment of waste will be determined in modeled systems and the emergy values will be calculated for the waste. Further, as treated waste is discharge to the receiving environment, it may still contain emergy above background levels. The work done by the environment will be estimated in order to understand how the cycling of emergy from a system to background levels should be evaluated (Objective 2). Through Objective 2, the importance of recognizing that there is an emergy gradient between waste streams and background levels of material or energy will be shown. This leads to an understanding that emergy should be assigned to flows that carry available energy above background levels, not only to those flows that are considered to have the subjective character of utility.

The second study builds on the first through Objectives 4 – 7. Systems that have internal cycles of conservative material as an important aspect will be selected. These systems will have a gradient of human management. Data will be collected through records of management and material budgets will be developed using similar systems, common literature values, or data previously collected at the site. Ideally, the aspect of cycling emergy will be compared along this management gradient. The process of

allocating emergy to internal material flows will be a major part of this study. Indices that use aggregate emergy and material values will be developed to make comparisons between systems.

Simulating the dynamics of emergy using a new minimodel will be achieved through Objectives 8 – 10 by adapting a similar existing model to reflect openness to material input and output. Simulating emergy dynamics through this new minimodel requires changing the equations of flows and state variables of the existing model and recalibrating to appropriate levels for the new system dynamics. The new model will be compared to performance of the previous model by simulating the old model using new calibration values. The simulation of emergy in a model open to material input and output is a major contribution to Dynamic Emergy Accounting. In addition, the methodology will be compared to previous rules for simulating emergy dynamics to show the improvement this model has made over previous methods. The model will undergo a sensitivity analysis in order to ensure response variables are robust with respect to calibration levels.

Chapter 2. Emergy Methodology for Waste Treatment Systems

2.1. Abstract

Waste from society's consumption of agricultural and industrial products must be treated using energy intensive processes in order to avoid creation of environmental and public health liabilities. The treatment of these wastes, or rather transformation into a resource useable by humans or nature, remains necessary in the face of energy scarcity. Therefore, it is equally important to evaluate the effectiveness and sustainability of treatment technologies. One method to evaluate the sustainability is emergy analysis. This evaluation technique enumerates the total energy required to create a product or service in solar energy equivalents based on a hierarchy of energy quality. Emergy principles dictate that waste products do not contain the same quality of energy as the products associated with their creation. Consequently, emergy methodology has not sufficiently addressed the concept of waste in the environment. This study introduces a

new index to emergy evaluation methodology while evaluating the effectiveness of various waste treatment technologies through comparisons of their resource use and downstream effect on receiving environments. A new index, the Treatment Sustainability Index (TSI) was developed to address the evaluation of waste in production systems using emergy and the work required by the environment to further treat effluent constituents to background concentrations. The TSI is the ratio of the sum of the environmental inputs and the emergy of wastewater removed (treatment) to the sum of the purchased inputs and the emergy required by the environment to absorb residual waste exergy. This index shows treatment systems with natural energy signatures (passive treatment) may be more sustainable than those with primarily non-renewable energy signatures (active treatment).

2.2. Introduction

Waste treatment technologies should be evaluated using sound emergy methodology. Using case studies, this work aims to clarify some of the principles regarding environmental accounting of waste products, waste treatment, and the resulting environmental work required to absorb residual waste exergy. The case studies are comprised of operating and modeled treatment systems for acid mine drainage and municipal domestic wastewater (Winfrey and Tilley, 2010, 2012). Traditional emergy evaluations for three treatment scenarios were performed for both wastewater types. Emergy analysis of the work required for environmental processing of emitted waste exergy was evaluated and used in a new index for assessing waste treatment systems.

2.3. Methods

Emergy evaluations were completed on existing and modeled systems according to guidelines in Odum (1996). Three treatment scenarios were evaluated for each wastewater- acid mine drainage and municipal wastewater. The three scenarios represent the cases of wastewater undergoing active treatment, passive treatment, and no treatment. In this study, active treatment is defined as a method for treating wastewater using unit processes that require primarily fossil fuels and non-renewable materials for construction and operation (traditional environmental engineering). Passive treatment, in this study, is defined as a method for treating wastewater using unit processes that require relatively low fossil fuel inputs and use mostly natural processes for mitigating wastewater constituents (ecological engineering). For each scenario, the required emergy inputs for construction, operation, and maintenance were calculated by multiplying the exergy or material needs of each input by its appropriate transformity or specific emergy, respectively.

2.3.1. Data Collection and System Descriptions

Acid Mine Drainage Treatment Systems

Background

Nearly a century of intensive mining in northeast Oklahoma ended in the 1970s, resulting in millions of tons of lead-contaminated waste material and artesian-flowing mine drainage impacting Oklahoma surface water bodies for decades (WSQ, 2000). Nearly 20,000 residents remain in the 11,000-ha Tar Creek Superfund Site after a targeted buyout of subsidence risk-prone properties by state and federal agencies (EPA, 2009). A passive treatment system (PTS) was constructed to treat three mine drainage

discharges (seeps) in North Miami, OK and Commerce, OK in late 2008. This PTS is designed for metal removal using a single initial oxidation pond followed by two parallel treatment trains of surface flow wetlands, vertical flow bioreactors, re-aeration ponds and horizontal flow limestone beds, and a common final polishing cell (Figure 2.1). Re-aeration is achieved using solar- and wind-powered aerators. The PTS design and construction cost $1.2 million and has a design life of 30 years (Nairn et al., 2009). In contrast to active treatment systems (ATS), this PTS has effectively removed contaminants of concern in its first year using renewable energy sources for operation rather than fossil fuels.

This study uses experimental, field-collected data and models to evaluate two treatment systems: a modeled ATS and a recently installed PTS that treats mine drainage in the Tar Creek Superfund Site. Additionally, prior to the construction of the PTS, mine drainage flowed into Unnamed Tributary (UT) and subsequently to Tar Creek (Figure 2.1). The environmental impact of this scenario was evaluated using emergy analysis. Because typical emergy-based indicators are not applicable to these systems, a new index was developed in this study. Active and passive treatment systems for wastewater have been previously evaluated and compared using emergy analysis (Arias and Brown, 2009; Geber and Björklund, 2001; Nelson et al., 2001; Vassallo et al., 2009; Zhang et al., 2009; Zhou et al., 2009). Most of these studies evaluated secondary wastewater treatment systems and none of them investigated acid mine drainage treatment systems. However, Wójcik et al. (2000) found conventional treatment of mine wastewater required more emergy purchased from the economy than treatment by a modified natural wetland in Poland.

Figure 2.1. Location map for the mine drainage site. Mine water flows from seeps to Unnamed Tributary and to Tar Creek. Currently, Passive Treatment System (PTS) intercepts mine drainage from seeps before it reaches Unnamed Tributary. Oxidation Pond (Ox. Pond), Surface Flow Wetland (SFW), Vertical Flow Bioreactor (VFB), Re-aeration Pond (ReAP), Horizontal Flow Limestone Bed (HFLB), Polishing Wetland (PWL) shown in inset labeled Constructed PTS.

Data Collection

Data from the Oklahoma Climatological Survey were collected from a weather station near the site in Miami, OK. Water quality samples were collected and analyzed

from reference sites, seeps, and downstream on Tar Creek for the year preceding completion of construction of the PTS by the University of Oklahoma Center for Restoration of Ecosystems and Watersheds (CREW). Following construction, water quality samples were collected and analyzed for each cell outflow, in addition to the previously sampled locations. Analyses of Al, As, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, and Zn concentrations were completed using a Varian Vista-Pro® simultaneous inductively coupled plasma-optical emission spectrometer (ICP-OES) following EPA methods 3050 and 6010 (Nairn et al., 2009).

System Descriptions

No Treatment

The scenario of No Treatment can be described as released acid mine drainage from a mine seep into Unnamed Tributary (Figure 2.1). The river was used as a receiving environment and constituents were modeled for their removal to determine the area of the environment required to return river water constituent concentrations to background levels.

Passive Treatment AMD Systems

CH2M_Hill, the design/build contractor, provided PTS as-built details (CH2M_Hill, 2009). Figure 2.2 shows a schematic of the PTS and its flow regime.

Active Treatment AMD Systems

Hypothetical ATS specifications were estimated using the software application AMDTreat (OSM, 2010) by using the water quality data of the seeps as the input data. Using the recommendations of the AMDTreat software, a $Ca(OH)_2$ system with a mechanical mixing tank and clarifier followed by a chemical oxidation treatment process containing thirty-three 9.5-m^3 $KMnO_4$ dosing tanks and a secondary clarifier was designed to have a lifespan of 25 years (Figure 2.3) The oxidizing agent $KMnO_4$ was chosen because this treatment technique represents a less resource-intensive method compared to other oxidizing options in the software. Both clarifiers were 5.6 m in diameter and 1.2 m deep with a concrete wall thickness of 0.3 m. Two pumps were required for initial lime dosing and one pump operates the $KMnO_4$ dosing. The system was subsequently gravity-fed. For ease of analysis, treatment performance and flow capacity of the ATS was assumed to be identical to those of the PTS.

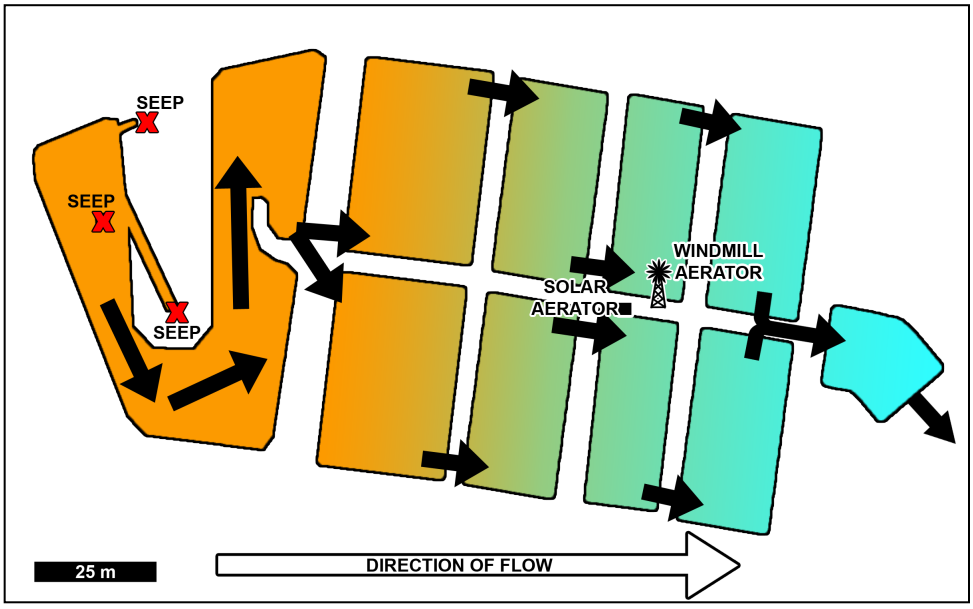


Figure 2.2. Schematic of PTS. Drawing not to scale, adapted from (CH2M_Hill, 2009).

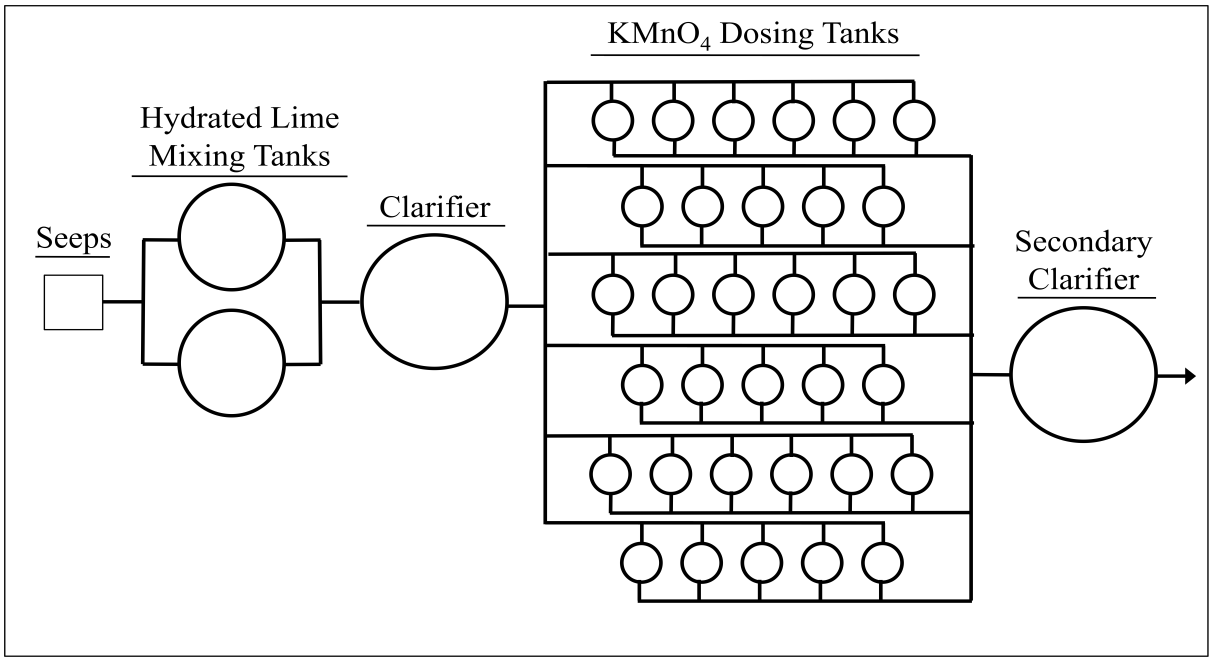


Figure 2.3. Active Treatment System conceptual schematic. Mine water enters mixing tanks on left, is pumped through the system, and exits after the secondary clarifier on the right. Not to scale.

Further site information, including chemical analysis data, system treatment parameters, and system construction details are shown in the results section.

Municipal Wastewater Treatment Systems

Background

Two treatment scenarios (WWTP and CTW) were designed and modeled using construction and performance criteria from the literature. Influent wastewater constituent concentrations were based on literature values (Hammer and Hammer, 2001) and used to design each system (Table 2.2). Models of both treatment systems were based off of influent wastewater constituent concentrations in a moderately–high strength wastewater

for a residential community with a population of approximately 5,000 at a flow of about 20 L/s (0.5 mgd) with Biochemical Oxygen Demand (BOD) of 250 mg/L (Hammer and Hammer, 2001).

Data Collection

Because these treatment systems were modeled, no measured data were obtained for the WWTP and CTW. Information on construction requirements of treatment systems were obtained from industrial catalogues and values from literature (Hammer and Hammer, 2001; Kadlec and Wallace, 2009; Metcalf & Eddy, 2003). Environmental data were gathered from online sources.

System Descriptions

No Treatment

The scenario of No Treatment can be described as releasing piped, grit-screened domestic wastewater into a river. The hypothetical river is 10 m wide, 40 cm deep river and flows at 3.2 m^3/s with a background dissolved oxygen (DO) concentration of 8 mg/L and BOD of 5 mg/L.

Active and Passive Treatment MWW Systems

The active treatment system, WWTP, was designed as a conventional treatment system for a small town with primary clarification, aeration and sedimentation, and disinfection (Figure 2.4a). Details on the construction of the WWTP follow in the Results and Discussion section.

The passive treatment system, CTW, was designed as a typical treatment wetland to treat the wastewater of the same small town (5,000 users, 20 L/s, 250 mg/L BOD) as the active treatment system. The CTW treated wastewater first in an anaerobic lagoon followed by a surface and subsurface flow wetland in series (Figure 2.4b). The CTW was modeled using the k-C* model according to (Kadlec and Wallace, 2009).

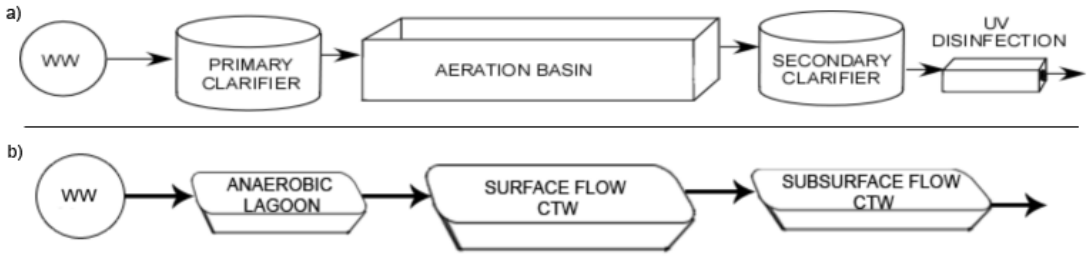


Figure 2.4**.** a) Schematic of Wastewater Treatment Plant (WWTP) unit processes, including a primary clarifier for initial solids removal, aeration basin to remove oxygen demand, secondary clarifier for final solids and nutrient removal, and disinfection by UV irradiation for pathogen removal. b) Schematic of Constructed Treatment Wetland (CTW) unit processes, including an anaerobic lagoon for primary settling, surface flow wetland for further settling and nutrient removal and a subsurface flow wetland for final filtration and nitrogen removal.

2.3.2. Emergy Analyses

Emergy analysis is a method used to quantify energy flows in systems normalized for their embodied energy (Odum, 1996). For instance, natural gas and wind can both be used to make electricity. They both waste energy due to second law of thermodynamics effects and thus have energy efficiencies. While a conventional energy analysis would focus on these inefficiencies to determine which energy source is 'better', an emergy

analysis takes the energy accounting to the next level by creating an inventory of the energy embodied in the other resources (e.g., water, concrete, steel, human service) used to make the electricity. By accounting for these additional flows of energy, emergy analysis captures a larger analytical boundary and offers the ability to compare how much energy the environment contributed to a process compared to how much was used from fossil fuels. These energy flows are accounted for in the analysis based on the direction of flow in the Energy Systems Diagram. Inputs and outputs of energy to the system are calculated and multiplied by their solar transformities, which are estimates of how much total solar energy is embodied in the energy of resource. Solar transformities are expressed in solar emjoules (sej) per unit, the unit depending on the energy source (e.g., grams for steel, joules for oil, hours for labor, etc.).

Accounting methods are used to allocate emergy inputs to energy outputs from the system. Indices are constructed to compare systems' inputs and outputs of emergy based on the categorization of their source (i.e., purchased, renewable, non-renewable energy). The Emergy Yield Ratio (EYR) is the ratio of emergy yielded to the purchased inputs of the system (Ulgiati et al., 1995). This index compares a products' efficiency in using purchased emergy from the economy. With high amounts of local, renewable emergy inputs to the system and low purchased inputs, the EYR will increase, indicating high yield of utilizing local resources and using less purchased emergy. The Environmental Loading Ratio (ELR) is the ratio of the sum of renewable and non-renewable to the renewable emergy inputs to a system (Brown and Ulgiati, 2002). This index can be used to evaluate the environmental inputs to a system. The ELR will decrease when the EYR is high, indicating less stress on the environment. The Environmental Index of

Sustainability is the ratio of the EYR to the ELR (Brown and Ulgiati, 2002). This index compiles the two previous indices to provide a measure of sustainability based on emergy inputs of a system. While these emergy-based indices are useful for comparing systems that have a product, or yield, they are less applicable to waste treatment systems, where the product is not something returned to the economy.

To complete the emergy syntheses, energy systems diagrams were generated for each treatment scenario: (i) *No Treatment*, (ii) *Active Treatment System*, and (iii) *Passive Treatment System*. These diagrams were used to determine the flows of energy into and out of each system. Environmental data, water quality data, and treatment system specifications were used to develop the emergy analysis tables. For instance, using the mean annual precipitation in Miami, OK, the chemical potential energy of rain for each system was calculated based on the area of the system and the Gibbs free energy of rainwater (~4.94 J/g). The joules of precipitation per year are multiplied by the solar transformity of rain's chemical potential (3.06E4 sej/J) (Odum et al., 2000). This solar transformity was determined based on the amount of energy used in the global water cycle to form rain.

One-time energy or material flows (e.g., pipe, limestone, concrete, et al.) were evaluated based on the embodied energy over the expected lifetime. Inputs from flow-through energy flows were determined by the difference of the emergy inputs and outputs of these flows. By accounting for the source of each emergy input and output, these flows were tabulated and classified based on their origin. Solar, wind, rain, and evapotranspiration are environmental sources (*R*) of energy. Non-renewable, purchased goods and services (*F*) included energy sources such as concrete, steel, seedlings, and

electricity. Emergy values for these sources include services such as transportation to the site and fuels required during construction in their transformities. In these systems, flow-through energy sources include mine drainage constituents, such as chemical potential and metals in the mine drainage (WW_{in}) and treated effluent (WW_{out}). Each line item in the emergy tables was calculated on a yearly basis from the specific energy, mass, labor time/area, or cost of a flow of energy into or out of the system and is multiplied by its transformity, specific emergy, or unit emergy value to obtain the emergy of that flow.

2.3.3. Emergy Allocation to Waste (Calculation of Residual Emergy in Environment)

Theory of Emergy Allocation to Waste

Because emergy is a measure of utility, it seems counterintuitive to assign emergy to waste, which by definition has no utility. It can be argued that the portion of waste streams used to do work (e.g., anaerobic digestion of biosolids or solid waste with methane recovery and use, composting, or manure fertilizer) is no longer labeled waste. Regardless, when waste is conveyed to receiving environments, even after treatment, they have residual emergy (Ulgiati and Brown, 2002). That is, some constituents in these wastes are above background concentrations. Consequently, a typical case is that the environment must do work to return these constituents to the background concentrations (Recycle pathway on Figure 2.5) because they still contain some emergy relative to the earth (Ulgiati and Brown, 2002). The emergy required by the receiving environment is not necessarily available for natural processes to occur if it is being invested in mitigating this residual emergy from waste. For instance, when a wastewater treatment plant

discharges elevated nutrients into a river, algae that increase ecosystem metabolism may grow then die-off, depressing oxygen levels through decomposition. This interruption to the river ecosystem causes changes that should be considered in systems that create waste.

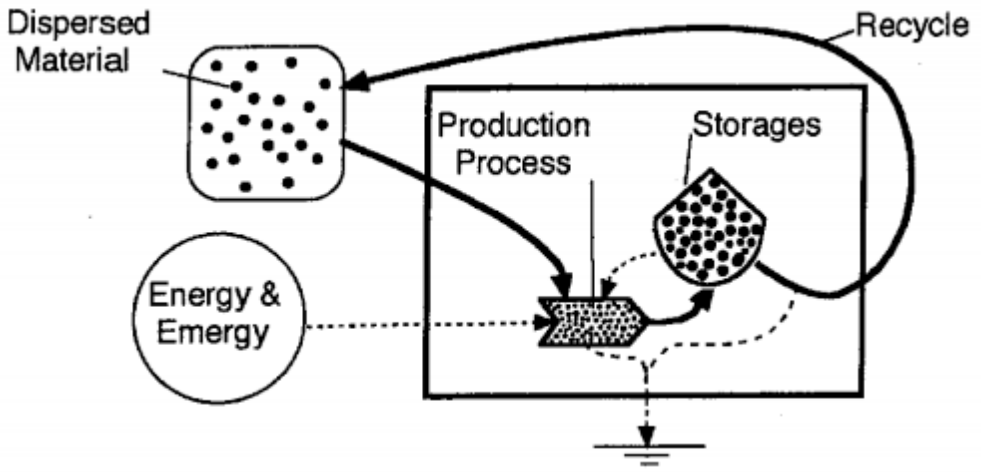


Figure 2.5. Material concentration process with eventual return to background concentrations (Dispersed Material). From Odum (1999).

By evaluating the constituent of most concern (i.e., the constituent that will take the most emergy from the environment to mitigate), an emergy analysis can better reflect the true cost of discharging waste to the environment, even after treatment (Figure 2.6). Certainly there are multiple constituents that require mitigation before reaching background levels, but by evaluating the constituent of most concern, double counting is prevented. Mitigation of residual emergy in the environment occurs in the same instance as natural processes (e.g., primary production, sedimentation, sorption, etc.), resulting in a co-product of absorbing the residual emergy and ecological function. Consequently, it

is appropriate to allocate to the residual emergy mitigation of the untreated waste all of the emergy inputs to that receiving environment. For this study, municipal wastewater and acid mine drainage had different constituents of most concern.

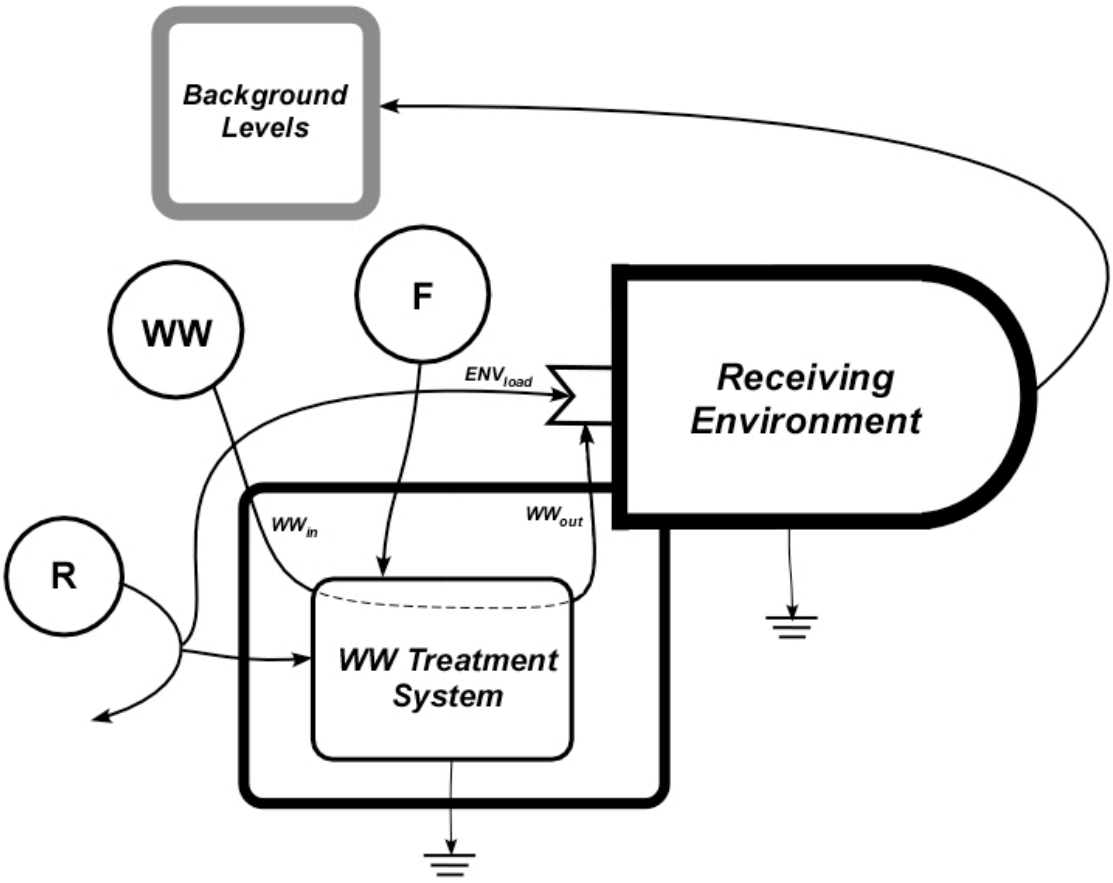


Figure 2.6. Wastewater treatment process with eventual return to background concentrations (Dispersed Material) accounting for work done by receiving environment.

Calculation of Residual Emergy in Acid Mine Drainage

Using water quality data from sampling locations at the seeps, reference sites, and downstream on Tar Creek (Figure 2.1), the distance downstream at which metals

concentrations were expected to reach reference site levels was approximated. These flow-weighted data were used to extrapolate an area of the river system needed to remove contaminants of concern (based on zero-order kinetics) from the seeps, henceforth referred to as 'receiving environment'. Seep and passive treatment system (PTS) cell outflow data were used in the emergy analyses to determine the extent of treatment of the PTS.

Calculation of Residual Emergy in Municipal Wastewater

Using water quality data from literature value and design specification, the distance downstream (on a hypothetical river) at which BOD was expected to reach background concentration was determined. The hypothetical river is 10 m wide, 40 cm deep river and flows at 3.2 m^3/s with a background dissolved oxygen (DO) concentration of 8 mg/L and BOD of 5 mg/L.

2.3.4. A New Index for Waste Treatment

Waste is a byproduct of economic activities in society. Emergy evaluations are traditionally targeted at systems and products that drive the economy, not their byproducts. Consequently, existing emergy indices do not lend themselves to properly evaluating the sustainability of a waste treatment system. Therefore, a new emergy index was developed. The Treatment Sustainability Index (TSI) value is decreased when a treatment system requires more non-renewable inputs from the economy and discharges more residual emergy to the receiving environment. The new TSI value increases with systems that use local, renewable resources and treat the wastes effectively. By increasing the purchased emergy to operate a system or decreasing the treatment effectiveness, the

TSI will decrease. Increasing the utilization of local, renewable energy or increasing the treatment effectiveness will increase the TSI. The TSI is the ratio of the sum of environmental resources used in treatment (R) and flow-through (WW_{in}-WW_{out}) emergy input to the treatment system to the sum of purchased, non-renewables (F) and environmental loading (ENV_{load}) emergy used in the receiving environment to reach background concentrations of the constituent of most concern (Equation 1).

$$TSI = \frac{R + (WW_{in} - WW_{out})}{F + ENV_{load}} \quad (1)$$

This index can be used to indicate the relative use of emergy source categories and compare the sustainability of treatment systems with identical influent characteristics (higher TSI represents more sustainable treatment). The environmental loading was determined using the approximated area required to return wastewater constituent concentrations to background levels from the outflows of each system, or in the case of *No Treatment*, from the seeps or untreated wastewater discharge. Environmental inputs (solar, wind, rain, and evapotranspiration emergy) to the area receiving the wastewater (effluent, in the case of *ATS, PTS, CTW, and WWTP*) are used to determine ENV_{load}. The TSI was used to compare all six treatment scenarios for their relative sustainability in the Tar Creek Superfund Site and in the hypothetical municipal wastewater treatment scenario.

2.4. Results and Discussion

2.4.1. Collected or Modeled Data and Site Information

Acid Mine Drainage Treatment Systems

Influent mine drainage from the three seeps flowed at a combined average 7 L/s. Table 2.1 shows mean, flow-weighted metals concentrations from the seeps, passive treatment system effluent, downstream Tar Creek, and reference sites. These reference sites were located in the general area of the Tar Creek Superfund Site, but have not shown evidence of being affected by mine drainage or overburden. Most metals of concern (Al, As, Cd, Cr, Cu, Fe, and Pb) at the outflow of the PTS were at or below reference site levels.

PTS design specifications were used to calculate the raw materials, machinery, and labor used in construction. Because the PTS has already been constructed, detailed specifications were available. The ATS was designed as a chemical treatment plant with mixing. Treatment of mine drainage using hydrated lime ($Ca(OH)_2$) for alkalinity production and potassium permanganate ($KMnO_4$) is common (Skousen et al., 2006). Quantities of materials used and earth moved for these systems were used in emergy analyses and are presented in emergy tables in Appendix A.

Table 2.1. Average metal concentrations at mine drainage seeps, Passive Treatment System (PTS) outflow, Tar Creek downstream of the seeps, and reference sites (Nairn et al., 2009).

	Average Concentration (mg/L)				
	Seeps	**PTS Effluent**	**Downstream Tar Creek**	**Reference**	***Detection Limit***
Aluminum	0.097	0.076	0.301	0.308	*0.001*
Arsenic	0.063	BDL*	BDL	BDL	*0.0223*
Cadmium	0.018	BDL	0.003	0.001	*0.0006*
Calcium	735.50	733.75	389.03	53.98	*0.0005*
Chromium	0.002	0.002	0.004	0.002	*0.001*
Copper	0.003	0.003	0.003	0.004	*0.001*
Iron	178.19	0.632	2.782	0.527	*0.0007*
Magnesium	201.05	199.92	43.36	5.22	*0.0004*
Manganese	1.51	1.44	0.729	0.203	*0.0002*
Nickel	0.947	0.038	0.074	0.015	*0.004*
Lead	0.066	BDL	0.037	0.030	*0.0116*
Zinc	8.27	0.109	3.14	0.033	*0.0013*

*BDL- Below Detectable Limit

Municipal Wastewater Treatment Systems

WWTP Design Results

The WWTP system was designed to include primary clarification, aeration and sedimentation, and disinfection unit processes, similar to conventional treatment in the US (Hammer and Hammer, 2001; Metcalf & Eddy, 2003). Figure 2.4a shows a schematic of the model WWTP. Each unit process was sized using typical removal performances for each treatment process and typical loading rates. The estimated amount of material used in construction of these unit processes was quantified. Following grit screening, which was neglected in the emergy analyses for all treatment scenarios, considering they were assumed to be present in each, a concrete primary clarifier separates solids from the

water column with a hydraulic residence time (HRT) of 2 h. This HRT fell within the typical residence times of 1.5 – 2.5 h in most conventional systems (Metcalf & Eddy, 2003). A steel weir bordered the top of the clarifier; effluent pours over the weir to collection troughs where it was pumped to the next unit process. Aeration and sedimentation tanks followed primary clarification. Ceramic disk air diffusers distributed air from a compressor at the bottom of the rectangular aeration basin. Aerated wastewater flowed into the secondary clarifier for sedimentation. The sedimentation unit process was designed similarly to the primary clarifier with concrete construction and a steel weir. Following sedimentation, effluent was pumped through a tube surrounded by UV lamps that destroyed pathogens in the UV disinfection unit process. This WWTP system is typical for small wastewater flow similar to the flow in this study. Table 2.2 shows the characteristics of wastewater and design parameters of the modeled systems' unit processes.

CTW Design Results

The CTW system design included an anaerobic lagoon, surface flow CTW and subsurface flow CTW in series. Figure 2.4b shows a schematic of the model CTW system. Using the *k-C** modeling methodologies from Kadlec and Wallace (2009) and design guidelines from ITRC (2003), this gravity-flow system utilized natural processes to treat BOD, total nitrogen (TN), total phosphorus (TP), and fecal indicator bacteria (FIB). Based on influent WW constituent concentrations and typical removal efficiencies of anaerobic lagoons, effluent concentrations for each constituent and unit process were calculated (Kadlec and Wallace, 2009; ITRC, 2003). An estimated 600 mm/yr annual

pan evaporation in the state of Maryland was subtracted from the effluent flow from the anaerobic lagoon to obtain a flow rate for the inflow to the next unit process. The surface flow (SF) CTW was sized based on the largest area required for WW constituent removal using efficiencies and rates from typical SF CTWs in the *k-C** model (Kadlec and Wallace, 2009). An estimated 760 mm/yr annual evapotranspiration in the state of Maryland was subtracted from the effluent flow of the SF CTW to determine the influent flow to the subsurface flow (SSF) CTW. Similarly, the SSF CTW was sized based on typical SSF removal efficiencies and rates using the *k-C** model.

Table 2.2. Wastewater characteristics for influent WW and effluent of treatment systems and system design specifications. These parameters were determined using methods from Hammer and Hammer (2001), Kadlec and Wallace (2009), and Metcalf & Eddy (2003).

	Influent WW	**WWTP System**			**CTW System**		
WW Constituent		*PC*[a]	*A+S*[b]	*D*[c]	*AL*[d]	*SF*[e]	*SSF*[f]
BOD (mg/L)	250	160	30	30	125	56	25
TN (mg/L)	40	25	15	15	32	18	15
TP (mg/L)	5	3	2	2	4	3	3
E. coli (10^6 cfu/L)	100	10	5	0	3.6	0.5	0.02
Design Parameters							
Area (m^2)		42	200	-	3,000	15,000	5,000
Depth (m)		3	3	-	1.8	0.45	0.6
Hydraulic Retention Time (d)		0.083	0.35	0.021	3.1	4.6	0.7
Loading Rate (cm/d)		4000	860	-	60	9.7	35

[a]Primary Clarifier; [b]Aeration and Sedimentation; [c]Disinfection; [d]Anaerobic Lagoon; [e]Surface flow CTW; [f]Subsurface flow CTW

2.4.2. Emergy Analyses

Acid Mine Drainage Treatment Systems

Energy systems diagrams were drawn for each system (*No Treatment*, *ATS*, and *PTS*; Figure 2.7, Figure 2.8, and Figure 2.9, respectively). Emergy inputs and outputs were classified and organized in a table for each treatment scenario (Appendix A). Each line item represents the sum of a given source of emergy in the system (e.g., line item "concrete" refers to the total amount of concrete used in construction of the clarifiers, treatment area, etc. for the ATS). These classifications were used to determine the type of emergy the system utilized to treat the mine drainage.

The *PTS* scenario relied upon free environmental inputs at a rate of 4 times that of the *ATS* scenario while the *ATS* scenario used 5 times as much purchased emergy (Table 2.3). However, 53% of the purchased emergy in the *PTS* scenario was from compost. This figure may be a high estimate as the solar transformity for compost from Ortega (1998) was calculated using a larger agricultural system that interacted with the economy to a greater extent than the mushroom compost used in these bioreactors. Since the mushroom compost in these bioreactors was locally available and relatively inexpensive, the true transformity may be less. Consequently, the purchased emergy for the *PTS* scenario would decrease. Based on the study's assumptions of equal treatment, both treatment systems discharged the same amount of emergy to the environment, but both were less than the *No Treatment* system.

Wójcik et al. (2000) found conventional treatment of mine wastewater in Poland required 270 times more purchased emergy than treatment with natural wetlands. However, this system adapted an existing wetland to treat the mine wastewater by building dikes around the wetland and planting specialized vegetation to better control the flow regime and uptake metals, respectively. Wójcik et al. (2000) did not account for direct emergy inputs. Rather, the cost of construction and operation of both treatment systems were multiplied by an emergy-to-money ratio that does not consider the specific type of emergy input to a system.

Table 2.3 Total emergy values of TSI components and TSI for each treatment scenario.

	Emergy (10^{17} sej)				
	R	WW_{in}-WW_{out}	*F*	ENV_{load}	**TSI**
No Treatment, AMD	0	0	0	0.14	0
ATS	0.008	1.02	31	0.08	0.03
PTS	0.045	1.02	5.8	0.08	0.18
No Treatment, MWW	0	0	0	6.9	0
WWTP	0.015	2.6	25	6.0	0.086
CTW	0.06	2.6	7.3	5.9	0.20

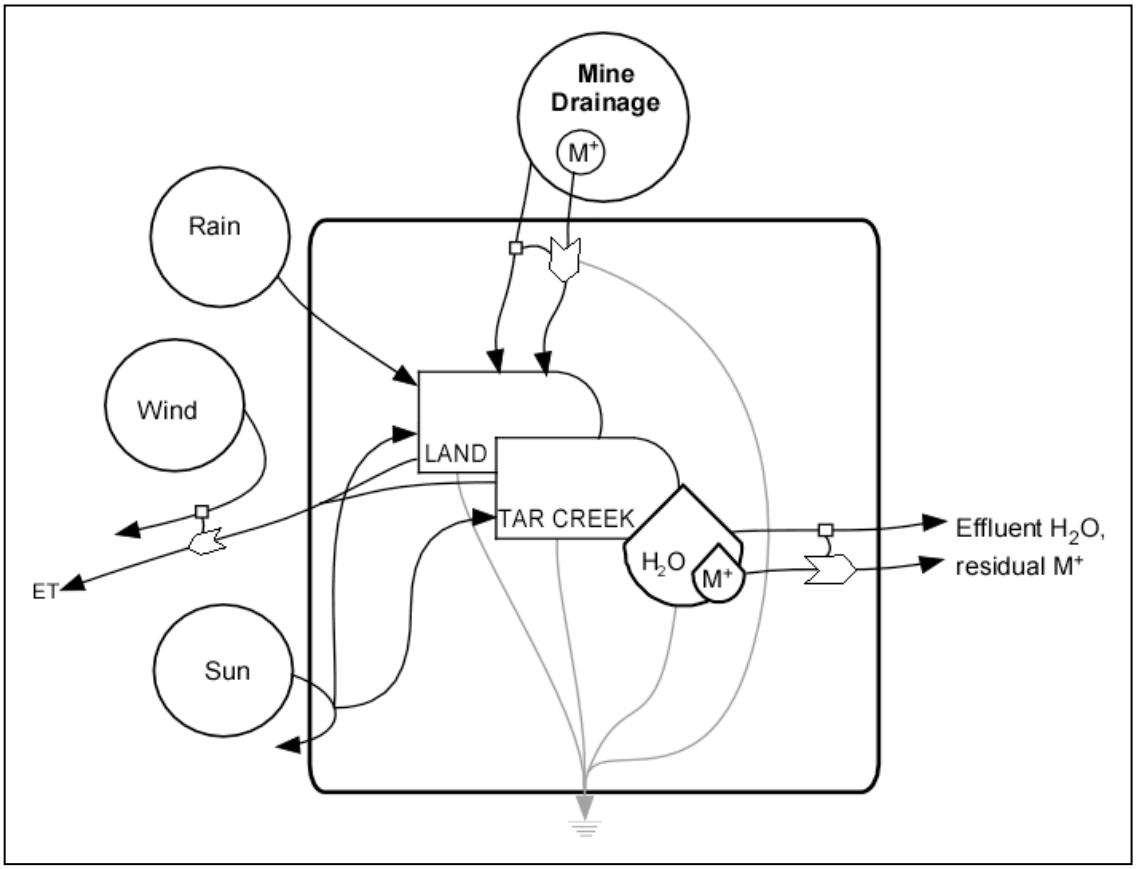


Figure 2.7. Energy systems diagram of *No Treatment* scenario. The energy from metals (M^+) is coupled to the mine drainage. Key- Metals: M^+

Figure 2.8. (Following Page) Energy systems diagram of Active Treatment System. Money is exchanged for goods and services, which drive most of the processes in this system. On the left, renewable sources of energy (Sun, Wind, Rain) minimally affect operations. Key- Metals: M^+, Hydrated Lime: $Ca(OH)_2$, Potassium Permanganate: $KMnO_4$.

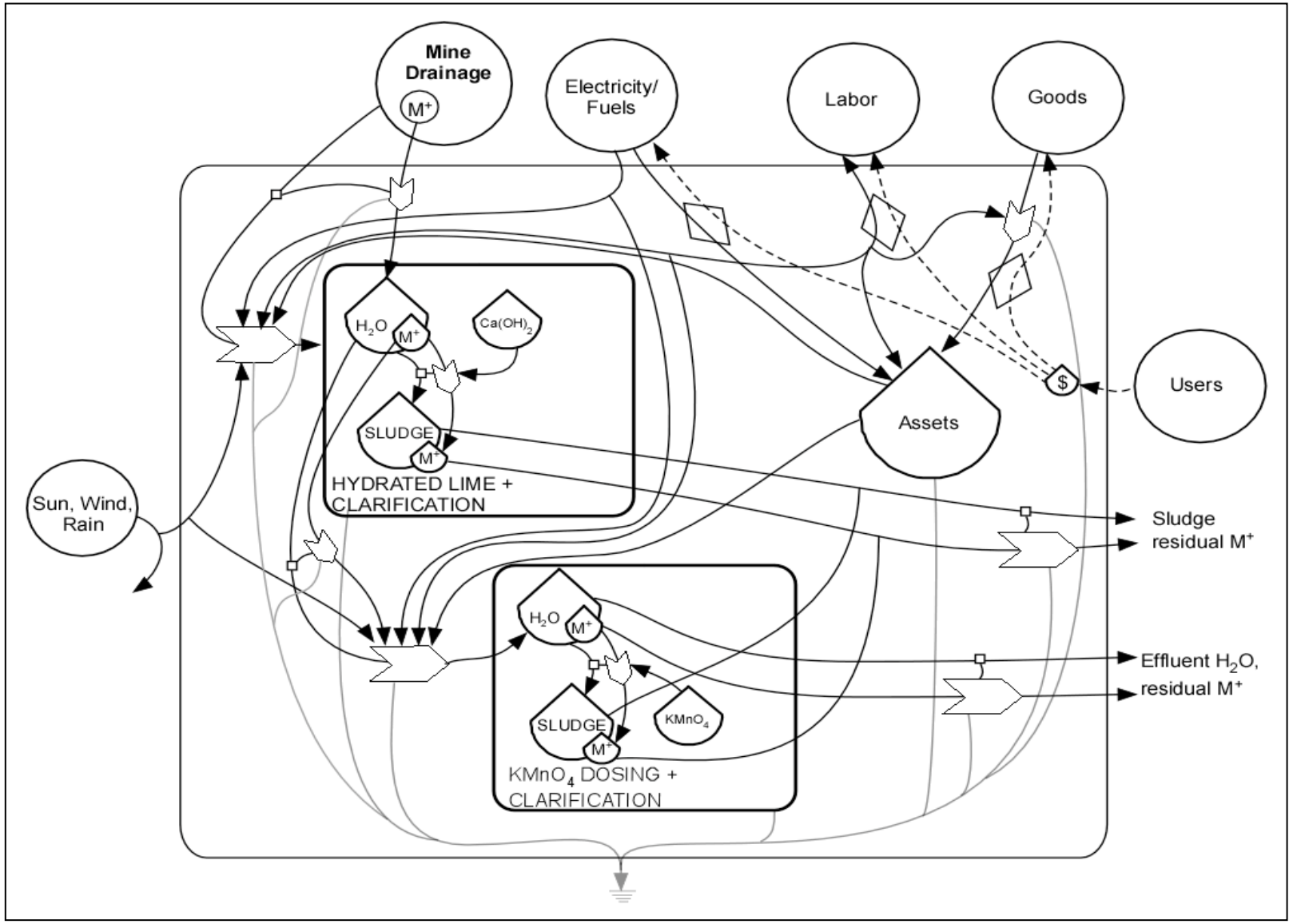
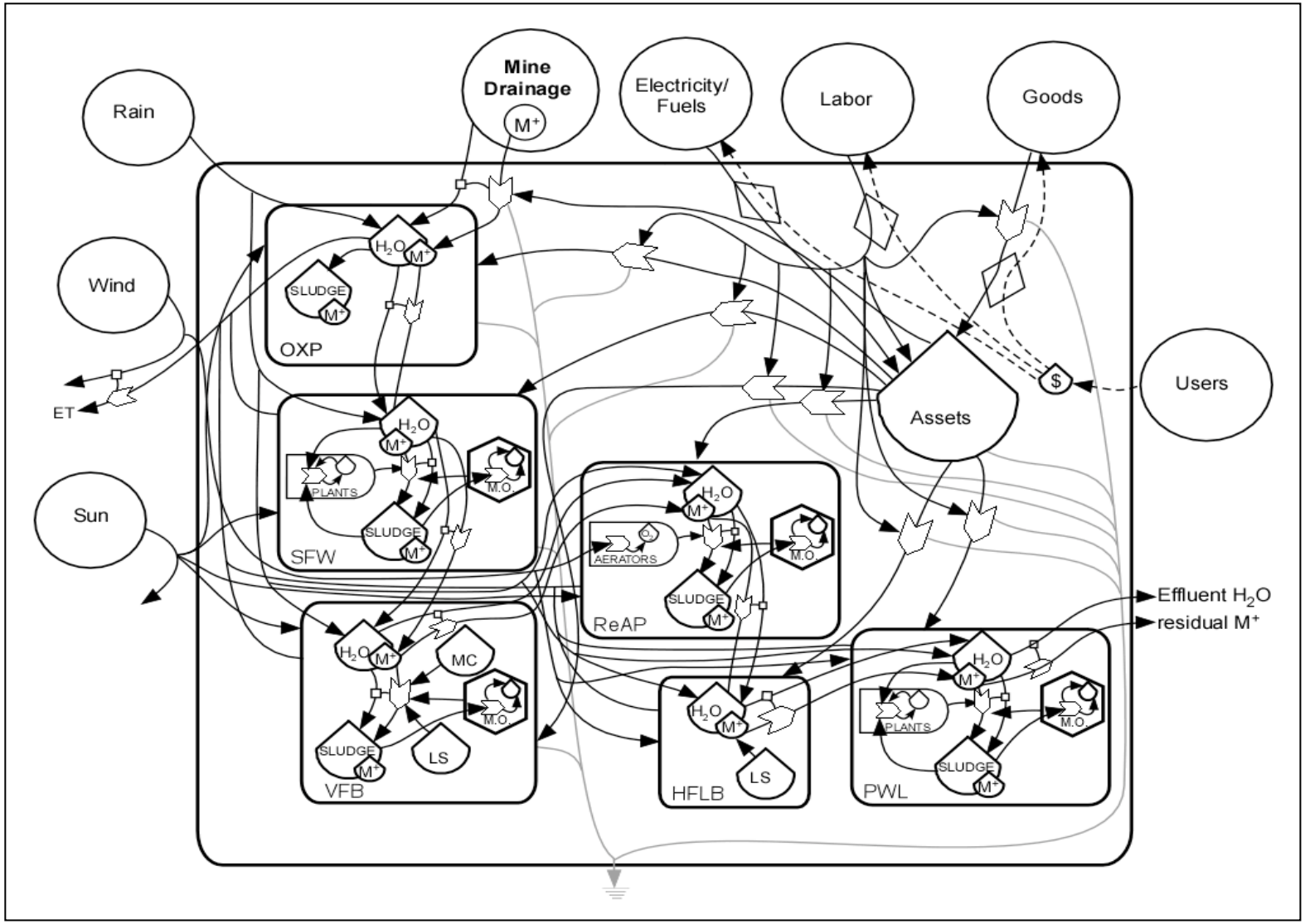

Mine Drainage
M+
Electricity/ Fuels
Labor
Goods
Users
$
Assets
H2O
M+
Ca(OH)2
SLUDGE
M+
HYDRATED LIME + CLARIFICATION
Sun, Wind, Rain
Sludge residual M+
H2O
M+
SLUDGE
M+
KMnO4
KMnO4 DOSING + CLARIFICATION
Effluent H2O, residual M+

Figure 2.9. (Following Page) Energy systems diagram of Passive Treatment System (PTS). Energy sources on left (Sun, Wind, Rain) drive much of the operation of this system. Each unit process operated on environmental inputs. One-time construction energy flows are present in the form of assets and labor. Microorganisms (M.O.), Metals (M^{+}), Limestone (LS), Mushroom Compost (MC) were storages in unit processes Oxidation Pond (OXP), Surface Flow Wetland (SFW), Vertical Flow Bioreactor (VFB), Reaeration Pond (ReAP), Horizontal Flow Limestone Bed (HFLB), and Polishing Wetland (PWL).


Rain
Mine Drainage
M+
Electricity/ Fuels
Labor
Goods
Wind
ET
Sun
Users
$
Assets
H2O
M+
SLUDGE
OXP
PLANTS
M.O.
SFW
AERATORS
O2
ReAP
MC
LS
VFB
HFLB
PWL
Effluent H2O
residual M+

Municipal Wastewater Treatment Systems

Energy systems diagrams were drawn for each system (*No Treatment*, *ATS*, and *PTS*; Figure 2.10, Figure 2.11, and Figure 2.12, respectively). Emergy analysis tables show all inputs and outputs of each treatment scenario categorized by Environmental, Purchased, and Wastewater inputs to both the treatment system and the receiving environment (Appendix A). Explanations of numeric data are provided in the Appendix A CALCULATIONS section.

The WWTP treatment scenario used over three times more emergy from purchased goods and services (F) than CTW scenario (Table 2.3). The WWTP treatment scenario used F in proportion to R over 13 times more than the CTW system. The WWTP used 2.46×10^{18} sej of purchased emergy while the CTW used only 0.73×10^{18} sej.

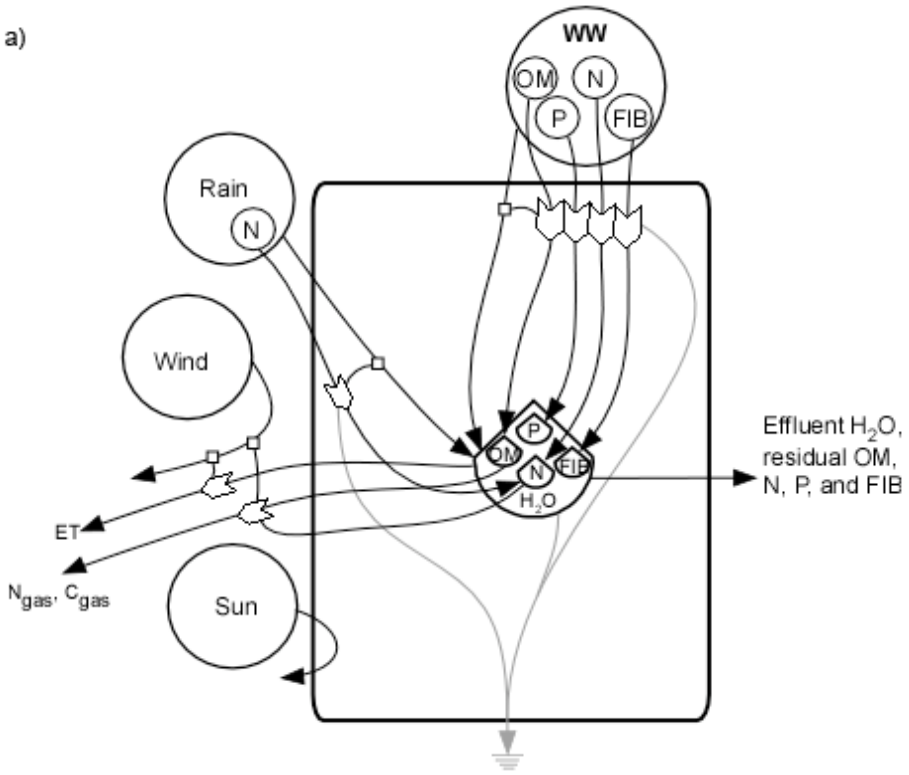


Figure 2.10. Energy systems diagrams for No Treatment scenario of municipal wastewater. Key: N- Nitrogen, OM- Organic Matter, P- Phosphorus, FIB- Fecal Indicator Bacteria, ET- Evapotranspiration, C_{gas}- Carbon dioxide, N_{gas}- gaseous nitrogen.

Figure 2.11. (Following Page) Energy systems diagrams for Wastewater Treatment Plant (WWTP) scenario, adapted from Arias and Brown (2009). Organic Matter (OM), Phosphorus (P), Microorganisms (M.O.), Fecal Indicator Bacteria (FIB), Nitrogen (N) are inputs from wastewater and stored in unit processes.

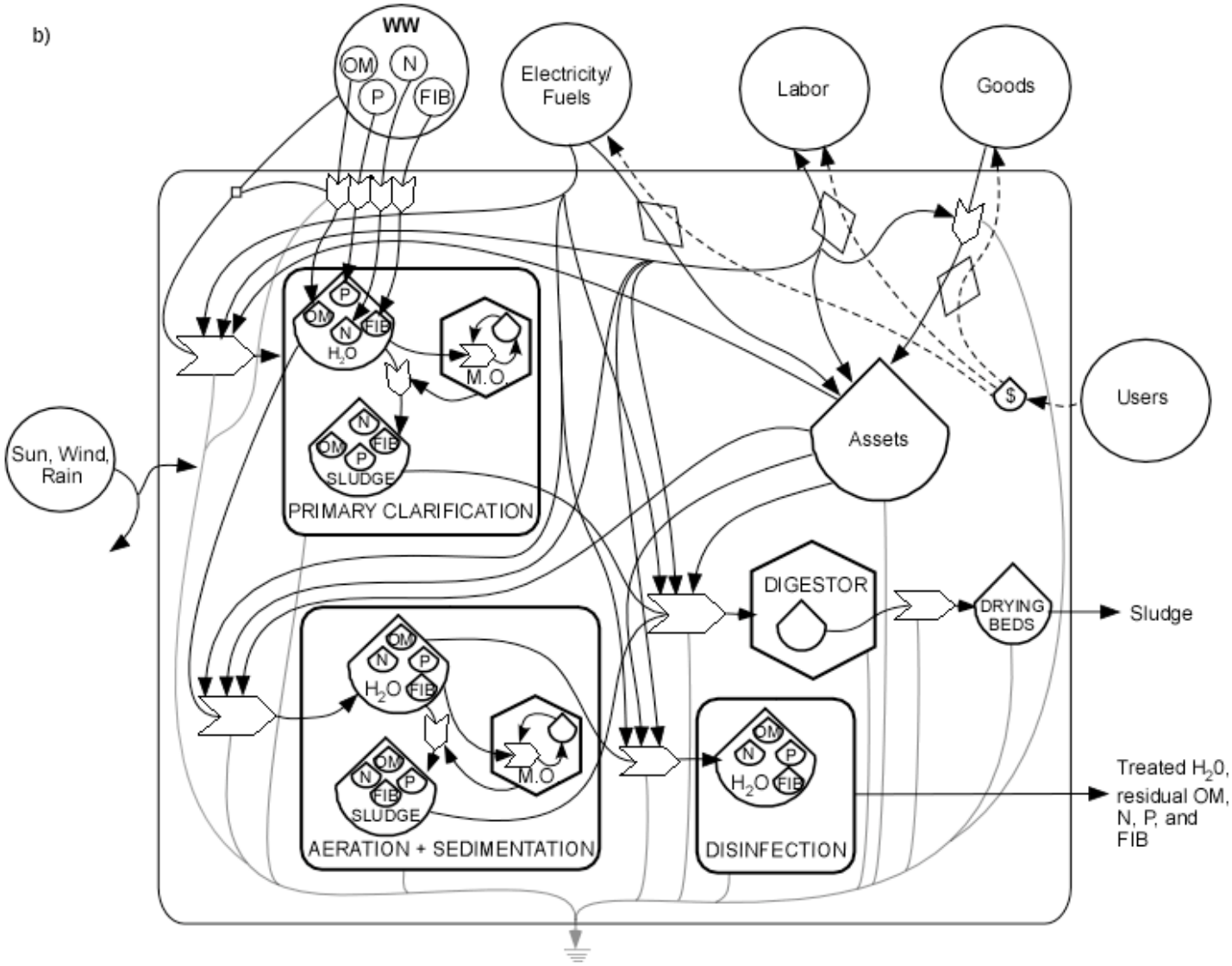
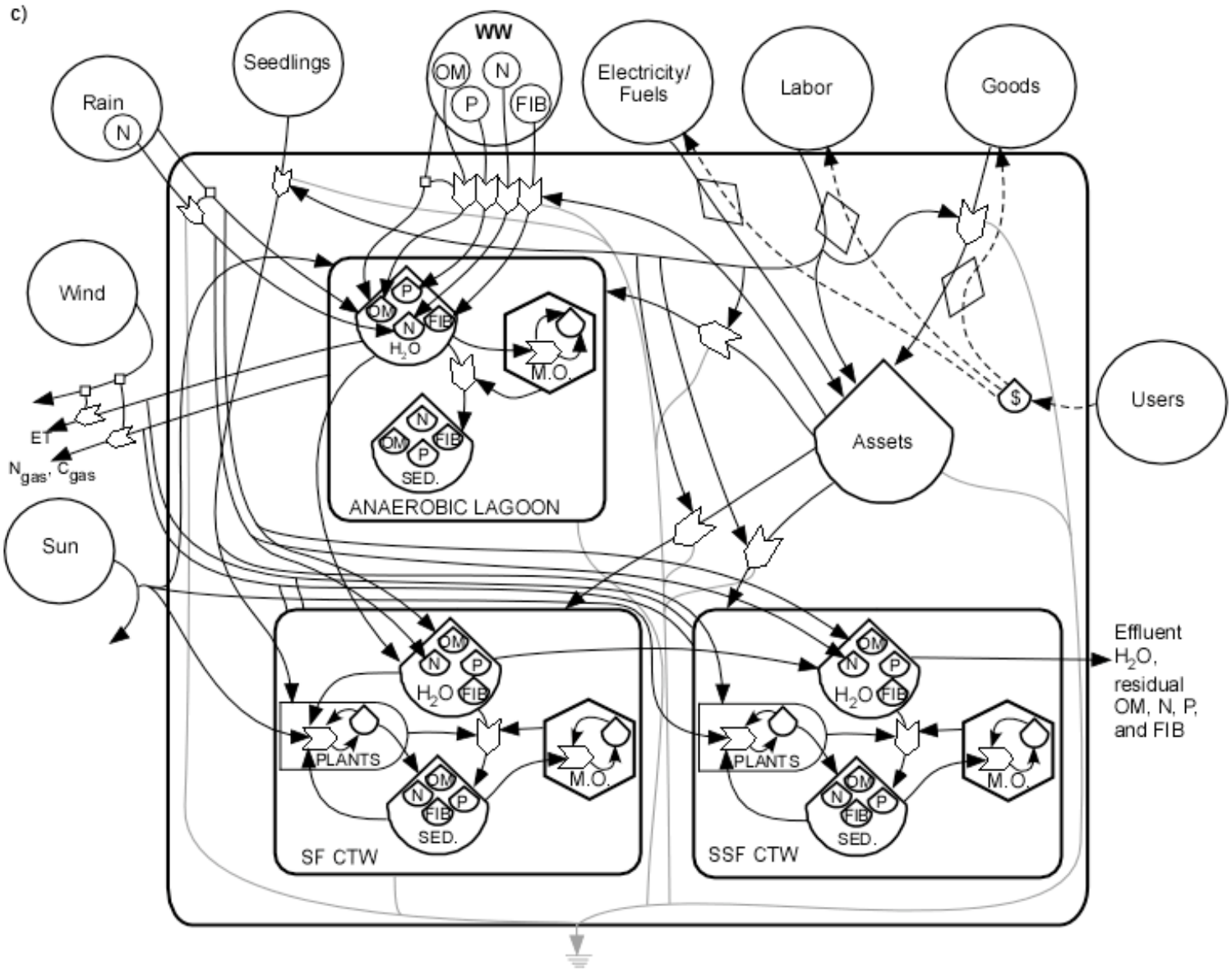

b)
WW
OM
N
P
FIB
Electricity/
Fuels
Labor
Goods
Users
$
Assets
Sun, Wind,
Rain
H2O
M.O
SLUDGE
PRIMARY CLARIFICATION
DIGESTOR
DRYING
BEDS
Sludge
AERATION + SEDIMENTATION
DISINFECTION
Treated H20,
residual OM,
N, P, and
FIB

Figure 2.12. (Following Page) Energy systems diagrams for Constructed Treatment Wetland (CTW) scenario. Organic Matter (OM), Nitrogen (N), Phosphorus (P), and Fecal Indicator Bacteria (FIB) present in wastewater (WW) were conveyed to each treatment scenario. M.O. represents microorganisms. Sed. represents the sediment in surface flow (SF) and subsurface flow (SSF) CTW cells. Adapted from Arias and Brown (2009).


c)
Seedlings
WW
OM
N
P
FIB
Rain
N
Electricity/
Fuels
Labor
Goods
Wind
H2O
M.O.
SED.
ANAEROBIC LAGOON
ET
Ngas, Cgas
Assets
$
Users
Sun
PLANTS
SF CTW
SSF CTW
Effluent
H2O,
residual
OM, N, P,
and FIB

Arias and Brown (2009) compared treatment systems to a modeled CTW system using emergy analysis. Their findings suggested a CTW system treated wastewater using less emergy than an active wastewater treatment system, but used more emergy than a waste stabilization pond. Zhou et al. (2009) found a CTW system used much less purchased emergy than a conventional treatment system relative to the amount of waste removed. However, the comparisons were made on two systems treating varying flows and levels of wastewater constituents. Similarly, inputs and indices of the same CTW system as the Zhou et al. (2009) study were compared to various conventional treatment systems around the world (Chen et al., 2009). These systems treated highly variable wastewater and served varying population sizes. The studied CTW had a lower environmental loading ratio than all other systems studied except another CTW system that served far fewer people than the studied CTW system. Björklund et al. (2001) and Geber and Björklund (2001) compared a conventional WWTP, a WWTP coupled to a CTW, and a natural wetland using emergy analyses. The authors found the conventional WWTP coupled to a CTW utilized far more free environmental inputs than the conventional treatment alone. However, the compared systems served different population sizes, which may have introduced bias in their comparisons. In that study, the WWTP and CTW system removed more N and P annually as well. The natural wetland exhibited similar removal performance, but did so over a much greater residence time.

2.4.3. Residual Emergy Conveyed to Environment

Residual Emergy in Acid Mine Drainage

In order to calculated the residual emergy conveyed to the environment from the waste treatment systems or seeps (in the case of No Treatment), reduction of constituent concentration to background levels in the receiving environment was modeled. Because there were no known models that describe the attenuation of metals from acid mine drainage in receiving environments, a 1st order removal model was developed. The constituent with the largest area required to return its concentration to background level was selected. Mn and Cd were not removed effectively in the river, which would suggest the removal of these would require the largest amount of area. However, these metals can be soluble at the pH of the receiving rivers and appear as dissolved and precipitated with little to no predictability (Meck, et al., 2011). Consequently, the attenuation of Mn and Cd cannot be modeled with any accuracy and may not be possible until reaching a large body of water where sedimentation is the only sink. Upstream of the discharge into the receiving stream, Zn was in quantities much higher than its background level, so environmental sources of Zn may have confounded a model of removal in that receiving stream. Nickel was selected as the constituent for determining the receiving environment area because it had low removal in the river and could be modeled.

For the No Treatment scenario, a piece-wise 1st order model was developed to represent the removal of nickel downstream of the seeps and determine the area required to return Ni concentration to its background level. A piece-wise model was chosen for the No Treatment scenario because the seeps, prior to discharge into Unnamed Tributary (Figure 2.1), created a volunteer wetland. Because the removal mechanisms and their

rates for Ni likely differ in a wetland from those in a river environment, they are modeled separately (Figure 2.13). The removal rate of Ni in the wetland area (1.5 ha) in the No Treatment scenario was determined from the Ni concentrations at the seeps and the discharge point into Unnamed Tributary. The removal of Ni was much higher in the wetland than in the receiving river (Figure 2.13). The calculation of the river area was determined from the equation of the trendline for data points of Ni concentrations at the discharge into the river and two points downstream. The area required to return Ni to background levels was determined by solving for the model with the response variable set to the background concentration of Ni (0.014 mg/L). This resulted in a river area of 5.4 ha, for a total required area in the No Treatment scenario of 6.9 ha. The emergy input to the wetland area and river area were calculated separately as the emergy of the evapotranspiration of each, respectively (Appendix A).

Nickel concentrations in the river that was receiving effluent from the treatment systems were modeled similarly to the concentrations in the river described for the No Treatment Scenario. The area required to return Ni concentration to its background level downstream of the treatment system was 3.8 ha (Figure 2.13). Figure 2.14 depicts all treatment scenarios as occurring simultaneously but each was evaluated separately.

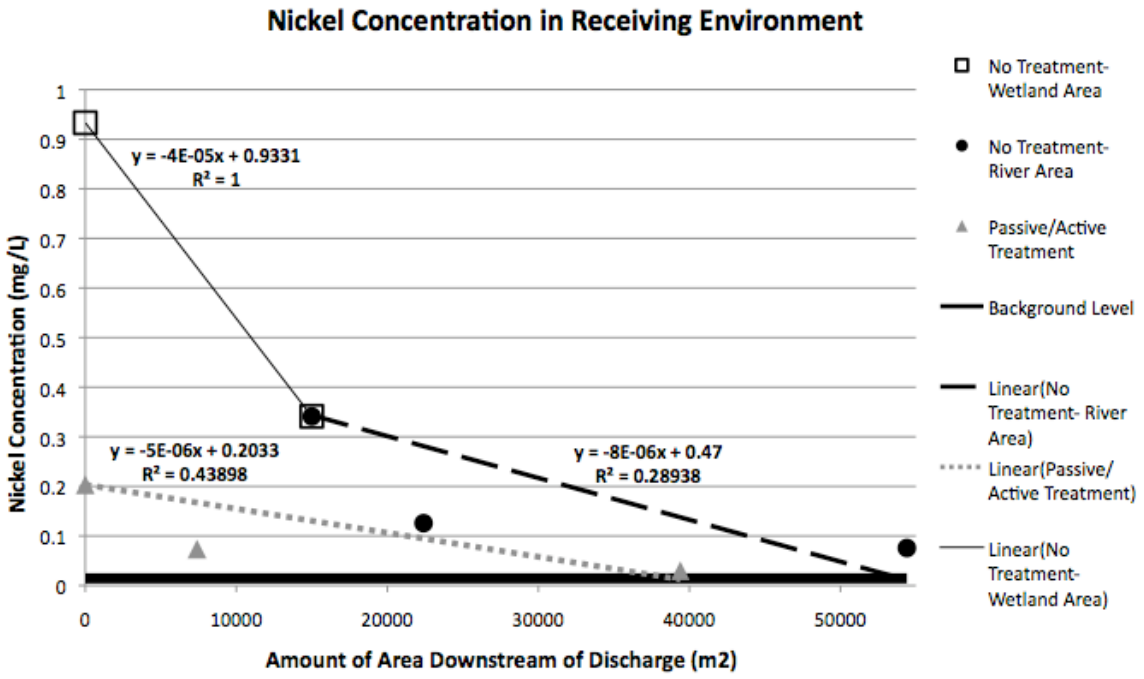


Figure 2.13. Piece-wise 1st order removal model for nickel in the No Treatment scenario of AMD (volunteer wetland area from seeps to river, solid trendline and river area, dashed trendline) and 1st order removal model for nickel in the receiving river area downstream of treatment systems, gray dotted trendline. Reference sites were used for background level, thick solid line. Two downstream sites on Tar Creek were used for removal models in river areas.

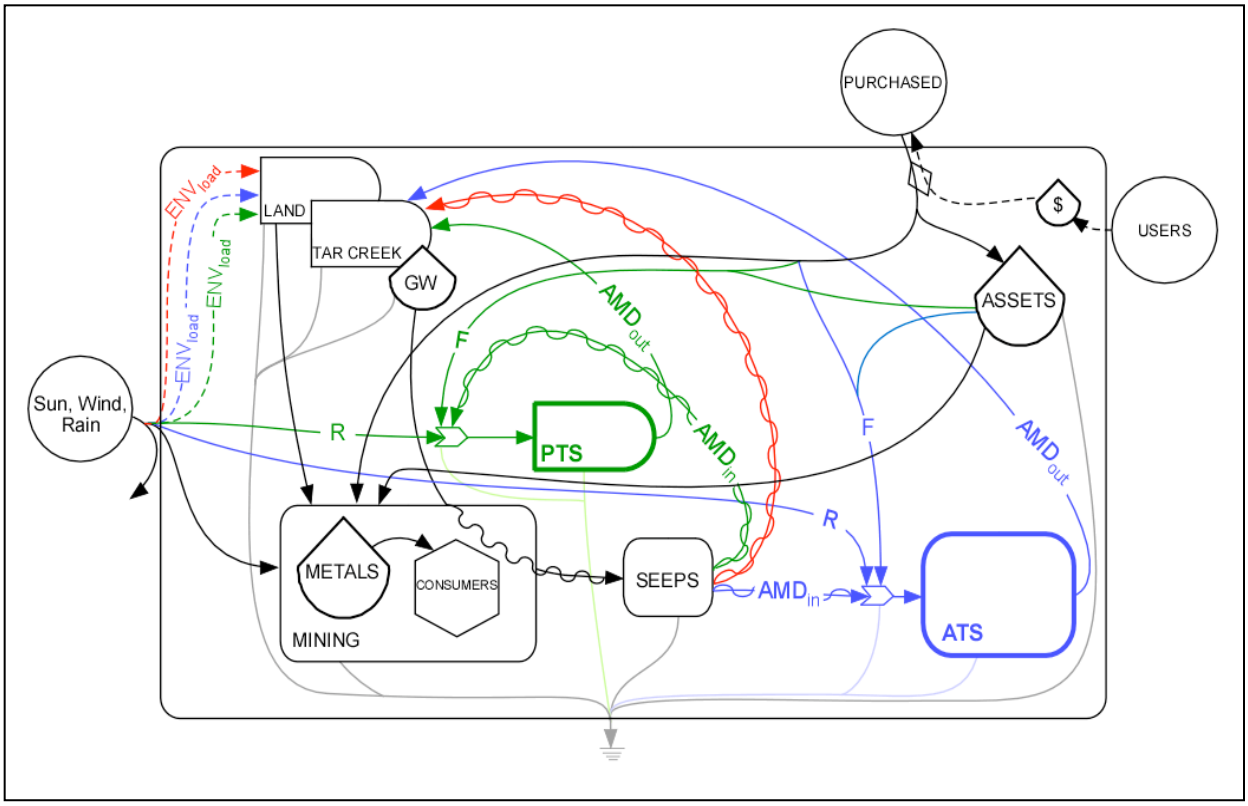


Figure 2.14. Energy systems diagram of the treatment process. Three treatment scenarios are shown- *No Treatment* (red), *PTS* (green), and *ATS* (blue), The wavy lines indicate the flow of energy is coupled to the mining waste. That is, the flow of energy from groundwater (GW) is coupled through the systems, as it eventually returns to the GW energy storage. Labels on flow lines correspond to energy flows used to calculate the emergy inputs in the TSI.

The environmental emergy that was required outside the treatment system (ENV_{load}) to reach background levels was much greater for the *No Treatment* scenario (Table 2.3). Local, renewable emergy used in treatment (R) was greater in the *PTS* than other treatment scenarios.

Residual Emergy in Municipal Wastewater

The recovery of DO in stream was modeled using the Streeter-Phelps equation. The area of river required to return DO to background levels was calculated using the results of this model. The effluent BOD concentration of each scenario (Table 2.2) was used in the Streeter-Phelps equation to model DO sag curves which determine a distance downstream from the effluent on a hypothetical river where DO concentrations would return to background conditions (Figure 2.15). The hypothetical 10 m wide, 40 cm deep river flowing at 3.2 m^3/s had a background DO concentration of 8 mg/L and BOD of 5 mg/L. Using a deoxygenation rate (k_D) of 0.017/h and a reaeration rate (k_r) of 0.021/h, the distance downstream where the river reaches saturated DO (9.1 mg/L) was modeled. However, this study used the distance downstream from the effluent discharge where background river DO was reached (Figure 2.15). This distance was used to determine an area of the river needed to return DO to background concentrations. The ENV_{load} was estimated using this area. Figure 2.16 depicts all treatment scenarios as occurring simultaneously but each was evaluated separately.

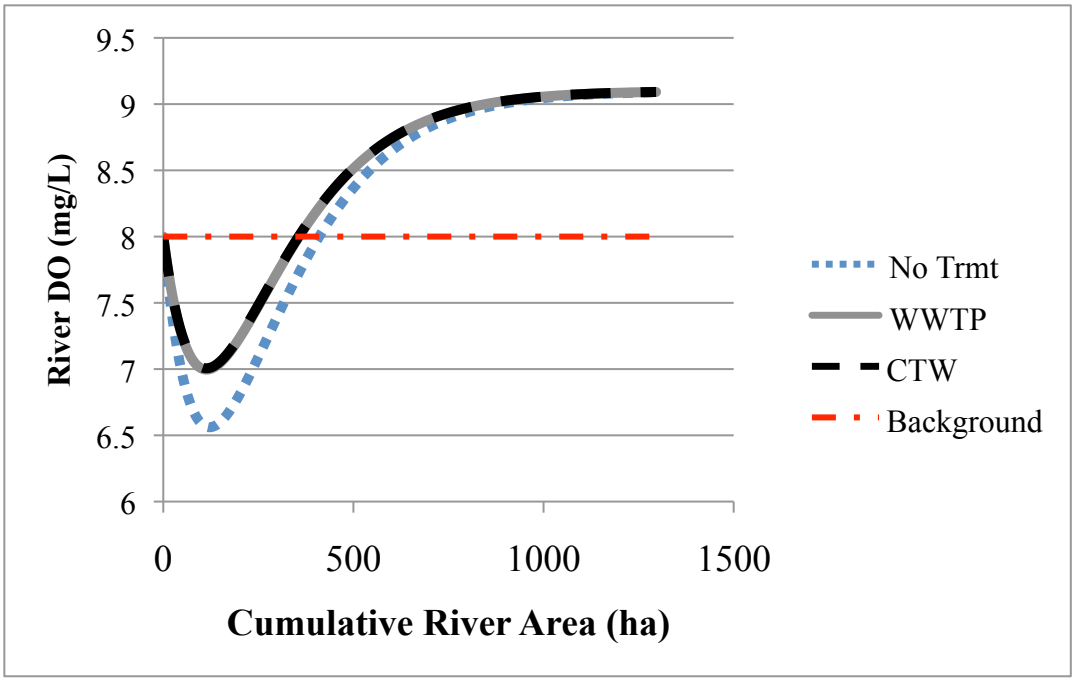


Figure 2.15. Dissolved oxygen sag curve in hypothetical receiving environment (river) modeled using the Streeter-Phelps equation. Linear river miles were calculated and converted to river area for emergy evaluations using the average river width of the hypothetical river.

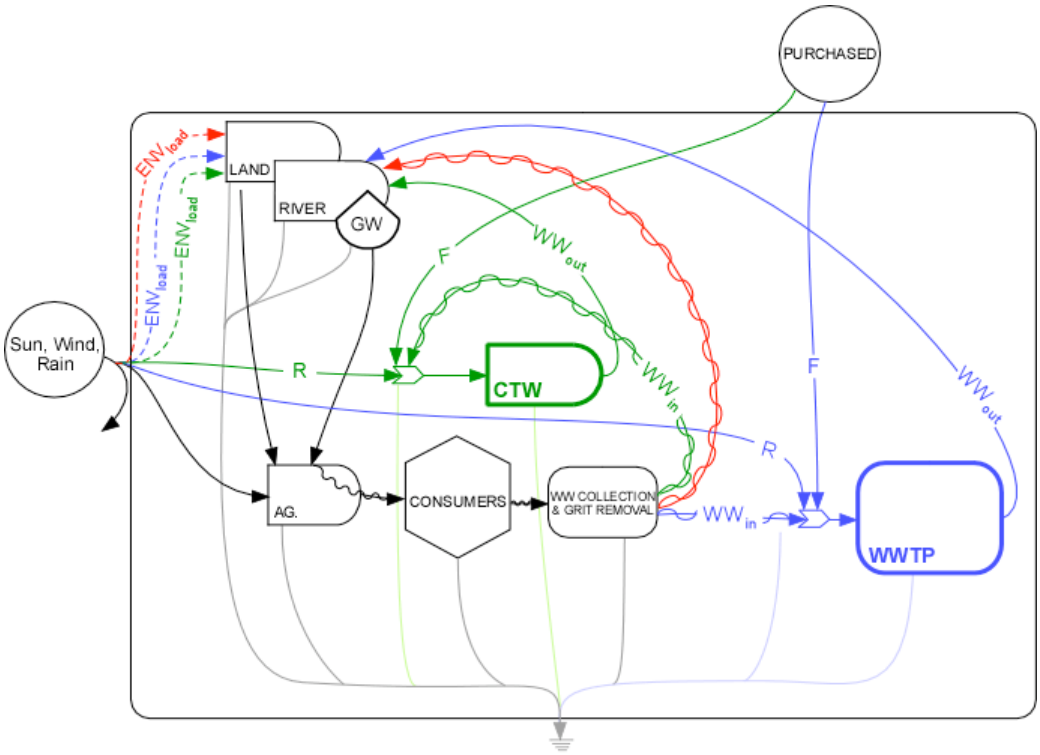


Figure 2.16. Treatment scenarios energy systems diagram. Three treatment scenarios are presented simultaneously in the diagram, but are evaluated separately in this study. They are shown here to suggest that these three systems are competing for resources. However, the internal processes and storages outlined in black (LAND, RIVER, GW, AG., CONSUMERS, and WW COLLECTION & GRIT REMOVAL) would exist regardless of which scenario is present. ENVload is the emergy required by the receiving environment to return effluent concentrations to background level. CTW is the Constructed Treatment Wetland treatment scenario. WWTP is the Wastewater Treatment Plant treatment scenario.

ENV_{load}, the amount of emergy from environmental processing of effluent, was similar for the WWTP and CTW treatment systems, but larger for the *No Treatment* scenario (Table 2.3), which was expected. The greater ENV_{load} required in the No Treatment scenario results in less emergy being available for natural processes to occur. The similarity in the two treatment scenarios is due to the removal of organic matter (OM) by the WWTP and CTW being roughly equivalent, while more environmental emergy was needed by the No Treatment Scenario to degrade OM.

Residual Emergy Calculation

The emergy associated with reaching background concentrations of constituents of most concern (ENV_{load}) was calculated for each scenario. This emergy was calculated as the total renewable inputs to the receiving environment. Alternatively, (Ulgiati and Brown, 2002) quantify the specific environmental service of diluting waste in the case of waste heat from electricity production. Similar to this study, when residual emergy was accounted for in their analyses, the authors found systems that discharged residual emergy to the environment had lower performance indicators (lower environmental loading ratio and emergy yield ratio). However, for wastes with multiple sources of residual emergy (i.e., wastewater), this approach may not adequately quantify the services provided by the environment in mitigating residual emergy.

2.4.4. Index for Waste Treatment

The present study used emergy inputs gathered from real and simulated data and their complementary transformities to find that, in the treatment of acid mine drainage,

the active treatment system used 5 times more purchased, non-renewable emergy (*F*) than the passive treatment system, decreasing the TSI for active treatment (Table 2.3). For municipal wastewater treatment, the constructed treatment wetland utilized more renewable emergy (R) for equivalent treatment performance (WW_{in}-WW_{out}), used less F, and required less ENV_{load} than the wastewater treatment plant, the constructed treatment wetland had a TSI more than twice that of the wastewater treatment plant (Table 2.3). A higher TSI suggests the passive treatment systems rely less on emergy inputs from outside sources that are non-renewable, utilizing more sustainable sources of energy that are locally available and renewable. Because treatment performances were assumed to be identical in these systems, the performance component (WW_{in}-WW_{out}) had no effect on the comparison of the TSI between active and passive treatment. However, if a comparison between real-world systems were made, treatment performance could affect the comparison of the TSI.

If a system failed to compensate for highly variable flows, wherein its capacity was exceeded, the treatment performance component of the TSI would capture and reflect that failure. Unfortunately, because the treatment performance may change over time for some systems, this index may overestimate the relative sustainability when assessed based on performance of the first year of operation. However, for the treatment of acid mine drainage in this study, a ten-fold decrease in the emergy associated with treatment performance would be required to decrease the TSI of the *PTS* to that of the *ATS*.

2.5. Conclusion

This work evaluated six scenarios of treating two types of wastewater (i.e., acid mine drainage and municipal wastewater) using data from two real systems (No Treatment scenario for acid mine drainage and passive treatment of acid mine drainage) and data from four modeled systems (No Treatment, active treatment, and passive treatment of municipal wastewater and active treatment of acid mine drainage). The emergy syntheses showed passive systems used more renewable emergy than active systems and required less purchased emergy. While this study was limited in scope of treatment performance comparisons using emergy, a new index was developed that reflects resource use, treatment performance, and the mitigation of residual emergy by receiving environments. The concept of residual emergy mitigation by the receiving environment was expanded upon in this study by acknowledgment that the mitigation requires multiple environmental processes and thereby requires accounting of all environmental inputs to the receiving environment. The TSI for passive systems was an order of magnitude higher than for active systems (on a wastewater type-comparison). The emergy required to absorb residual waste was larger for scenarios of no treatment, as expected.

Future work includes analyzing real systems using the TSI and residual emergy framework. Because most of the systems in this study were models, an accurate reflection of the utility of the TSI is limited here. It would be useful to compare TSI values for operating systems to compare residual emergy discharged to the environment (ENV_{load}). If enough information on receiving environments is available, these analyses can be applied to existing case studies in the literature, which would be the next logical step for

this research. However, this is unlikely considering most studies do not account for the receiving environment and, consequently, it is rarely described.

Additionally, improvements to the calculation of the ENV_{load} term could be made. It is appropriate to allocate to the residual emergy mitigation (ENV_{load}) all of the emergy inputs to that receiving environment. However, Ulgiati and Brown (2002) quantify the specific environment service of diluting waste in the case of waste heat from electricity production. For wastes with multiple sources of residual emergy, this approach may not adequately quantify the services provided by the environment in mitigating residual emergy.

Chapter 3. Recycling of Mass and Emergy in Natural and Human-Dominated Systems

3.1. Abstract

Emergy Algebra rules may not allow for appropriate accounting of recycled material emergy. The loss of emergy is not permitted using Emergy Algebra rules, but is necessary to address recycling material. It has been proposed to use Dynamic Emergy Accounting so that emergy loss can be factored in when allocating emergy to material recycle pathways. However, systems are often evaluated at steady-state (and when stationary or slowly transient) following Emergy Algebra rules. By studying these natural and managed systems, indices that address recycling of materials and the most appropriate allocation of their emergy will be developed to improve emergy methodology regarding emergy cycling. Current methodology does not explicitly address emergy tied to material recycling pathways in both natural and managed systems, the aim of this study is to improve methods of allocating emergy to material recycle pathways.

Three production systems in Maryland and the District of Columbia will be evaluated for emergy inputs and outputs. Each system will be evaluated on a per hectare basis. First, a hectare of Maryland forest will be evaluated. The primary emergy inputs to the natural forest are from environmental sources. Two agricultural systems will also be evaluated: a traditional farm and an organic CSA farm. The traditional farm is a small, family-owned and -operated farm on Maryland's Eastern Shore that employs conservation tillage, herbicide application, manure and rock phosphate fertilization, and center pivot sprinkler irrigation. The Community Supported Agriculture (CSA) farm, located in suburban Columbia, MD, used cover crops and reduced tillage, small farm equipment, and more human labor. The CSA farm also rotates crops and adds organic amendments to promote soil biological and physical health, maintain pollinators, and attract wildlife while irrigating and fertilizing conservatively. Material recycle in both agricultural systems is roughly equal to that in the forest. Emergy associated with recycling material was larger in the farms, suggesting the forest more efficiently recycled the material internally, using less emergy to do so. The forest had much lower material input and output than the farms. In each system, the largest emergy flow associated with material was internal to the system.

3.2. Introduction

Using emergy for evaluating ecological and economic systems is becoming increasingly widespread. The methods for environmental accounting of systems that recycle material are not fully formed. It is important to work towards an understanding of

how emergy is allocated to materials that recycle. Particularly, transformed materials that recycle within systems may not be adequately represented in the emergy methodology.

Phosphorus is an important element in ecosystems. The phosphorus cycle is "closed" in the sense there is no large sink where P can flow as there is in the nitrogen and carbon cycles (i.e., the atmosphere). Because of this conservative nature of P, it was studied as a cycling material in forest and agricultural ecosystems. P enters terrestrial ecosystems primarily from rock weathering at low rates (compared to other nutrients N and C) and cycles within ecosystems at a relatively large rate (Walker and Syers, 1976; Yanai, 1992). In a forest, phosphorus enters the ecosystem through rock weathering of apatite and some atmospheric deposition (Vitousek, 2004). Phosphorus in the form of phosphate in soil is taken up by plants and microorganisms and returned as organic phosphorus through litterfall or death. Microorganisms mineralize organic P by producing phosphatase enzymes for conversion to phosphate (Vitousek, 2004). Because phosphates bind strongly to soil particles, most of the outflow of P from a terrestrial ecosystem is through erosion and stream runoff (Yanai, 1992). Phosphorus is also of concern because of its role in the global food economy. Globally, the natural P cycle has been disturbed by mining of phosphorus rock, redistribution along large spatial gradients, and indirect effects related to the coupling with the N-cycle (Caraco, 1993).

Using the phosphorus cycle as a backdrop for emergy evaluations of material cycles may improve methodology for allocating emergy to internal cycles. Phosphorus balances and emergy evaluations for three study sites were completed and compared using ratios of mass and emergy flows. Decisions on how emergy is assigned to mass recycling flows were made in this study and will be discussed. The aim of this work was

to explore how emergy associated with a conservative material was cycled in natural and managed systems. The phosphorus balance of a natural forest and two agricultural systems served as the basis for studying emergy flow and cycling.

3.3. Methods

Three systems were selected for their ease of comparison regarding function (one agro-forestry system and two agricultural systems of varying degrees of management). While all systems recycle phosphorus similarly, phosphorus (and emergy) flows were expected to be variable between systems. A phosphorus budget and emergy evaluation was completed for each system for calendar year 2010. Emergy flows for mass recycling pathways were calculated and assigned to the appropriate flows.

3.3.1. Study Sites

a. Maryland Forest

A privately owned forest in central Maryland (MD Forest) was evaluated. The 12.3-ha forest contained mostly oak, poplar, and beech species. Elevation was approximately 500 m. Net primary production was about 5.5 Mg C/ha/yr (~14400 kg biomass/ha/yr; Tilley, 1999). The forest was used for minimal, sustainable timber extraction (about 900 kg biomass/ha/yr) resulting in modest material export beyond what is presumed to be natural. No irrigation or other management was identified. Due to lack of site-specific data, much of the phosphorus budget was

adapted from Yanai (1992) and Tilley (1999). Forest management records were obtained from (Moss, 2007).

b. Community-Supported Agriculture (CSA, Shaw Farm)

A community-supported agriculture (CSA) farm (Shaw Farm) was also evaluated. The 0.4-ha farm was situated in a suburban area in central MD. Although the entire farm area was about 0.8 ha, only about half of that area was used for production (including that area kept fallow for rotation). The other half of the farm that was not considered in this study consisted of a gravel parking area, a storage yard, and buffers between crop fields and roads. Zero- to low-tillage was performed on soil prior to planting. Organic fertilizer/compost was used as much as possible. Crops were irrigated with well-water. During the study period, the farm was managed by an agro-ecologist and owned by Shaw Farm CSA. Because many of the CSA members picked up shares from the farm in Columbia, MD, produce was refrigerated on site. Refrigeration of produce, a central service of the farm, was the only use of electricity. Small portions of the farm area were used to grow plants to attract beneficial insects. While these techniques did not directly increase crop yield, it is presumed they were involved in maintaining a healthy ecosystem that prevented pesticides from being used on this certified organic farm. The farm manager's time spent implementing these techniques was included in

emergy calculations. Seed, fertilizer, and electricity purchases, planting plans, well-water and fuel use, soil chemistry data, labor and harvest records, and management plans were obtained from the farm manager (Hughes, 2010). Shaw Farm produced 1,950 kg of produce for the calendar year 2010 (Hughes, 2010).

c. Traditional Farm (Greenway Farm)

Greenway Farm, a typical northeast Maryland, USA 2.8-ha farm using traditional farming techniques was evaluated. The family-owned farm consisted of several buildings, including a residence, on about 12 ha. For this study, only the infrastructure required to operate and maintain the area of the farm used for production was considered (2.8 ha). This included areas kept fallow for rotation. Greenway Farm used conventional tilling, well water irrigation, and mineral fertilizer to grow specialty greens, berries, and vegetables. Harvested crops were sent to regional farmers' markets seasonally. The farm produced about 5,400 kg/yr of raspberries, watermelon, specialty salad greens, squash, and onion. Farm records for calendar year 2010 were obtained from Dill (2010).

For the purposes of comparisons in this study, MD Forest represents a natural system, Shaw Farm a managed system, and Greenway Farm a heavily managed system.

3.3.2. Phosphorus Mass Balance

The mass balance for each site was calculated using inputs and outputs documented in site management records along with inputs, outputs, and recycling of phosphorus found in literature. The mass balance was completed for the calendar year 2010. Phosphorus concentrations provided in other forms (typically phosphate) were converted to elemental P for the mass balance calculations. System boundaries were defined as the physical boundary of the field (farm sites) or landowner's property lines (forest site). Because this evaluation was done for the year 2010 and storages in phosphorus could change year to year, the change in storage over time (i.e., the mass balance) was not set equal to zero for the purposes of finding a missing input or output. When no documentation existed for phosphorus flows, a most-likely value was presumed. This value was determined by examining similar systems in the literature. For instance, atmospheric phosphorus inputs to each system were unknown. However, the inputs were small compared to fertilizer applications and a similar value was used for each site. Additionally, where mass flows were known, but the phosphorus content was not, typical phosphorus contents of the mass were used to calculate the P flow. For instance, the P content of certain vegetables was used to calculate the P flow when only the mass of the harvested vegetable was known.

3.3.3. Emergy Evaluation and Traditional Indices

Energy systems diagrams were drawn for each study site. Using the data provided by site managers, environmental data, and values from literature, emergy evaluations for each system were completed using standard emergy accounting methods (Odum, 1996).

Emergy of recycle pathways was based on the emergy required to support that pathway. For instance, phosphorus that was recycled in the farm through crop residues received all of the emergy associated with crop residues based on the total energy content of crop residues and a literature value for transformity of crop residues.

Traditional emergy indices were calculated for each system with and without labor and services (EYR, ELR, ESI). While Brown and Ulgiati (1997) provided most of the equations for indices, this study used one of Odum's (1983) original approaches to estimate emergy yield rather than the approach offered by Brown and Ulgiati (1997), which is more common in emergy evaluations conducted during the last decade.. Specifically, Brown and Ulgiati (1997) defined emergy yield solely as the sum of all the inputs, which appears to adhere to Odum's original definition of emergy, but fails in some situations to best represent the emergy value of an item. For example, poorly inefficient or emergy intense systems would have high emergy yields under Brown and Ulgiati (1997) approach, but low energy yield. Odum's approach, on the other hand, would estimate the emergy yield as the energy yield times the solar transformity of an appropriate or equivalent energy form. Of course the contention with the latter is selecting an "appropriate" solar transformity. That important question is beyond the scope of this work, but is addressed by Tilley (Unpublished). Consequently, the best approximation of the yield is to multiply the exergy or mass of the products by an appropriate transformity or specific emergy from the literature (Tilley, Unpublished).

Transformities for forest and crop NPP were calculated in this study using methods from Odum (1996) and Tilley (1999). Biomass exergy (in J) were found for each system. The emergy it took to create that exergy in MD Forest was calculated as the

emergy of evapotranspiration (ET), deep heat, and atmospheric deposition on the forest. The emergy it took to create the biomass exergy in the farm systems was calculated as the emergy of ET, deep heat, atmospheric deposition, fertilizer and manure, irrigated water, seeds, and fuel. The transformity of NPP was this emergy divided by the biomass exergy (NPP). The 15.83 E24 sej/yr emergy baseline was used for these calculations (Odum, et al., 2000).

3.3.4. Recycling Mass and Emergy Indices

Several indices comparing input, output, and recycled emergy and mass were calculated for each system using the quotient of: mass input to output, mass input to recycled mass, mass output to recycled mass, emergy input to output, emergy input to recycled emergy, emergy output to recycled emergy, and recycled emergy to recycled mass. Comparisons of these indices were made between systems.

Emergy was calculated for recycling pathways based on the process required to support that pathway. In order to determine the amount of emergy associated with recycling phosphorus, the exergy or mass of the recycling pathways responsible was quantified. A transformity or specific emergy for that recycling pathway was either calculated or found in the literature and multiplied by the exergy or mass, respectively (Table 3.1). For instance, phosphorus that is recycled in the farm through crop residues received all of the emergy associated with crop NPP based on the total aboveground and belowground biomass production and the calculated transformity of crop NPP. This method was applied to all recycling pathways shown in Figure 3.1–Figure 3.3. However, for calculating indices, when multiple recycling pathways existed between storages that

were connected (i.e., soil phosphorus, belowground biomass phosphorus in MD Forest, Figure 3.1), only the largest of the pathways was used in order to prevent double counting.

Mass Recycle Rate was calculated by dividing the amount of mass recycled by the sum of the mass recycled and inputs. Emergy Recycle Rate was calculated by dividing the Emergy Recycle (EM_r) by the sum of the Emergy Input (EM_i) and EM_r. Emergy Recycle Rate with Total Emergy Inputs was calculated by dividing EM_r by the sum of the total emergy inputs to each system (Renewable, Non-Renewable, and Purchased Emergy without labor and services) and EM_r.

Table 3.1: Recycling pathway emergy calculation method. These methods were used to calculate emergy flows for the recycling indices, not all flows are in the emergy tables used in traditional indices. Index #s correspond to flows in Figure 3.1–Figure 3.3.

Site	Index #	P Source	Emergy Flow Calculation Method	Input/ Output/ Recycle?
MD Forest	1	Atmospheric	Mass of P in Atmospheric Deposition * Specific Emergy of Atmospherically Deposited P (Brandt-Williams, 2000)	Input
	2	Rock Weathering	Mass of Weathered Material * Spec. Emergy of Weathered Mat. (Brown and Bardi, 2001)	Input
	3	Runoff	Runoff Exergy * Transformity of Stream Discharge (Brown and Bardi, 2001)	Output
	4	Timber Harvest	Exergy of Harvested Timber * Transformity of Timber (Brown and Bardi, 2001)	Output
	5	Root Uptake	Exergy of NPP * Transformity of MD Forest NPP (Brown and Bardi, 2001)	Recycle
	6	Root Transfer	Exergy of NPP * Transformity of MD Forest NPP (Brown and Bardi, 2001)	Recycle
	7	Litterfall	Exergy of Litterfall * Transformity of Litterfall (Brown and Bardi, 2001)	Recycle
Shaw Farm	8	Atmospheric	Mass of P in Atmospheric Deposition * Specific Emergy of Atmospherically Deposited P (Brandt-Williams, 2000)	Input
	9	Rock Weathering	Mass of Weathered Material * Specific Emergy of Weathered Material (Brown and Bardi, 2001)	Input
	10	Fertilizer	Mass of P Fertilizer * Specific Emergy of P Fertilizer (Odum, 1996)	Input
	11	Runoff	Runoff Exergy * Transformity of Stream Discharge (Brown and Bardi, 2001)	Output
	12	Crop Harvest	Exergy of Harvested Produce * Transformity of Produce (Brandt-Williams, 2002; Comar, 2000)	Output
	13	Crop NPP	Exergy of NPP * Transformity of Shaw Farm NPP (Brown and Bardi, 2001)	Recycle
Greenway Farm	14	Atmospheric	Mass of P in Atmospheric Deposition * Specific Emergy of Atmospherically Deposited P (Brandt-Williams, 2000)	Input
	15	Rock Weathering	Mass of Weathered Material * Specific Emergy of Weathered Material (Brown and Bardi, 2001)	Input
	16	Fertilizer	Mass of P Fertilizer * Specific Emergy of P Fertilizer (Odum, 1996)	Input
	17	Runoff	Runoff Exergy * Transformity of Stream Discharge (Brown and Bardi, 2001)	Output
	18	Crop Harvest	Exergy of Harvested Produce * Transformity of Produce (Brandt-Williams, 2002; Comar, 2000)	Output
	19	Crop NPP	Exergy of NPP * Transformity of Greenway Farm NPP (Brown and Bardi, 2001)	Recycle

3.4. Results and Discussion

Energy systems diagrams with phosphorus flows superimposed help to show both the components of the phosphorus mass balance and the emergy evaluation (Figure 3.1–Figure 3.3). Comparison of the phosphorus mass balance showed that the two farms cycled phosphorus via similar pathways, which were conceptualized as different from the forest. Crops recycle P similarly to forests in the sense that organic P from decomposing biomass is mineralized, entering the soil P pool or transported from the system in runoff as phosphate. However, the recycle of P in these systems differed in that the crops mostly recycled P left in residues on the field after harvest and forests recycled P in mineralization of P in litterfall. Recycled P from litterfall, root uptake, and root transfer (all defined as internal to the system) occurred in similar quantities in MD Forest (Table 3.2).

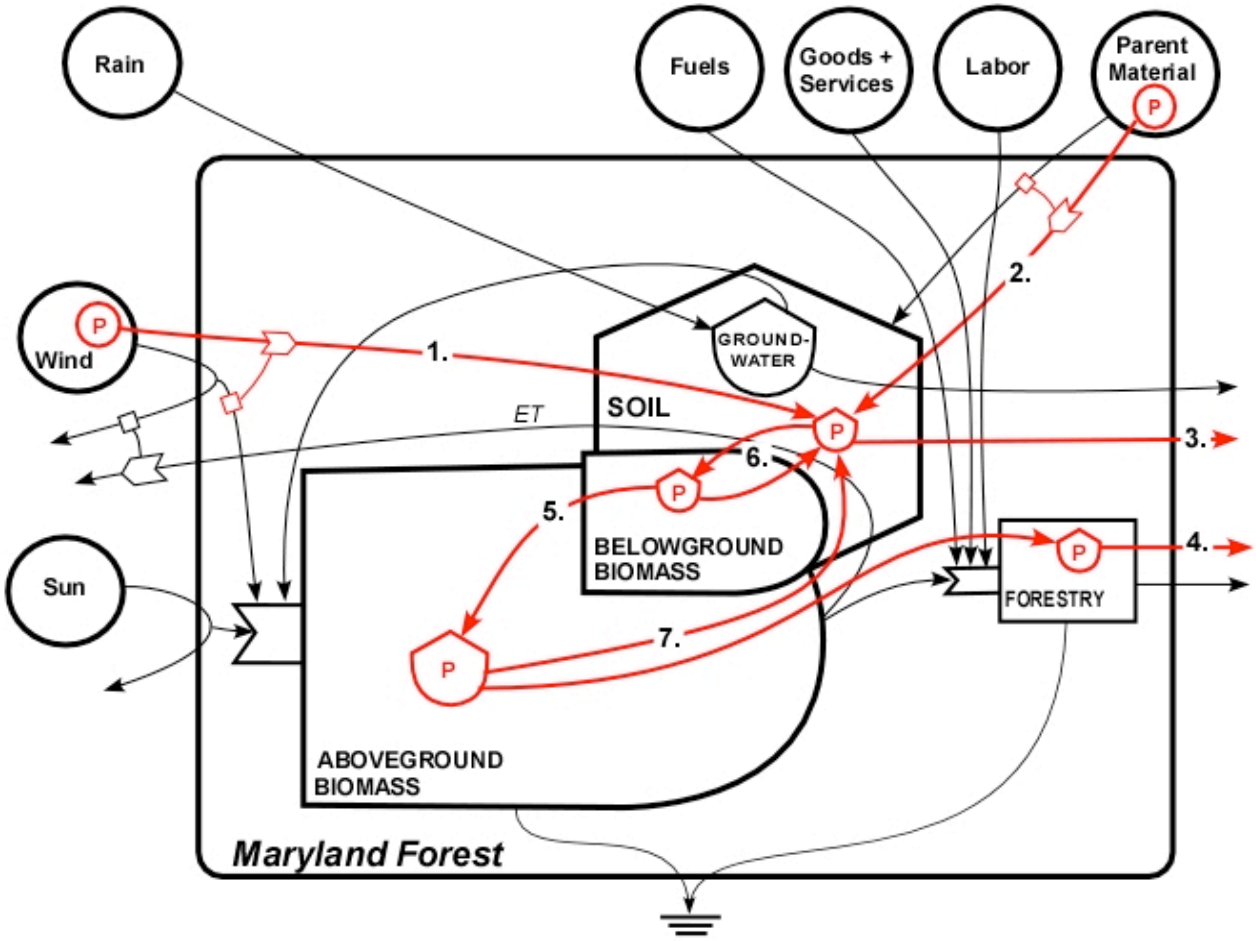


Figure 3.1: Energy systems diagram of Maryland Forest with phosphorus mass flows superimposed in red and numbered to correspond to Index #s in Table 3.1.

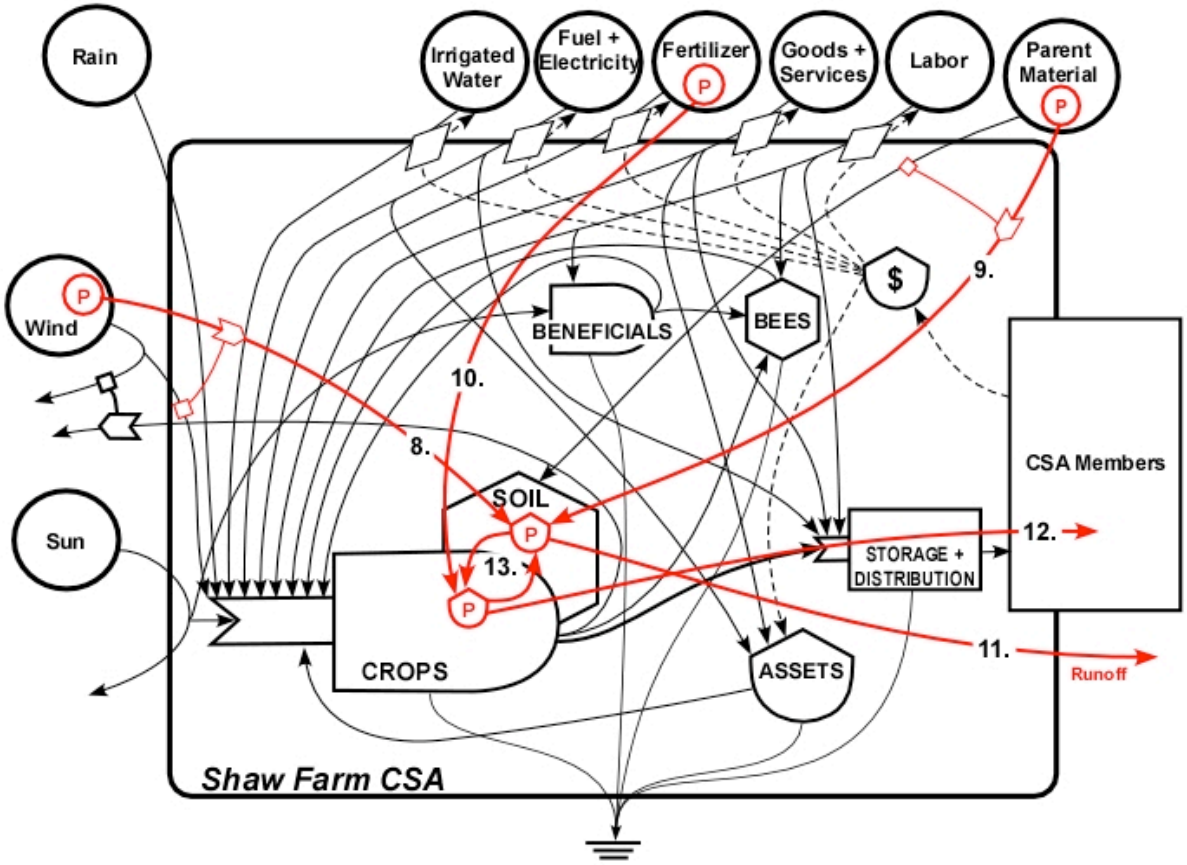


Figure 3.2: Energy systems diagram of Shaw Farm with phosphorus mass flows superimposed in red and numbered to correspond to Index #s in Table 3.1.

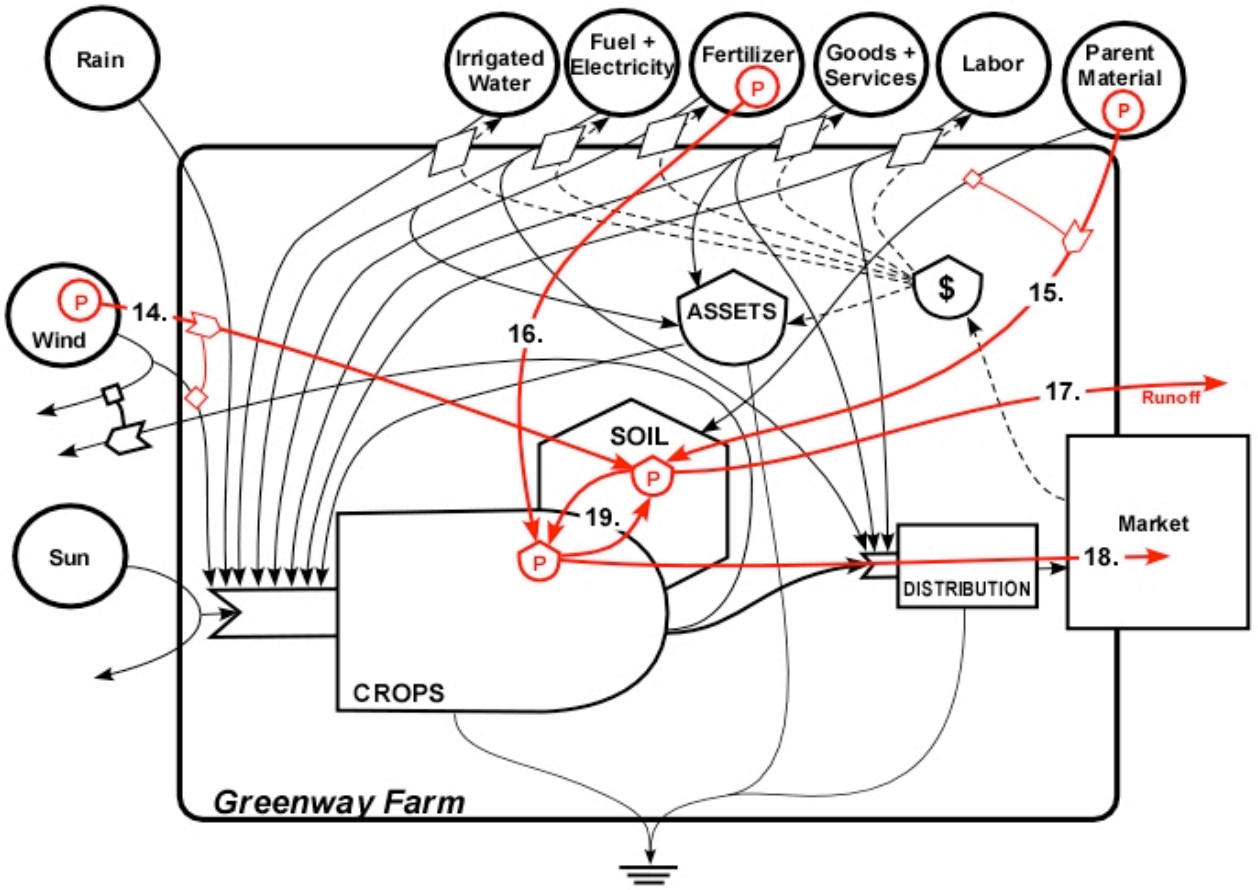


Figure 3.3: Energy systems diagram of Greenway Farm with phosphorus mass flows superimposed in red and numbered to correspond to Index #s in Table 3.1.

3.4.1. Phosphorus Mass Balance

Phosphorus inputs to MD Forest were atmospheric deposition and weathering of parent material. Streamflow and timber extraction were the P outputs from the forest. Internal cycling of P was primarily due to litterfall, root uptake, and "root to shoot" transfer (Figure 3.1). As shown in Figure 3.1, there are 3 major pathways for recycling P in MD Forest: 1) root uptake from soil, 2) root transfer from roots to aboveground biomass, and 3) litterfall from aboveground biomass to the forest soil. The rate of P transfer for each pathway is the net sum of the transfer. That is, while root uptake from soil occurs, so does root exudation and death. The rate of this recycling pathway is the rate of root uptake minus the rate of root exudation and death.

The internally cycled P in MD Forest receives a relatively small amount of input and has similarly small output of P, whereas the input and output of P in the farms was much larger than the internally cycled P (Figure 3.2). Consequently, the internal cycles of P in the farms were simplified to represent only the root uptake of P by crops and the transfer of P in crop residues after the growing season via tillage. In the farms, the main input of P was mineral fertilizer. The main outputs of P were runoff and harvest of crops (Figure 3.2 and Figure 3.3). While both farms received most of their P as mineral fertilizer, the MD Forest had more recycling of P that was carried out by multiple pathways (Table 3.2).

3.4.2. Emergy Evaluation and Traditional Indices

The purchased emergy for both farm systems was an order of magnitude larger than MD Forest. Shaw Farm had higher renewable and lower purchased emergy than Greenway Farm (Table 3.3). These relative emergy trends were expected for the types of systems studied.

Table 3.2. Phosphorus balance for each site. Index #s correspond to flows in red in Figure 3.1–Figure 3.3.

				kg P/ha/yr	
Site	**Index #**	**P Source**	**Inputs**	**Outputs**	**Recycle**
MD Forest	1	Atmospheric	0.04		
	2	Rock Weathering	0.05		
	3	Runoff		0.02	
	4	Timber Harvest		3.16	
	5	Root Uptake			5.86
	6	Root Transfer			5.49
	7	Litterfall			4.53
Shaw Farm	8	Atmospheric	0.04		
	9	Rock Weathering	0.05		
	10	Fertilizer+Compost	11.7		
	11	Runoff		3.00	
	12	Crop Harvest		0.44	
	13	Crop Residues			4.64
Greenway Farm	14	Atmospheric	0.04		
	15	Rock Weathering	0.05		
	16	Fertilizer	19.5		
	17	Runoff		12.8	
	18	Crop Harvest		0.62	
	19	Crop Residues			6.00

Table 3.3. Emergy inputs, yield and traditional emergy indices for each system: Emergy Yield Ratio (EYR), Environmental Loading Ratio (ELR), Percent Renewable (%Ren), and Emergy Sustainability Index (ESI).

	MD Forest	Shaw Farm	Greenway Farm
Renewable (1E9 sej/ha/yr)	1,280,000	1,500,000	1,280,000
Non-Renewable, local (1E9 sej/ha/yr)	38	36	94
Purchased (1E9 sej/ha/yr)	405,000	72,400,000	39,300,000
Purchased w/o L&S (1E9 sej/ha/yr)	73,300	49,800,000	30,800,000
Yield* (1E9 sej/ha/yr)	799,000	756,000	103,000
EYR	1.97	0.010	0.0026
EYR w/o L&S	10.9	0.015	0.0033
ELR	0.32	48.4	30.8
ELR w/o L&S	0.057	33.3	24.1
%Ren	0.76	0.020	0.031
%Ren w/o L&S	0.95	0.029	0.040
ESI	6.26	0.00022	0.000085
ESI w/o L&S	191	0.00046	0.00014

*Yield calculated by multiplying outputs by transformities/specific emergy values found in literature (following methods in Tilley (Unpublished)).

Traditional emergy indices were similar for both farm systems. MD Forest had higher Emergy Yield Ratio, Percent Renewability, and Emergy Sustainability Index than the farms. Both farm systems had higher Environmental Loading Ratio (Table 3.3). Relative values of these traditional emergy indices were expected. On a proportional basis, purchased emergy was affected more by labor and services in MD Forest than in the farms (Table 3.3), resulting in a 10-fold greater EYR with labor and services than without for MD Forests. In the farms, the difference in EYR (with and without L&S) is only about 50%, but nearly 1/100th of the forest. In the case of the Emergy Sustainability Index (ESI), including labor and services as a purchased input decreased the ESI value by almost 2 orders of magnitude in the MD Forest, but roughly halved the ESI value for the two farms.

Because the method of calculating yield was based on the product of the energy yield and its most appropriate solar transformity, traditional emergy indices from recent studies cannot be directly compared to our results. Most recent studies of farming and forestry systems estimate the emergy yield as the sum of the inputs. (Tilley, Unpublished) recently challenged the widespread use of this latter method as the best way to estimate transformities and the emergy yield of systems. Transformities of NPP calculated in this study for MD Forest, Shaw Farm, and Greenway Farm were 9550, 23700, and 27400 sej/J, respectively, which are within the range reported in other emergy evaluations (Doherty, 1995; Tilley 1999, Bardi and Brown, 2001; Brandt-Williams, 2001). These transformities were calculated in this study (Appendix B, Table B.4).

3.4.3. Recycling Mass and Emergy Indices

The indices developed for mass and emergy recycle were used to compare these three systems. The recycling indices (Table 3.4) were calculated using aggregated input, output, and recycled mass and emergy (calculated using the phosphorus balance in Table 3.2 and methods in Table 3.1, respectively; values of indices shown in Table 3.5). Emergy was calculated only for outputs that carried phosphorus. Each system had two outputs associated with P transfer: either in products or in runoff/erosion. To prevent double counting, Root Transfer and Litterfall were omitted from the recycling emergy used in calculating indices for MD Forest.

Table 3.4. Recycling mass and emergy indices for each system. Calculations of each parameter shown in Appendix B, Table B.5.

				Percent Of (%)		
Pathway, units	**MD Forest**	**Shaw Farm**	**Greenway Farm**	**MD Forest/ Shaw Farm*100**	**MD Forest/ Greenway Farm*100**	**Shaw Farm/ Greenway Farm*100**
Mass Inputs (M_i), g P/ha/yr	90	1,180	1,950	0.8	0.5	60.3
Mass Recycle (M_r), g P/ha/yr	5,860	4,640	6,000	126	97.7	77.3
Mass recycle per input, M_r/M_i	65.1	0.39	0.31	16,500	21,200	128
Emergy Inputs (Em_i), E9 sej/ha/yr	186,000	535,000	767,000	34.8	24.2	69.7
Emergy Recycle (Em_r), E9 sej/ha/yr	2,013,000	5,600,000	8,430,000	35.9	23.9	66.5
Emergy recycle per input, Em_r/Em_i	10.8	10.5	11.0	103	98.6	95.3
Specific emergy of recycled mass, Em_r/M_r (E9 sej/g P)	344	1,200	1,400	28.5	24.5	86
Specific emergy of input mass, Em_i/M_i (E9 sej/g P)	2,070	45.5	39.3	4,500	5,260	116
Recycle Rate (%)	98	28	23	348	419	120

Table 3.5. Emergy of input, output, and recycling pathways associated with phosphorus for each system. Index #s correspond to flows in Figure 3.1–Figure 3.3.

			E12 sej/ha/yr		
Site	**Index #**	P Source	Inputs	Outputs	Recycle
MD Forest	1	Atmospheric P	0.00048		
	2	Rock Weathering	186		
	3	Runoff		758	
	4	Timber Harvest		799	
	5	Root Uptake			2,013
	6	Root Transfer			2,013
	7	Litterfall			967
Shaw Farm	8	Atmospheric P	0.00048		
	9	Rock Weathering	186		
	10	Fertilizer	349		
	11	Runoff		1,073	
	12	Crop Harvest		450	
	13	Crop NPP			5,601
Greenway Farm	14	Atmospheric	0.00048		
	15	Rock Weathering	186		
	16	Fertilizer	581		
	17	Runoff		1,073	
	18	Crop Harvest		103	
	19	Crop NPP			8,427

While the MD Forest had several orders of magnitude lower mass inputs of phosphorus than both of the farms, the emergy associated with P inputs did not differ much between MD Forest and the farms (Table 3.4,

Figure 3.4). Consequently, the specific emergy of input mass (Em_i/M_i) was about 50 times greater in MD Forest than the average of the two farms (Table 3.4). Because the farms have such high mass input of P relative to MD Forest, the difference in the Em_i/M_i index between systems suggested that the farms' phosphorus inputs are more

concentrated than the MD Forest. Fertilizer inputs of P are focused; more P is delivered to the farms with similar emergy inputs associated with that P input. In MD Forest, a similar amount of emergy is required to get a much smaller amount of P mass input (Figure 3.5). All of the emergy associated with delivering P to MD Forest was from rock weathering. The amount of P in the concentrated P fertilizer added to the farms was relatively larger compared to the increased amount of emergy in the fertlizer added to the farms. The farms also had the emergy of the rock weathering as an input. Virtually all of the emergy associated with recycled P in MD Forest was that of the recycling pathway with the highest emergy, root uptake/transfer (Table 3.1). For this process to occur, all of the net primary production (NPP) of the forest was required. Consequently, the emergy associated with MD Forest NPP was assigned to this pathway. MD Forest NPP was calculated by using the estimated forest biomass multiplied by its calculated transformity (Table 3.1). The emergy associated with recycling P in the farms was that of the emergy of the crop NPP, calculated by using the exergy of crop biomass multiplied by their calculated transformities (Table 3.1). Recycled mass of P did not differ much between systems (Table 3.4), but the emergy associated with recycled P in MD Forest was less than in the farms (Table 3.4, Figure 3.6). Greenway Farm, the conventionally operated farm, had about 60% more emergy associated with recycling P than Shaw Farm (Table 3.4). Consequently, the specific emergy of recycled mass (Em_r/M_r) in MD Forest was 28% and 24% of Shaw and Greenway Farms, respectively (Table 3.4). The specific emergy of recycled mass in Shaw Farm was 86% of Greenway Farm; Shaw Farm had lower Em_r and M_r than Greenway Farms.

The decisions for allocating emergy to recycling pathways are intended to account for all of the emergy required to carry out that process. In the case of MD Forest, net primary production was required to cycle P in the root zone. The only recycling pathway for P in the farm systems was the unharvested P left in crop residues each year (Table 3.2). In order for the P to be recycled, the crops' total NPP was required. Similar to MD Forest, the emergy associated with NPP was assigned to this P recycling pathway in the farms (Table 3.1 and Table 3.5). Because both the NPP and the NPP transformities were higher in the farms than in the forest, more emergy was allocated to that recycle flow. NPP in each system was 2.1, 2.4, and 3.1 E11 J/ha/yr in MD Forest, Shaw Farm, and Greenway Farm, respectively. As diagrammed, the recycling of P in MD Forest is more complex than in the farms (Figure 3.1–Figure 3.3, red lines). There are more pathways of internal cycle for phosphorus in the MD Forest than in the farms (Figure 3.1–Figure 3.3), but the accounting for MD Forest internal P cycles included just one net P internal cycle, root uptake. Root transfer and litterfall, also identified as internal P cycles, were not accounted for in the recycling indices to avoid double counting. However, if the time scale of these analyses (year) include recycle of P on these pathways, it may be appropriate to include them in the indices. Amponsah et al. (2011) detail emergy evaluation methods for recycling flows and their time scales, but focus on the number of times of recycle in industrial processes. There should be further investigation into the effect of P turnover time on these indices.

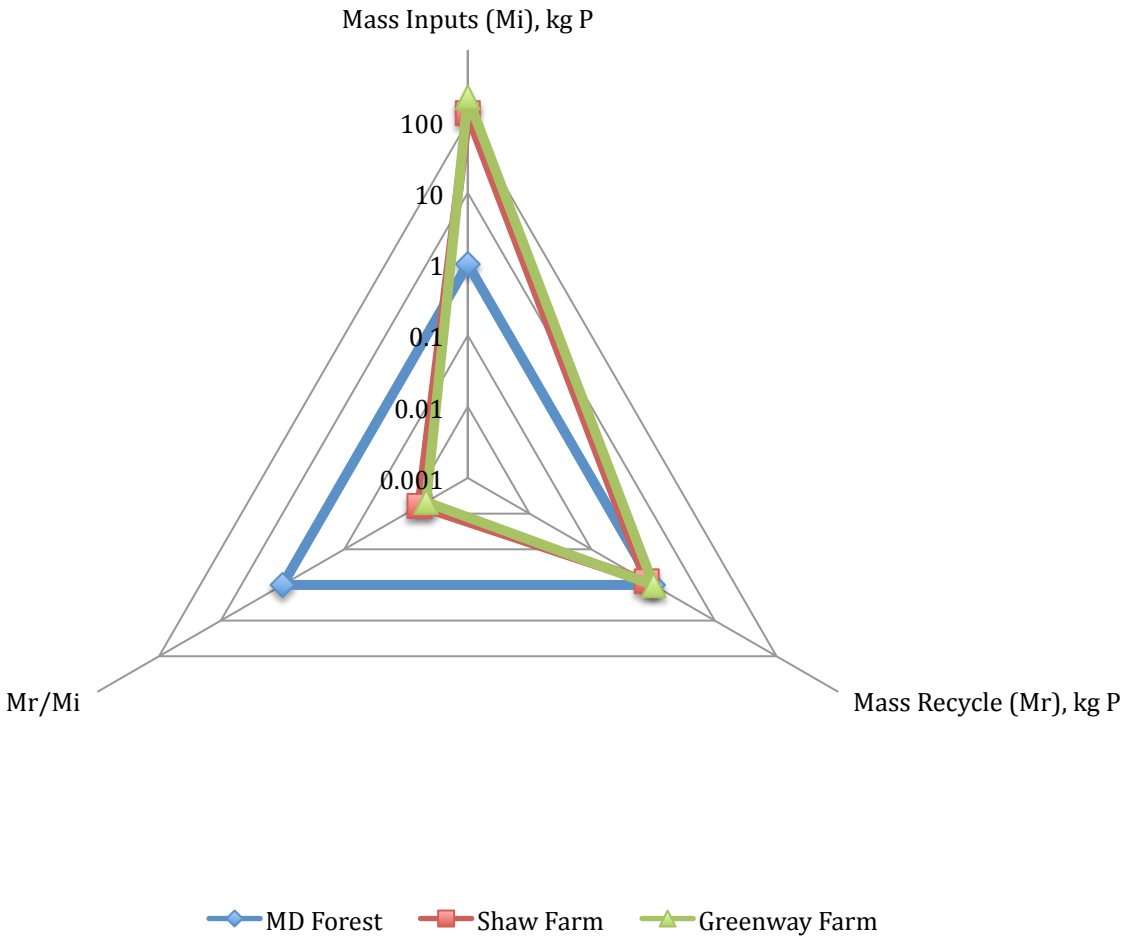


Figure 3.4. Mass inputs, recycle, and their ratio (dimensionless) in three systems normalized by MD Forest (i.e., each parameter was divided by the value for MD Forest).

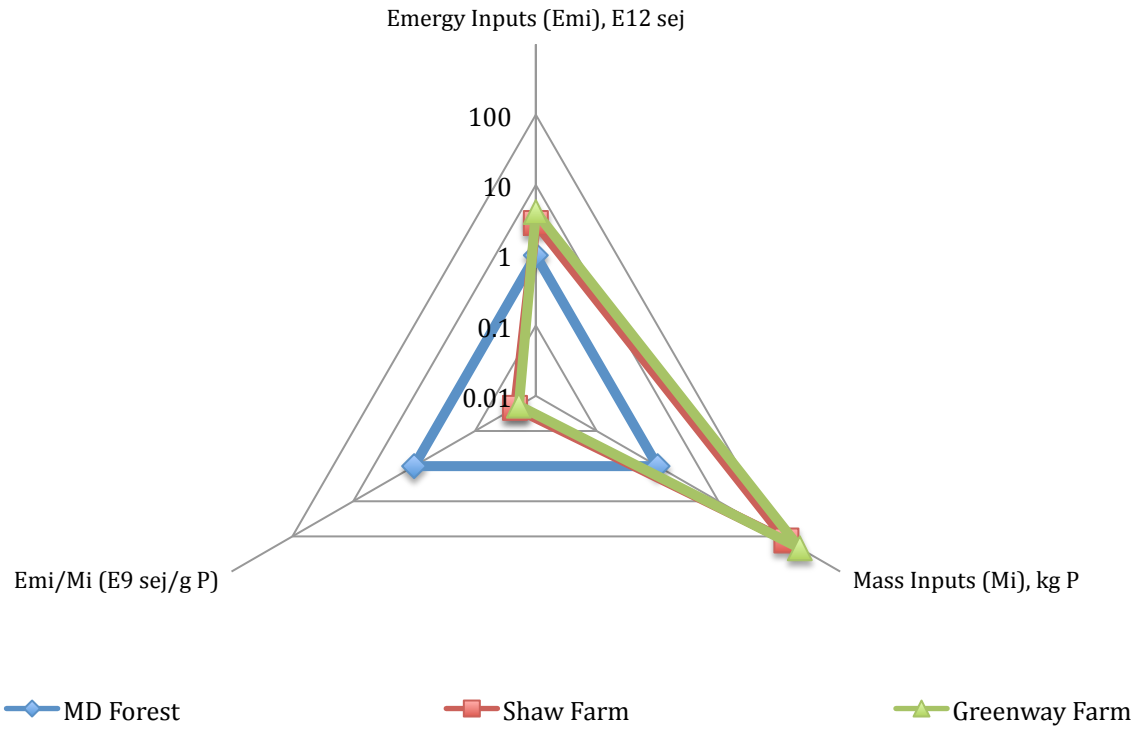


Figure 3.5. Emergy and mass inputs and their ratio in three systems normalized by MD Forest (i.e., each parameter was divided by the value for MD Forest).

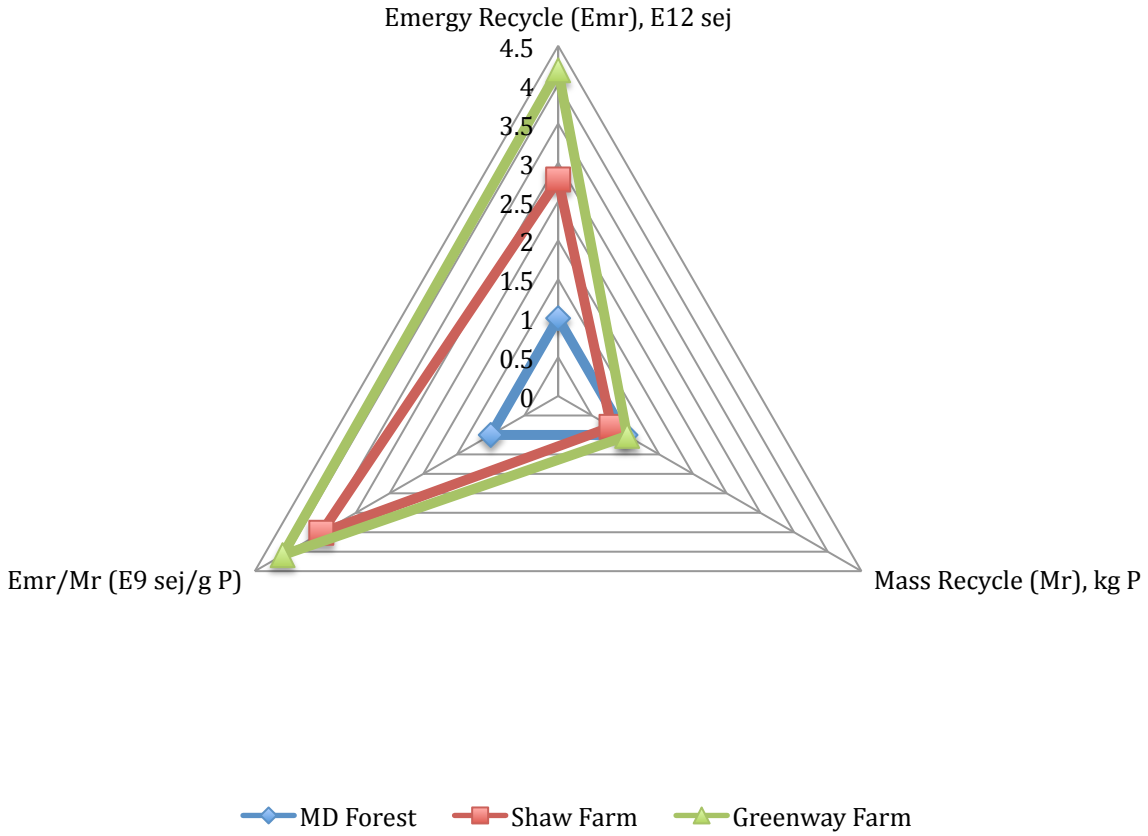


Figure 3.6. Emergy and mass recycle and their ratio in three systems normalized by MD Forest (i.e., each parameter was divided by the value for MD Forest).

The specific emergy of recycle (Em_r/M_r) is the amount of emergy used in the recycling of a certain type of mass (in this case, P). This index was lower in the MD Forest than in the farms (Figure 3.7). Em_r/M_r was 344, 1200, and 1400 E9 sej/g P in MD Forest, Shaw Farm, and Greenway Farm, respectively. Much of the emergy associated with NPP (and consequently, recycle) in the farms comes from purchased sources (60% and 76% in Shaw Farm and Greenway Farm, respectively). Without these purchased emergy sources, the specific emergy of recycle of the farms would be closer to that of the forest at 477 and 334 E9 sej/g P in Shaw Farm and Greenway Farm, respectively. Clearly, the farms rely on this purchased emergy to produce this NPP, so simply discontinuing use of purchased emergy in the farms would not necessarily result in a similar specific emergy of recycle (or yield) to the forest system. The forest was able to recycle P using less emergy (lower Em_r/M_r than farms), and so was utilizing P more efficiently. While this study and the indices represent one year, it appears the minimally managed MD Forest uses less emergy to recycle P than the farms. It would be worthwhile to evaluate and compare this index for other conservative materials.

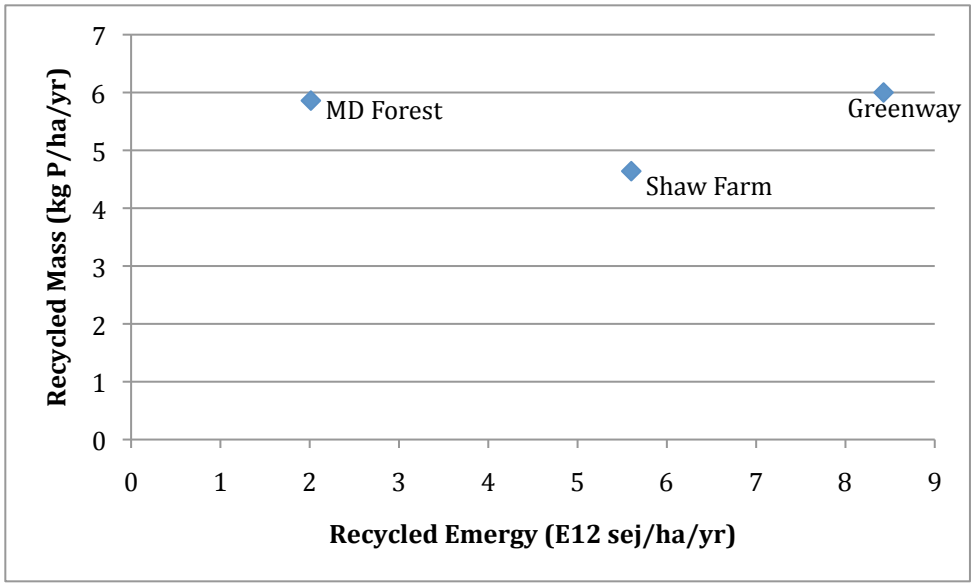


Figure 3.7. Emergy recycled vs. recycled mass at each site.

Mass Recycle Rate for MD Forest was near 100% (Figure 3.8) due to relatively low P input. Mass Recycle Rate for both farms was around 25% (Figure 3.8), meaning the farms recycled about one quarter of the mass coming into the system. Emergy Recycle Rate for all systems was about 90% (Figure 3.8). The discrepancy between Mass and Emergy Recycle Rates in the farms further shows these systems require more emergy per unit mass for recycling. The high Emergy Recycle Rates (~90%) for all three systems are largely due to the close relationship between input emergy and NPP transformity. The transformity of NPP for each system was determined using renewable and purchased input emergy associated with forest and crop growth for MD Forest and the farms, respectively. Consequently, recycle emergy relative to input emergy were similar, resulting in similar Emergy Recycle Rates for each system. Because the emergy of NPP was assigned to the recycling of P in the system, Emergy Recycle was relatively high to the Emergy Input, which was only the emergy associated with delivering P to the system

(rock weathering and atmospheric deposition, Table 3.1). The high Emergy Recycle Rate indicates that the amount of emergy associated with P flows into the system is much smaller than the emergy of P flows internal to these systems (EM_r).

When emergy associated with internal recycling processes (EMr) are compared to the total emergy inputs, the recycling rates are different (Figure 3.8). Shaw Farm has the lowest recycling rate (15%) when total inputs are considered, compared to Greenway Farm (21%) and MD Forest (55%). Because the inputs to both farms were similar, the lower Emergy Recycling Rate considering Total Emergy Inputs in Shaw Farm was due to lower NPP (Emergy Recycle). While the internal recycle of P was larger in Shaw Farm, it did not recycle as much emergy as Greenway Farm.

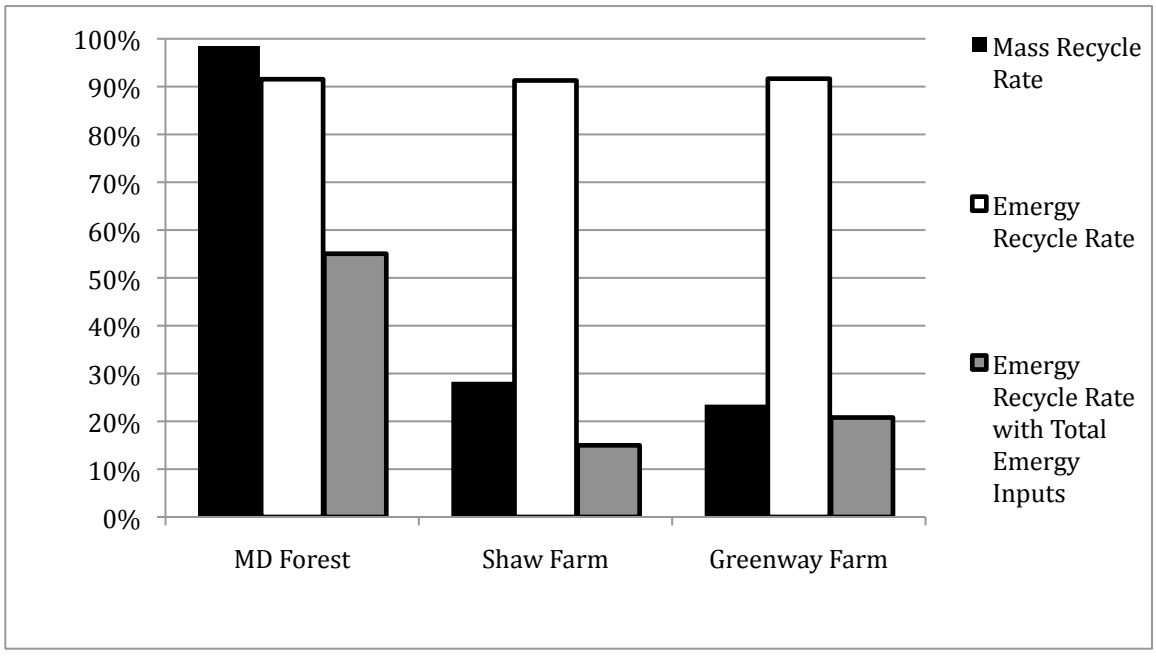


Figure 3.8. Mass and Emergy Recycle Rates for each system.

These results show that emergy flows associated with internal cycles are larger than the system inputs for phosphorus. This is an important recognition because it suggests that empower is maximized within the system. Traditionally, only system inputs and outputs were considered. This work shows that it may be important to evaluate internal emergy flows to determine maximum empower.

3.5. Conclusion

This method of accounting for recycled emergy and mass shows the natural system required less emergy to recycle P than the human-dominated systems. The natural system had a higher material and emergy recycle rate (when considering total emergy inputs), indicating more efficient use of P. A lower specific emergy of recycle for the forest than the farms was a result of the farms using more purchased emergy. Because these indices rely heavily on NPP, the age of MD Forest may have a significant effect on the outcome for analyses of just one year. Most importantly, it was found that the internal emergy cycles were larger than the system inputs.

In the future, dynamic modeling of the emergy associated with mass and recycling will improve comparisons of these systems. Evaluating mass inputs other than phosphorus could also help determine better ways of allocating emergy to recycle pathways.

Chapter 4. Simulation Models of Recycling Mass and Emergy

4.1. Abstract

It is important to have emergy accounting rules that appropriately reflect the quality (emergy) of material and energy cycling in a system, especially if these flows compose a large amount of the emergy relative to the throughput. Several studies have addressed the need for clarification on emergy accounting rules of material cycles. Here, a simulation model, EmCycOpen, was developed in order to aggregate concepts and expand upon the current state of the theory of dynamic accounting of emergy cycling. This simulation model was based on Tilley's (2011) EmCycClos mini-model, which was composed of a closed material cycle with energy throughput. Emergy associated with material and energy was tracked separately in a storage with concentrated material. Material was allowed to leave in a dispersal pathway while being replenished by low quality material from a constant force source. Separate tracking of material- and energy-emergy within a

single storage caused the overall emergy density of the storage to be split between the material and energy, requiring partial transformities and partial specific emergy values. Cohen (2002) presented a similar model that did not track material- and energy-emergy separately, but instead assigned the transformity of the low quality storage to equal the recycled material flow. EmCycOpen was developed using both the Dynamic Emergy Accounting rules from Tilley and the Network Emergy Rule from Cohen separately. EmCycOpen behaved very similar to EmCycClos in all response variables. However, the concentrated storages accumulating material reached a higher steady state level than the closed system model. Consequently, the specific emergy of this concentrated storage was lower in the EmCycOpen. This work serves to better understand how emergy cycles within dynamic systems that have large material cycles and are open to material inputs and dispersal. Methods of dynamic emergy accounting have been improved by including internal cycles of emergy and input and output of materials carrying emergy in a dynamic system, as opposed to the previous model of a system closed to material input and output. Consequently, the new model, EmCycOpen, can be applied to a greater number of systems.

4.2. Introduction

The goal of this study was to expand the capabilities for modeling the dynamics of emergy in energetically open systems with material cycles and material throughput. A more detailed introduction to the background of accounting for dynamics of internal emergy flows was presented in Chapter 1. This work builds on Tilley's (2011b) EmCycClos model and Cohen's (2002) EmRecycle model to include material cycling

and material throughput that carries emergy into and out of the system separate from the flows of energy. Like EmCycClos, the model developed here, EmCycOpen, tracks the emergy of materials and energy separately to better represent the emergy of cycling materials. EmRecycle did not make this type of distinction between emergy of material and energy. In addition it used older rules for simulating the dynamics of emergy, which were recently simplified by Tilley (2011a). EmCycOpen will be evaluated using rules from the EmRecycle model in order to show the improvement in simulating the dynamics of emergy achieved with this model.

Comparisons between the ability of EmCycOpen and EmCycClos to track emergy of open/cycling systems, particularly materials, provides improved theoretical basis for accounting rules in emergy evaluations, which will ultimately lead to improved accounting in emergy evaluations conducted based on steady state conditions, which is the prototypical application of emergy.

4.3. Methods

Because this model is meant to reflect new rules in emergy accounting, it is appropriate to list a few assumptions of the conditions:

1. A material has emergy as long as it has ability to do work. Material input to the system at background levels (that cannot disperse further) does not add emergy to the system.

2. A material with emergy contributes emergy to a process or storage, regardless of whether it crosses a system boundary. Energy, some of which dissipates in the process, is what drives material flows.
3. Emergy of material and energy are tracked separately. Material-emergy inputs to a process will remain in the product in upstream processes. Material-emergy that cycles back into production processes and does not cross system boundaries is subtracted from the exported product's emergy.
4. Emergy and energy/material storages are dynamic, resulting in dynamic transformities and specific emergy values for all storages. Partial transformities are used to track unit emergy values of material and energy separately within a storage based on Tilley (2011b).

4.3.1. Model Description

The minimodel, EmCycOpen, was developed to simulate emergy cycling with material in a dynamic system. The model simulates the dynamics of flowing material, energy, and emergy between two storages and into and out of the system. One storage represents low quality material. One storage represents high quality material. The model EmCycOpen includes material input to and dispersal from the low quality storage (Figure 4.1). These are the only flows of material that cross the system boundaries. In this open system, energy drives the concentration of low quality material into high quality material from an energy input to the production process. Energy is exported from the system after becoming separated from the material-emergy that flows into the low quality storage. That is, material-emergy is being cycled within the system and energy-emergy leaves.

The concentration of material-emergy in the high quality material storage and its flow back through the system is of particular interest in this model. In the high quality material, accounting of material and energy occurs separately according to Dynamic Emergy Accounting rules (Tilley, 2011b). In previous models, dynamics of internally cycling material-emergy were simulated, but the system was closed to material input and output. EmCycOpen simulates the dynamics of internally cycled material-emergy when the system has material inputs and outputs.

These internal storages of energy and material are represented by Qe and Qn (Figure 4.2). The flow into material storage Q is coupled, but separate accounting begins inside storage Q. Material, energy, and emergy output from storage Q (μ3, J3, and M3, respsectively) are subsequently split for export of energy and emergy (J4 and M4, respectively), and recycle of material and emergy (μ7 and M7, respectively). Material is recycled in a lower quality material storage, N, where it is dispersed out of the system (μ10) and new material enters from source C. Material is then again concentrated in the production process using S as the driving energy concentrating flow μ5 (Figure 4.2). Emergy flows into storage N with material from source C and out of storage N with material dispersal flow μ10. EmCycOpen differs from EmCycClos in that it is open to both material and energy inputs and outputs.

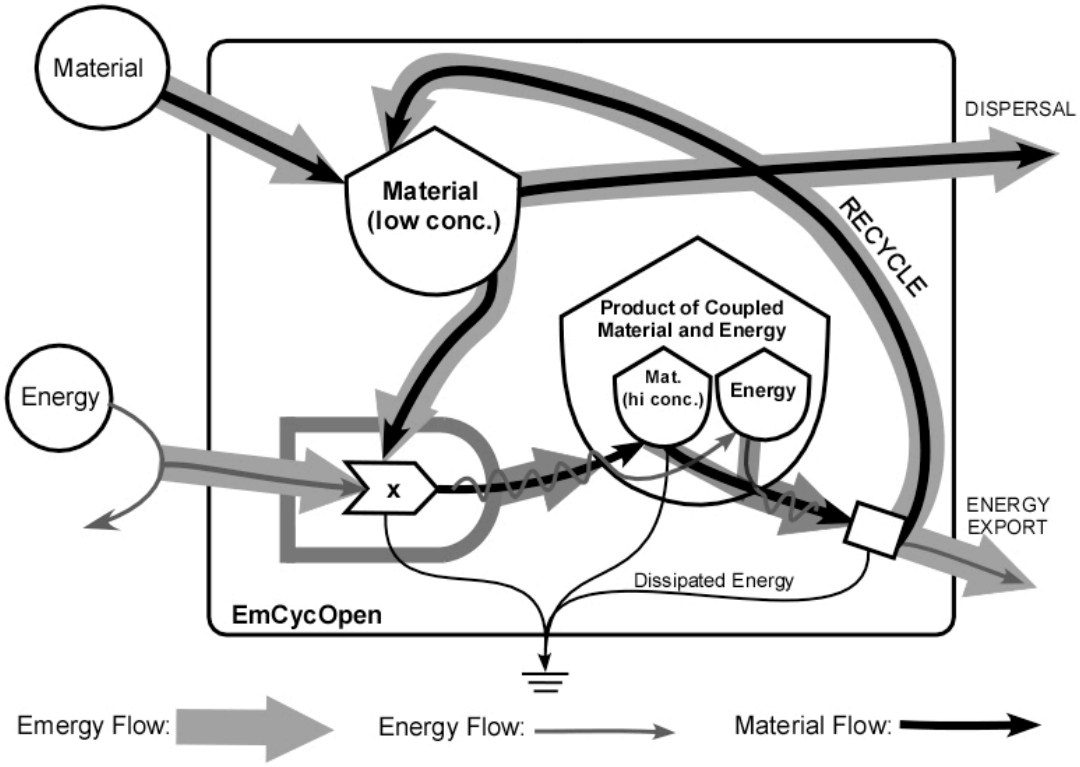
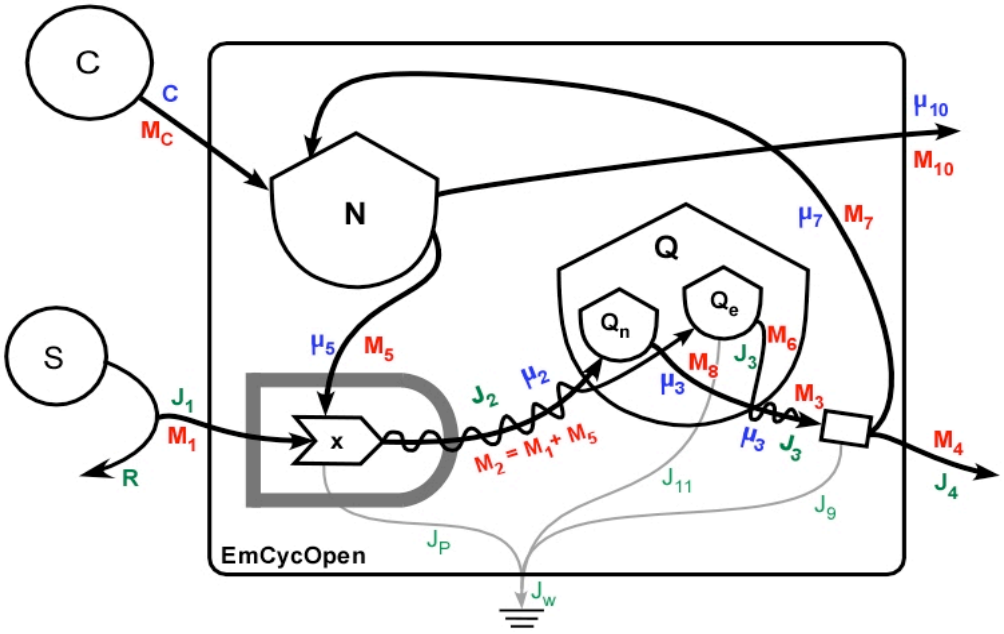


Figure 4.1. Energy and material are coupled in production. Energy and material are both required for the production process and shown as separate storages for accounting purposes. When exported from the product, material and energy split for recycle within and export from the system, respectively. Energy does not follow the recycled mass pathway (Recycle).

Figure 4.2. (Following Page). Energy flows represented by J, material flows are μ, emergy flows are M, transformities are T, and specific emergy values are σ. High quality storage, Q is split into material storage, Qn and energy storage, Qe. Low quality material storage, N, receives input from outside material source, C. Energy source, S, is a constant flow source, with unused flow represented by R.



Energy and Material Flows

$J_1 = k_1RN$
$J_2 = k_2RN$
$J_3 = k_3Q_e$
$J_4 = k_4Q_e$
$J_8 = k_8Q_e$
$J_9 = J_3 - J_4$
$J_P = J_1 - J_2$
$J_w = J_P + J_8 + J_9$

$\mu_2 = \mu_5$
$\mu_3 = (Q_n/Q_e)J_3$
$\mu_5 = k_5RN$
$\mu_7 = \mu_3$
$\mu_{10} = k_{10}N$
C = constant

Emergy Flow

$M_1 = T_sJ_1$
$M_2 = M_1 + M_5$
$M_3 = T_QJ_3$
$M_4 = M_3 - M_7$
$M_5 = \sigma_N\mu_5$

$M_6 = \rho\sigma_{Qe}J_3$
$M_7 = \rho\sigma_{Qn}\mu_7$
$M_8 = \rho\sigma_{Qn}\mu_3$
$M_{10} = \sigma_N\mu_{10}$
$M_C = \sigma_CC$

Energy and Material Change Equations

$dN/dt = C + \mu_7 - \mu_5 - \mu_{10}$
$dQ_n/dt = \mu_2 - \mu_3$
$dQ_e/dt = J_2 - J_3 - J_8$

Emergy Change Equations

$dM_N/dt = M_C + M_7 - M_5 - M_{10}$
$dM_N/dt = \sigma_CC + \rho\sigma_{Qn}\mu_7 - \sigma_N\mu_5 - \sigma_N\mu_{10}$

$dM_{Qn}/dt = M_5 - M_8$
$dM_{Qn}/dt = \sigma_N\mu_5 - \rho\sigma_{Qn}\mu_7$

$dM_{Qe}/dt = M_1 - M_6$
$dM_{Qe}/dt = T_sJ_1 - \rho T_QJ_3$

$M_Q = M_{Qn} + M_{Qe}$

Unit Emergy Values

T_Q = transformity of Q
$= M_Q/Q_e$
σ_Q = specific emergy of Q
$= M_Q/Q_n$
σ_N = specific emergy of N
$= M_N/N$
ρT_{Qe} = partial transformity of energy in Q
$= M_{Qe}/Q_e$
$\rho\sigma_{Qn}$ = partial specific emergy material in Q
$= M_{Qn}/Q_n$

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*Dynamic Emergy Accounting (DEA, Tilley, 2011b) methodology was used to calculate this recycled emergy flow; the specific emergy of recycled material flow is the partial specific emergy of Q. Using the Network Emergy Rule (Cohen, 2002) would require multiplying the flow μ7 by the specific emergy of the destination storage, N (σ_N).

Energy and material equations followed respective conservation laws. At steady state, system inputs are equal to system outputs of energy, material, and emergy. However, energy and material are not conveyed along all of the same pathways. Pathways with the symbol J represent energy pathways. The symbol μ is used for mass flow. The only input of emergy is from the energy source (S) and the only output is the flow M4. Energy is also input through S, but leaves through the heat sink as it is degraded through energy transformations (Jw). Material enters through C and is dispersed through μ10, neither of which conveys emergy.

Dynamic behaviors of EmCycOpen state variables over time are dictated by equations in Figure 4.2. As in Tilley (2011b)'s EmCycClos model, material- and energy-emergy are tracked separately to follow the proposal of Brown (2005). Material-emergy remains with the material recycle flow as an input to a lower quality material storage. The material-emergy adds to the lower quality material (N) and reenters the production of higher quality material in storage Q (Figure 4.2).

Energy from Q outflows as J3 and is based on the energy storage in Q (Qe). As J3 outflows from Q, energy is lost (J9) and exported from the system (J4). Material from Q is conveyed back to the system via μ7. This material flow is driven by the energy flow from Q (J3, Figure 4.2) and the ratio of the material to the energy in Q (Qn/Qe).

Material enters storage N through source C at a state of zero emergy and leaves through μ10 at a state of zero emergy. Material export through dispersal is dependent on storage N and eventually reaches steady state when equal to C. The dynamic nature of storage N with regards to external inputs and outputs of material is the major difference

between EmCycOpen and EmCycClos. Openness to material import and export in this simulation model is an important step in the development of dynamic emergy accounting.

4.3.2. Model Calibration

Following similar methods to Tilley (2011b), EmCycOpen was calibrated using steady state values for energy throughput and material cycling (Figure 4.3 and Figure 4.4). These calibration values were chosen based on those in EmCycClos, but because the system was open to material, steady state values for storages were higher. Additionally, because energy drives the internal flow of material, a larger throughput of energy was used for calibration. Similar to EmCycClos, the input energy flow from a constant flow source, S, was 250 W (watts), but only 100 W went unused. Thus, the calibration value for J1 was 150 W (Figure 4.4). Of the 150 W, 148 W was dissipated as heat and 2 W of useful energy was produced. Emergy was likewise conserved through the system. At steady state, the output emergy associated with J4 (M4) was equal to the input emergy associated with J1 (M1, in Figure 4.2).

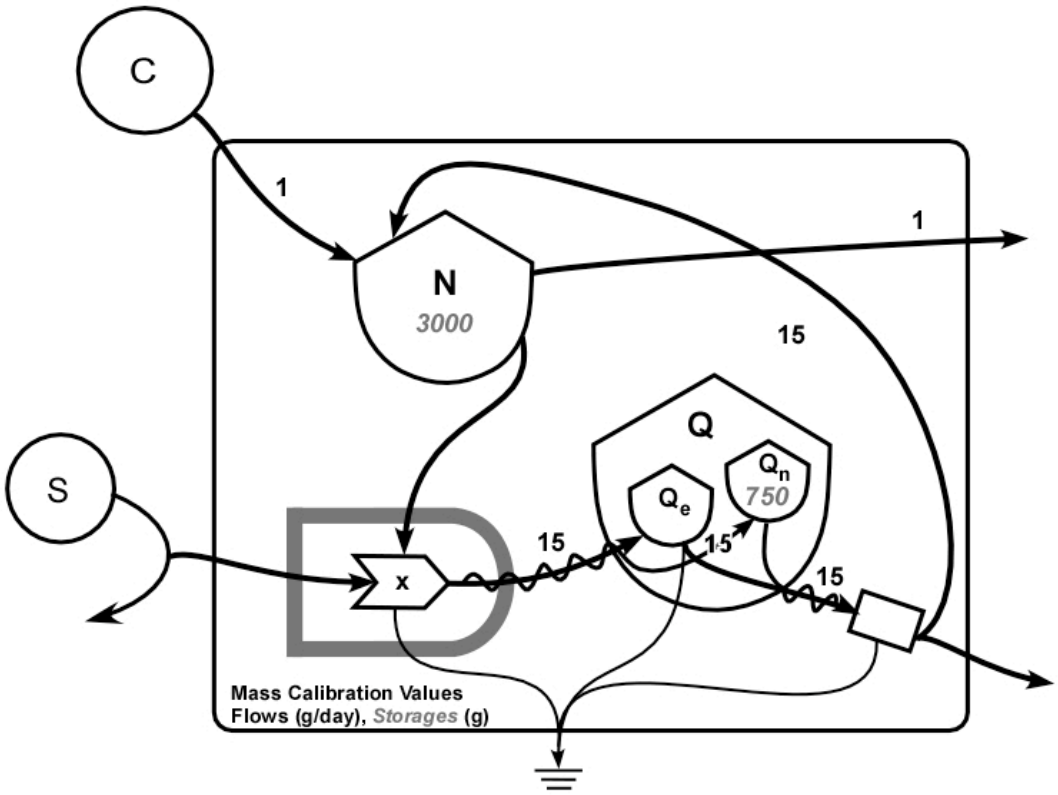

Figure 4.3. Steady state values for calibration of mass flows and storages.

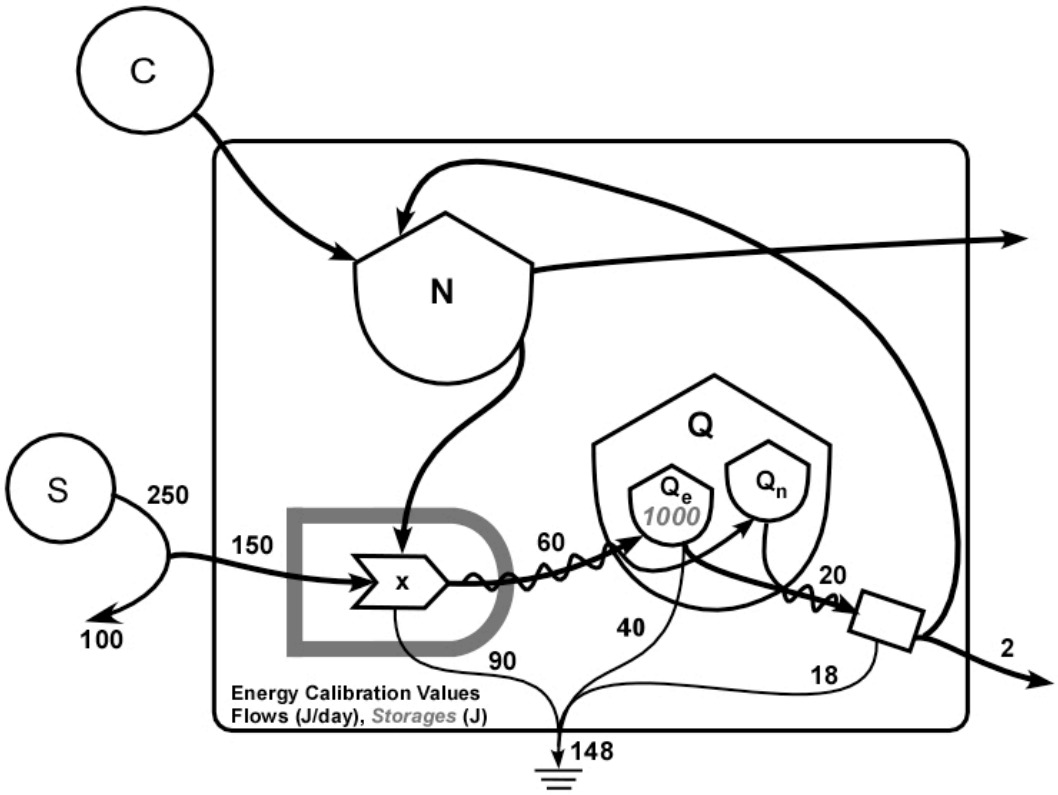

Figure 4.4. Steady state values used for calibration of energy flows and storages.

Relevant Examples of Emergy Cycling

Phosphorus in a Forest Ecosystem

Phosphorus is deposited in the large P pool of a forest soil from the atmosphere. Some is taken up by roots and transferred to biomass in processes driven by photosynthesis. Much of the material is recycled back to the soil through litterfall. Some of the decomposed organic matter in the soil P pool is removed from the system via erosion. Energy is exported via organic matter or evapotranspiration. Like EmCycOpen,

external energy drives the concentration of low quality material into high quality material that cycles. Energy is exported and material is dispersed.

Kibbutz

A kibbutz is a collective community generally centered on agriculture that is intended to be self-contained. In a kibbutz, members grow their own food using minimal resources from outside the community. Most kibbutzim are located in Israel; in order to meet agronomic requirements, the government subsidizes most kibbutzim. Exports from a kibbutz include food, tools, and crafts, as well as education when some members leave. Ideally, much of what is grown in a kibbutz remains there, as human waste can be recycled into the crops. The major energy input to growing food on a kibbutz (aside from internally provided labor) is solar energy. While this system is complex, it relates to the EmCycOpen model in that energy flows in at a low quality (sun) and out at high quality (information). Fertilizer inputs provide the material needed to grow food, which is largely recycled within the kibbutz, but some is exported.

External Combustion Engine

A heat engine using an internal "working" fluid that is heated by an external source and allowed to cool is an external combustion engine. The external heat source increases the energy of a fluid (in many cases air), causing it to pressurize and convert the pressure differential into mechanical work. Through this, the energy in the air is returned to its lower energy state and the process is repeated. At times, engine components are not perfectly sealed, allowing air into the compartment (typically a piston) of air when

pressure is below the atmospheric pressure. Similarly, air can leak out of the piston when it is above atmospheric pressure. Applying this example to EmCycOpen, the external heat force drives the pressurization of air that is recycled as cool air, which again becomes pressurized in the next cycle. The input and output of air at low quality energy states occurs when a piston leaks. The high quality energy export of this system is the mechanical work.

4.3.3. Verification

EmCycOpen will be evaluated for following energy, material, and emergy conservation at steady state at the system and storage levels. At steady state, inflow energy should equal outflow in the heat sinks (Jw) and outflow through J4. For storages, energy, material, and emergy are also conserved at steady state (e.g., J2 should equal the sum of J8 and J3, μ10 should equal inflow C, and M7 should equal M5, all referring to flows in Figure 4.2).

Additionally, energy flows should follow 2nd Law depreciation. That is, the overall inflow, J1, should be higher than subsequent flow J2. Likewise, J2 should be higher than J3 and J4 should be less than J3. Emergy is conserved throughout and does not follow heat sink energy flows. Because the model does not use data from a real system, its calibration cannot be validated against an existing system. Model validation may be a subject of future work.

4.3.4. Sensitivity Analysis

Calibration parameters were increased and decreased by 50% in order to qualitatively assess the response variables in a sensitivity analysis. If response variable behavior is similar to the original calibration, the model is considered robust regarding the changed parameter (Ford, 1999). For EmCycOpen, the calibration parameters that were changed in this sensitivity analysis were material flows (C, μC, μ5, μ7, and μ10), energy flows (R, S, J1, J2, J3, and J4), material and energy storages (Qe, N, and Qn), and input energy transformity (Ts). Response variables analyzed for sensitivity were flows of material, energy and emergy; storages of material, energy, and emergy; and transformities and specific emergy values. Response variables that exhibited a change in behavior and were most affected by changes in calibration values will be presented.

4.4. Results and Discussion

4.4.1. Energy and Material Flows- Inputs, Outputs, and Internal Cycles

Material and energy flows (Figure 4.5 and Figure 4.6) exhibited expected behavior: Material flows converged to steady state conditions used in model calibration (at steady state, μ5 = μ7; μ10 = C; Figure 4.5). Energy flows decreased after each transformation, as expected (J1 < J2 < J3 < J4; Figure 4.6).

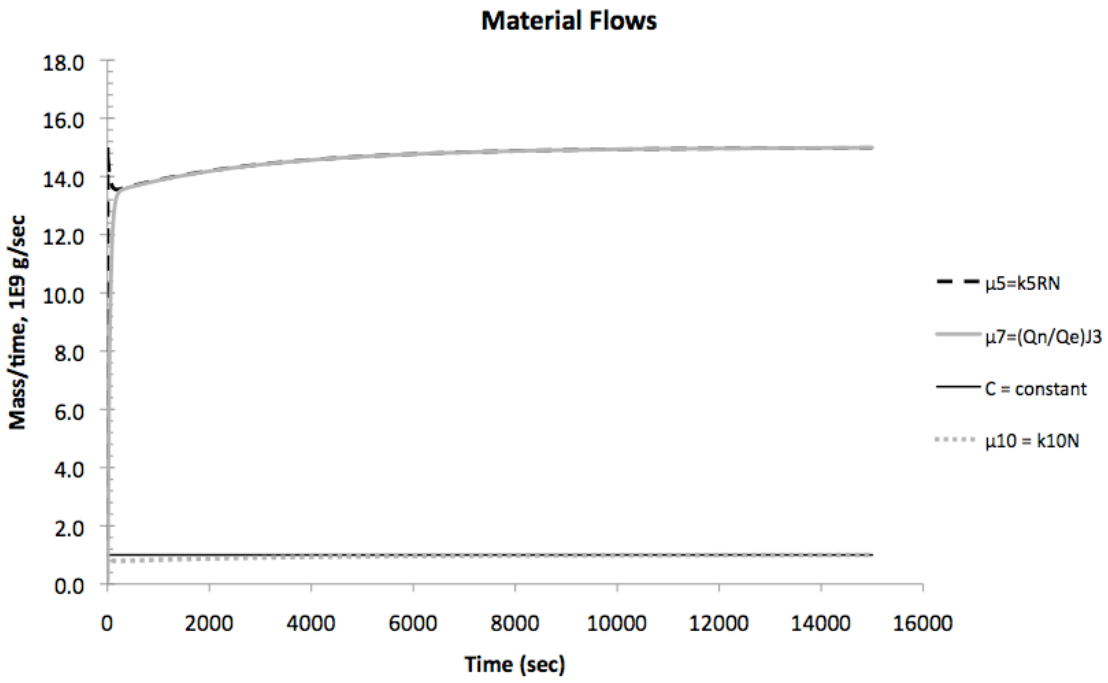

Figure 4.5. Material flows in EmCycOpen. Input material flow C remained constant throughout. Output material flow, μ10 reached steady state value equal to C. Internally cycled material flows μ5 and μ7 were about 15 times higher than input/output material flows at steady state. Steady state conditions are approached gradually. EmCycOpen response variables are presented in this figure to show the gradual approach to steady state (by time = 10000).

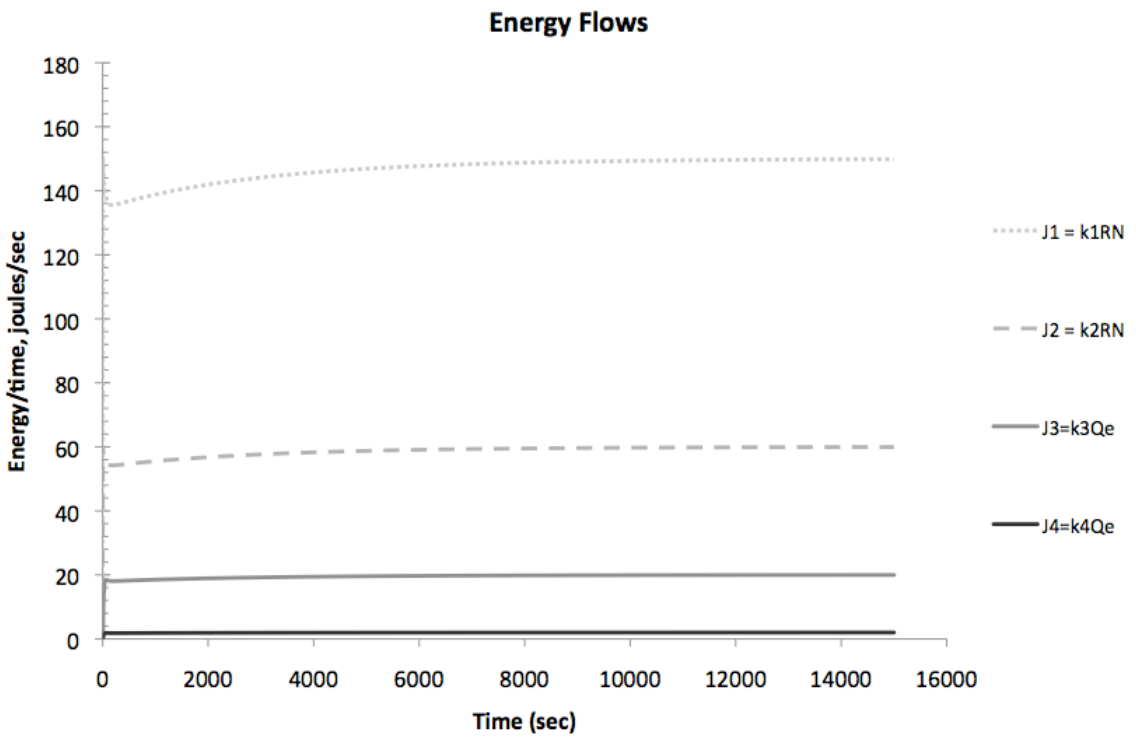

Figure 4.6. Energy flows in EmCycOpen. Incoming energy flow, J1 higher than energy flows that underwent energy transformation (J2, J3, and J4). Output energy, J4, had lowest energy value at steady state. Steady state conditions are approached gradually. EmCycOpen response variables are presented in this figure to show the gradual approach to steady state (by time = 10000).

Material outflow from storage N (μ5) increased fast, reaching near steady state conditions before time ≈ 20, due to a large initial N value. Because initial Qn was small, material inflow to N (μ7) increased at a slower rate than μ5. Dispersal from N (μ10) increased rapidly (due to large initial N) initially, but slowly decreased to steady state conditions at time ≈ 8000. This slow decrease in μ10 prevented the N storage from reaching steady state until approximately time ≈ 15000, as the incoming mass, C, remained constant.

4.4.2. Emergy Flows- Inputs, Outputs, and Internal Cycles

Emergy flows were evaluated using both the Dynamic Emergy Accounting (DEA) rule for allocating emergy using the partial specific emergy of Qn, $p\sigma_{Qn}$ (Tilley, 2011b), and the Network Emergy Rule (NER; Cohen, 2002). Comparisons to Tilley (2011b)'s EmCycClos are presented in discussion of DEA below. Comparisons to Cohen (2002)'s EmRecycle are made in the discussion of the model using NER methods.

EmCycOpen using Dynamic Emergy Accounting (DEA)

Respective pairs of flows are the input and output of a storage or the entire system (i.e., M1=M4, M2=M3, and M5=M7 at steady state, Figure 4.2). Emergy inputs M1 and M2 started out higher than the respective output flows M4 and M3 until convergence by time = 250 seconds (Figure 4.7). This resulted in an accumulation of emergy in storage Q. Conversely, output emergy flow from storage N, M5, started higher than the respective input flow M7. Internally cycled flows (M2, M3, M5, and M7) were higher than system inputs and outputs (M1 and M4) (Figure 4.7), suggesting the importance of using DEA for systems with significant internal material cycles.

Internal cycles of emergy (M2 and M3, M5 and M7) converged and slowly decreased (together) to reach steady state. Conversely, system input and output emergy flows (M1 and M4) converged and slowly increased to reach steady state. Thus, as empower maximizes over time for the entire system (M1 and M4 reach maximum), empower of internal cycles (M2 and M3; M5 and M7) is decreasing until steady state is reached. This behavior was not observed when the system was closed to material inputs and outputs.

When EmCycOpen was closed to material (C and μ10 set to zero), emergy flows exhibited change in reaching steady state conditions. In the materially closed model, respective pairs of flows (i.e., M1 and M4, M2 and M3, M5 and M7) converged and increased quickly together to reach steady state earlier than when the system was open to material inflow and outflow (by time = 300 in EmCycClos, time = 12,000 in EmCycOpen, Figure 4.8). This behavior suggested empower increased for all flows, internal and system input and output when closed to material. By opening the system to material inflows and outflows, it is apparent that internal emergy flows, while containing higher empower than system input and output emergy flows, approach steady state after decreasing. This is in contrast to system input and output emergy flows, which approach steady state by increasing. Still, this phenomenon agrees with Tilley (2011b) that empower is maximized at the production process where the energy source (M1) and the recycled material (M5) are coupled (Figure 4.2). However, as the emergy of the energy (M4) splits from the energy of the material (M7), empower continues to increase for energy while empower decreases over time for the cycled material (Figure 4.8).

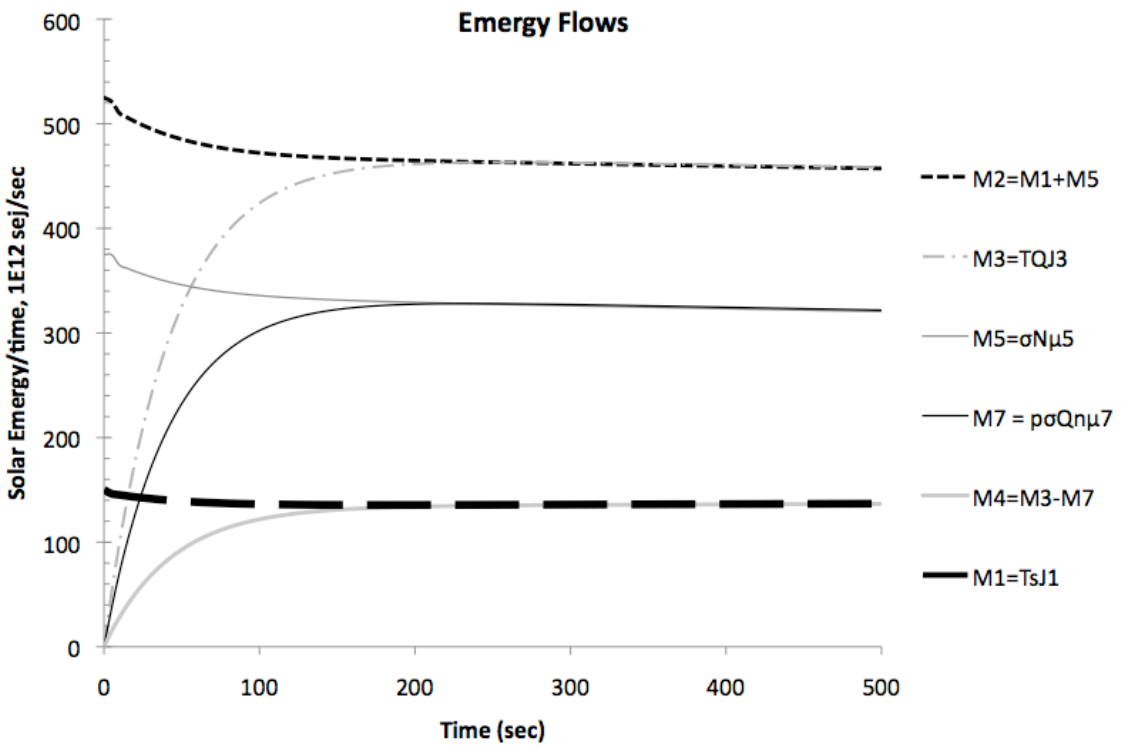

Figure 4.7. Emergy flows of EmCycOpen. Emergy flowing to and from storages simulated over time based on equations accompanying systems diagram. Emergy flows are paired based on destination and storage (M2 and M3; M5 and M7) and source and output (M1 and M4). Emergy flowing within system is higher than output (M2 and M3; M5 and M7 > M1 and M4). Note the x-axis only extends to 500 seconds. Steady state reached by time ≈ 12000 seconds.

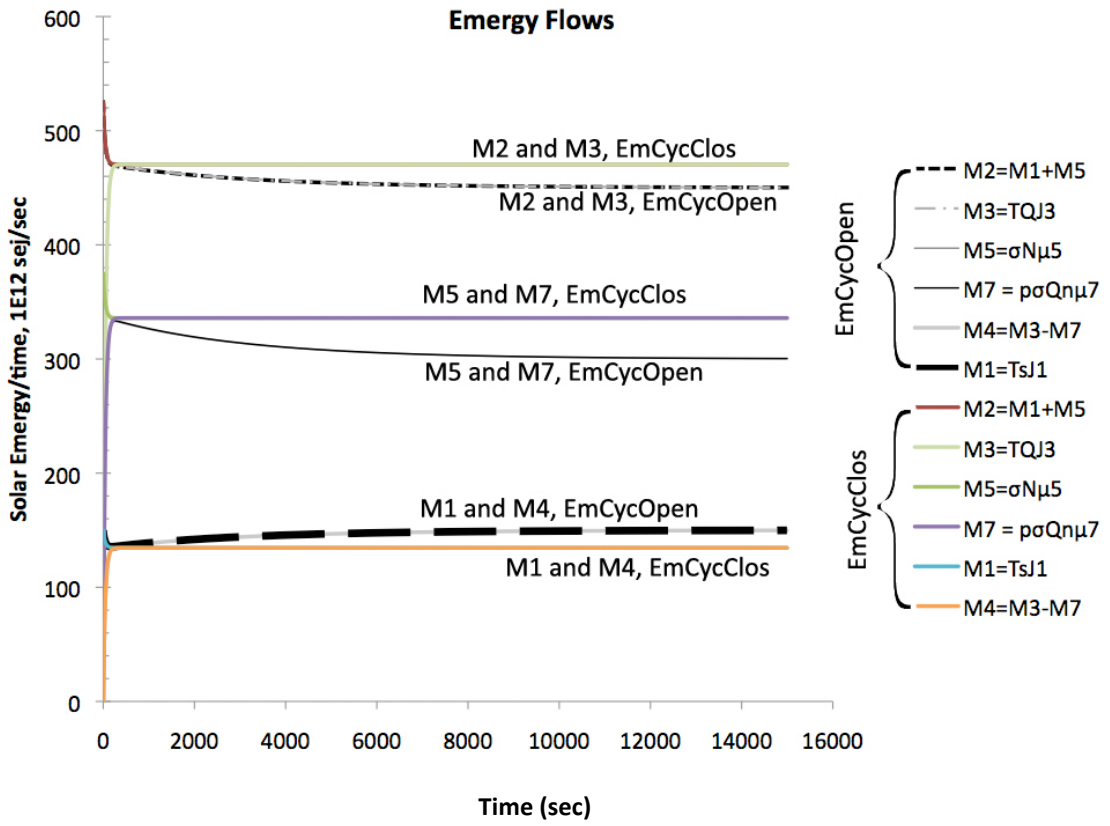

Figure 4.8. Emergy flows in EmCycOpen and EmCycClos (using calibration levels of this study). The lines in color represent flows from EmCycClos- steady state is approached earlier than in EmCycOpen, where steady state is approached after a decrease in internal emergy flows (M2 and M3; M5 and M7) and an increase in external emergy flows (M1 and M4).

Using the example of a forest ecosystem cycling phosphorus, the input emergy drives concentration of material in a lower quality energy state (storage N). The emergy driving that concentration is small compared to the emergy cycling with nutrients between the two material storages. The material-emergy (M7) that flows with cycled phosphorus from the high quality storage (Q, biomass) to the low quality storage (N, soil

P) re-enters the cycle with material flowing from the low quality storage through the production process into the high quality storage (root uptake of P). EmCycOpen allows material and emergy to flow into and out of the low quality storage (N, soil P) through flows C (atmospheric deposition) and μ10 (erosion), representing a dynamic material storage (Figure 4.2). To apply the example to emergy flows in EmCycOpen, the process of growth (M2, which includes photosynthesis (M1) and root uptake (M5)) represents the highest emergy flow of the system and is most responsible for the emergy accumulation in storage Q. Litterfall, represented by the flow from Q to N (M7), builds slowly as the forest matures (as storage Q increases). This material-emergy is recycled in the soil P pool (storage N) to be used again as an input to growth (M2). The dynamic nature of material of the soil P pool (through deposition and erosion) is represented in EmCycOpen.

EmCycOpen using the Network Emergy Rule (NER)

Cohen (2002)'s EmRecycle model had emergy inputs from the material source to the "low quality" storage (J5*Tr2 in Figure 1.1). The NER states the recycled material, which is above background level should be assigned the downstream specific emergy of the "low quality" storage (Cohen, 2002). In Cohen's model, the transformity of the storage would have artificially depressed the emergy of storage relative to background levels, so the transformity of the input emergy (Tr2, Figure 1.1) was used. However, in this model, Cohen (2002)'s NER was applied using the statement of the rule in his text. That is, the specific emergy of the material recycle in EmCycOpen using NER is the specific emergy of the destination storage, N, or σ_N. In addition, Cohen's EmRecycle

model pre-dated the formal conceptualization of "emformation" (Brown, 2005), and so it did not include this principle (Cohen, 2002). Because EmRecycle did not track material- and energy-emergy separately, the export of emergy (Yield in Figure 1.1) was simulated in the model as the energy multiplied by the transformity of the storage, Q and included material (Cohen, 2002). In order to apply NER to EmCycOpen, the relative emergy values changed based on the calculation of M7 (i.e., σ_N*μ7 instead of $\rho\sigma_{Qn}$*μ7 using DEA) Similar to Dynamic Emergy Accounting rules, the Network Emergy Rule applied to the EmCycOpen model for calculation of exported emergy was the difference between the emergy from Q (M3, Figure 4.2) and emergy cycled back to storage N (M7, Figure 4.2). Because M 7 and M5 were lower using NER, the resulting emergy recycled back into storage Q (M2) was lower). System output emergy flow (M4) remained the same using NER because emergy was conserved and system input (M1) was unaffected by using NER).

Emergy flow from N was evaluated separately for DEA and NER because the cycled emergy along the μ7 pathway was different for each method. Consequently, specific emergy values for N varied between DEA and NER methods. Emergy flows into and out of N (M7 and M5, Figure 4.2) were lower using NER than when using DEA (Figure 4.9). Again, for each storage at steady state, emergy flows pair up as follows: M2 = M3 and M5 = M7 (Figure 4.2). Both DEA and NER allow internal emergy flow to be larger than input or output flows. This suggests maximum empower (emergy/time) occurred within the system (M2, Figure 4.9). Applying NER to the EmCycOpen model resulted in lower internal emergy flows, which resulted in lower specific emergy and

transformity of storages N and Q, respectively. This suggests the quality of the material flowing in a recycle loop was underestimated by using NER in the EmCycOpen model.

Cohen (2002)'s EmRecycle model also used logic conditions for calculating changes in emergy storages (i.e., when energy or material is decreasing, $dQ/dt < 0$, change in emergy equals the change in energy times the transformity of the storage, $dMQ = TQ*dQ$ and when $dQ = 0$, $dMQ = 0$; Cohen, 2002). The application of the Network Emergy Rule is applied to EmCycOpen in order to illustrate only the difference in accounting for emergy on material recycle. Dynamic Emergy Accounting rules that regard logic equations were used in EmCycOpen with the application of NER (i.e., emergy accumulation is controlled by differential equations, regardless of change in energy or material storage, rather than accumulation stopping artificially with logic equations when the change in energy or material is zero; Tilley, 2011a, 2011b).

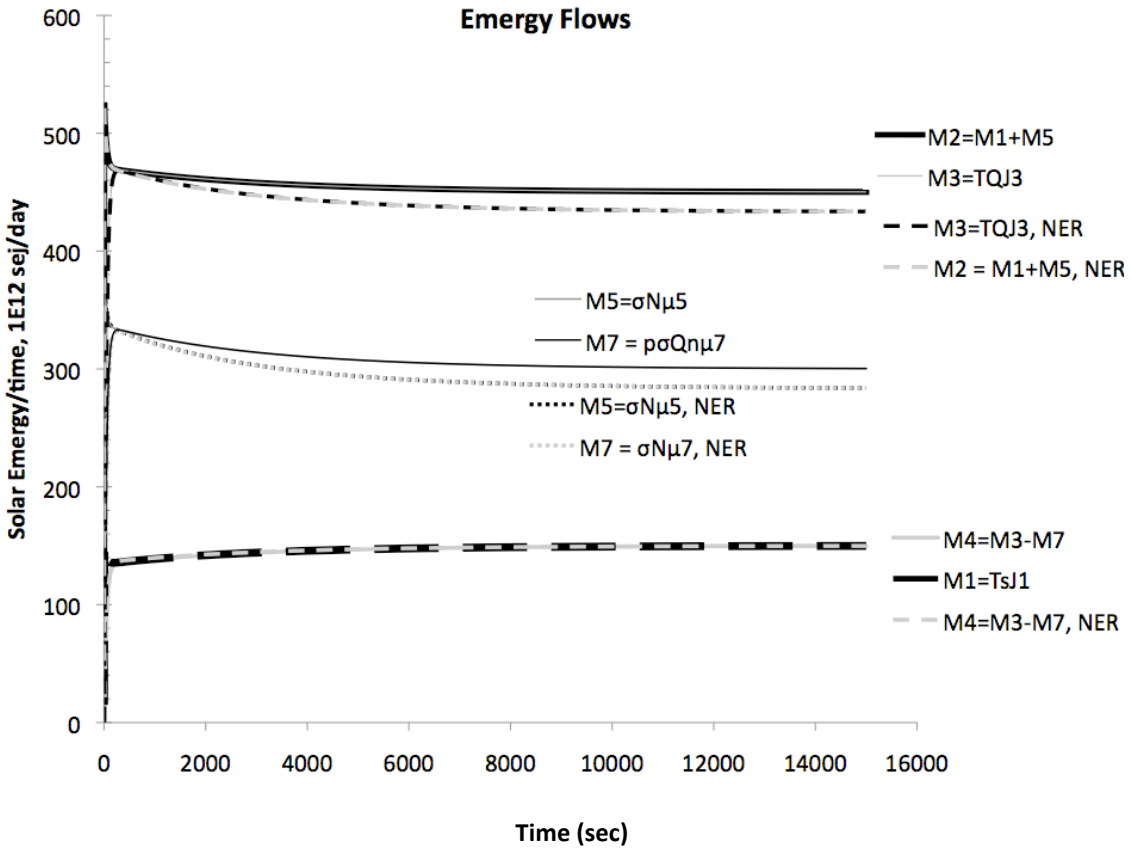

Figure 4.9. Emergy flows in EmCycOpen with Cohen (2002)'s Network Emergy Rule applied. M7 was calculated using both the Dynamic Emergy Accounting (DEA) rule for allocating emergy using the partial specific emergy of Qn, $p\sigma_{Qn}$, Tilley (2011b) and the Network Emergy Rule (NER) using the downstream specific emergy of N, σ_N Cohen (2002) multiplied by μ7. M5 was evaluated separately for DEA and NER as well. Because M5 controls M2 and subsequently M3 (through change equation for MQ), M2 and M3 were also calculated using NER.

4.4.3. Energy and Material Storages

Energy and material storages in EmCycOpen reached steady state after an intial decrease that was due to high initial μ5 (controlled by storage N) and low initial μ7 (controlled by storage Qn) (Figure 4.10). EmCycOpen had higher steady state values for

both material and energy storages than EmCycClos (Figure 4.11). This difference in steady state was due to an early accumulation of material in N from material source C and low initial dispersal flow µ10 (refer to Figure 4.2). Because material dispersal (µ10) from storage N reached steady state slowly (Figure 4.5), storage N approached steady state slowly.

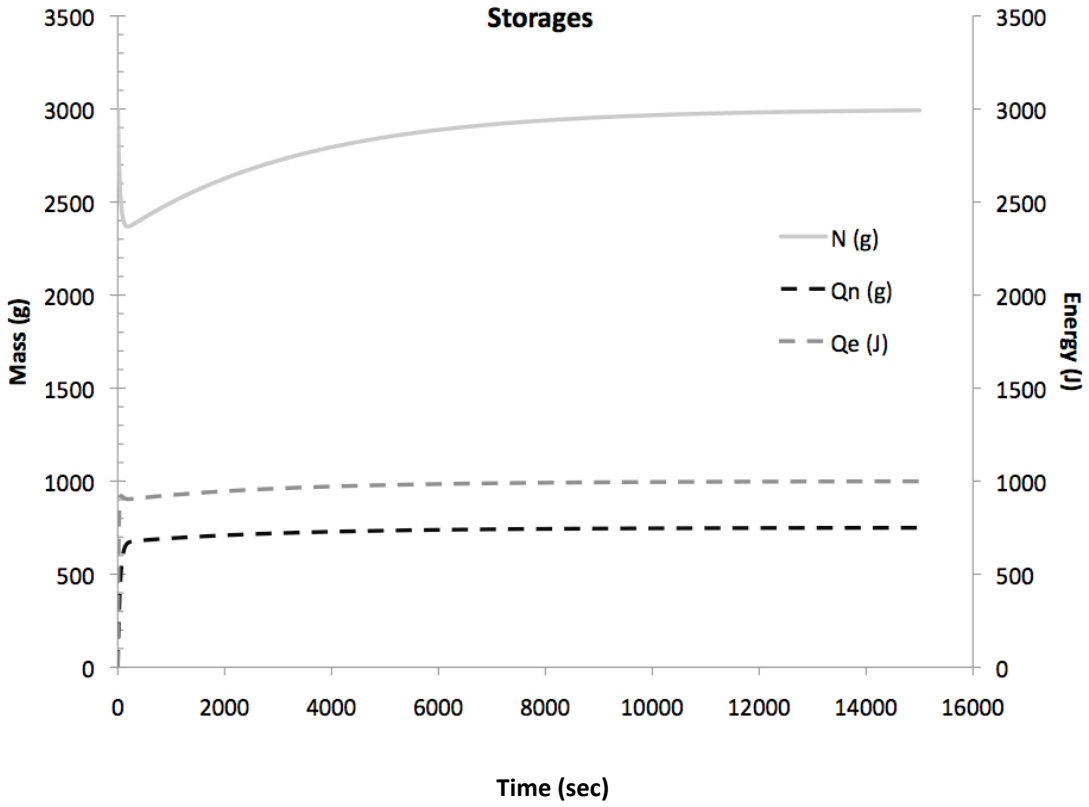

Figure 4.10. Energy and material storages in EmCycOpen. Low quality material storage (N) starts at steady state calibration level (3000 g) decreases due to high initial µ5 and low µ7 initially. Energy storage (Qe) increases to steady state faster than material storages N and Qn.

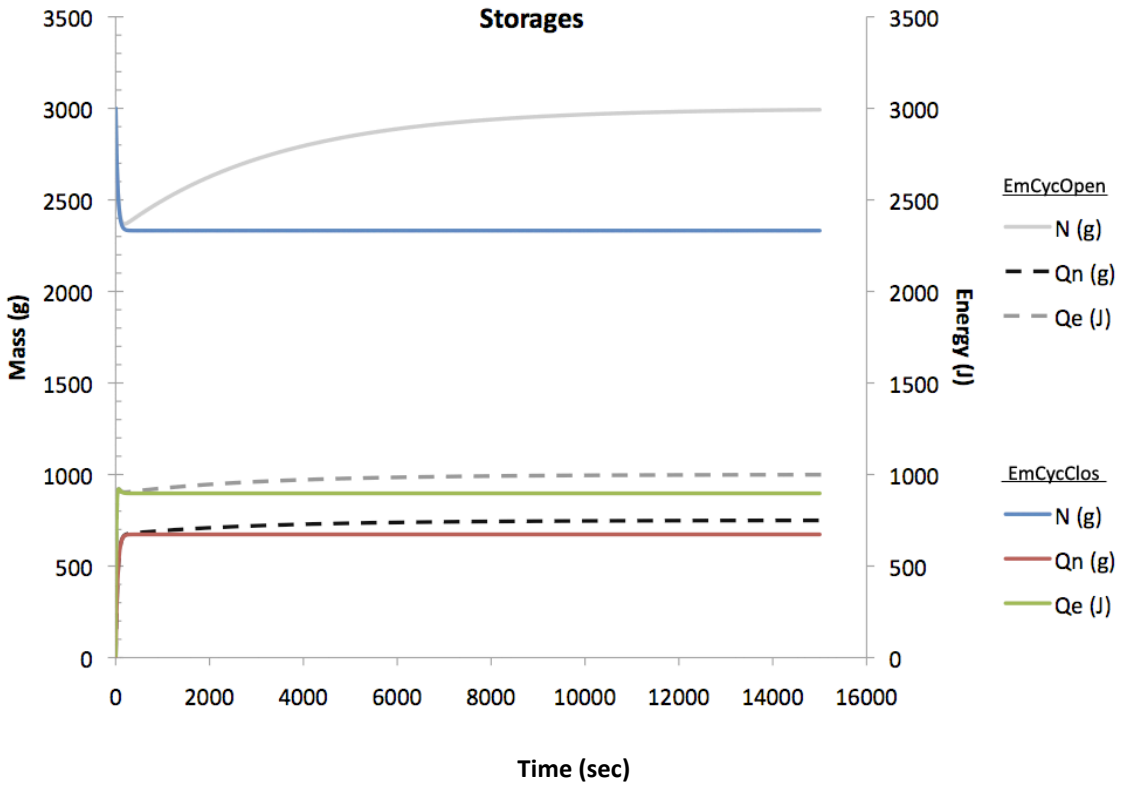

Figure 4.11. Energy and material storages in EmCycOpen and EmCycClos using calibration values for this study. EmCycOpen had higher steady state values for all storages as the constant input from material source C allowed N to accumulate material in the initial stages which subsequently affected Qn (μ5 controlled by storage N) and Qe (J2 controlled by storage N).

4.4.4. Emergy Storages

EmCycOpen using Dynamic Emergy Accounting (DEA)

Emergy storages reached steady state values slowly after a short initial period of change (Figure 4.12). Unlike EmCycClos, this study assigned emergy to N storage (i.e., concentration gradient between background level and N), so the emergy of low quality material (N) could be simulated dynamically. Emergy of storage N (MN) reached a higher steady state in EmCycOpen than in EmCycClos (Figure 4.13). This difference was

likely due to the lower system input emergy (M1) to EmCycClos (Figure 4.8) and a higher steady state value of material storage N in the open model (Figure 4.11). Steady state values for emergy storages MQ and MQn were higher in EmCycOpen than the model closed to material inputs and outputs, EmCycClos (Figure 4.13). This relative difference between EmCycOpen and EmCycClos was in contrast to the energy and material storage differences (Figure 4.11). The energy-emergy storage, MQe was lower in EmCycOpen than in EmCycClos (Figure 4.13). Consequently, the emergy of the high quality storage (MQ) was comprised of a lower proportion of material-emergy (MQn) in EmCycOpen than in EmCycClos, 67% compared to 71%, respectively. By allowing the system to be open to material input and output, the material-emergy is relatively lower in the high quality emergy storage. Later, differences in partial transformities between the open and closed models will be discussed.

Again, the example of phosphorus in a forest ecosystem is applied. Overall, emergy of soil P (MN) is expected to be higher than the emergy in biomass due to the larger quantity of soil P (storage N) relative to the quantity in biomass (Q). If considering the forest ecosystem closed to material input and output (as in EmCycClos), the emergy in the soil P (MN) would be expected to be lower because less has accumulated over time. The emergy in biomass (MQ) is higher in the closed system because less material accumulates and the specific emergy of biomass (σ_Q) is higher (discussed in next section). When less soil P accumulates (lower steady state value of storage N) in the closed system, less P flows to biomass (lower $\mu 5$) and so less input emergy (M1) is required to drive the production of biomass. However, the amount of emergy associated with biomass P (MQn) in the closed system is still higher than in the open system. This is

due to higher material accumulation of low quality (N) in the open system and a similar amount of emergy inflow, effectively diluting the emergy with more material in the open system. In terms of the forest, if the soil P pool of a forest is modeled as having material inputs (rock weathering or atmospheric deposition) and outputs (runoff, erosion), more material accumulates in an open system than in a closed system. Because the input emergy required concentrate the material into biomass does not increase at a 1:1 ratio with material increase, the resulting emergy in biomass is "diluted" by the increase in material. Likewise, when the soil P pool of a forest is modeled as being closed to material (EmCycClos), emergy of the biomass increases, suggesting the material-emergy of the biomass becomes more important to a closed system that is never supplied with outside material (i.e., cycling of emergy is more important in a closed system). In this scenario, emergy of the soil P pool (MN) still decreases when closed because the storage of soil P is so much lower when it does not accumulate (see Figure 4.11).

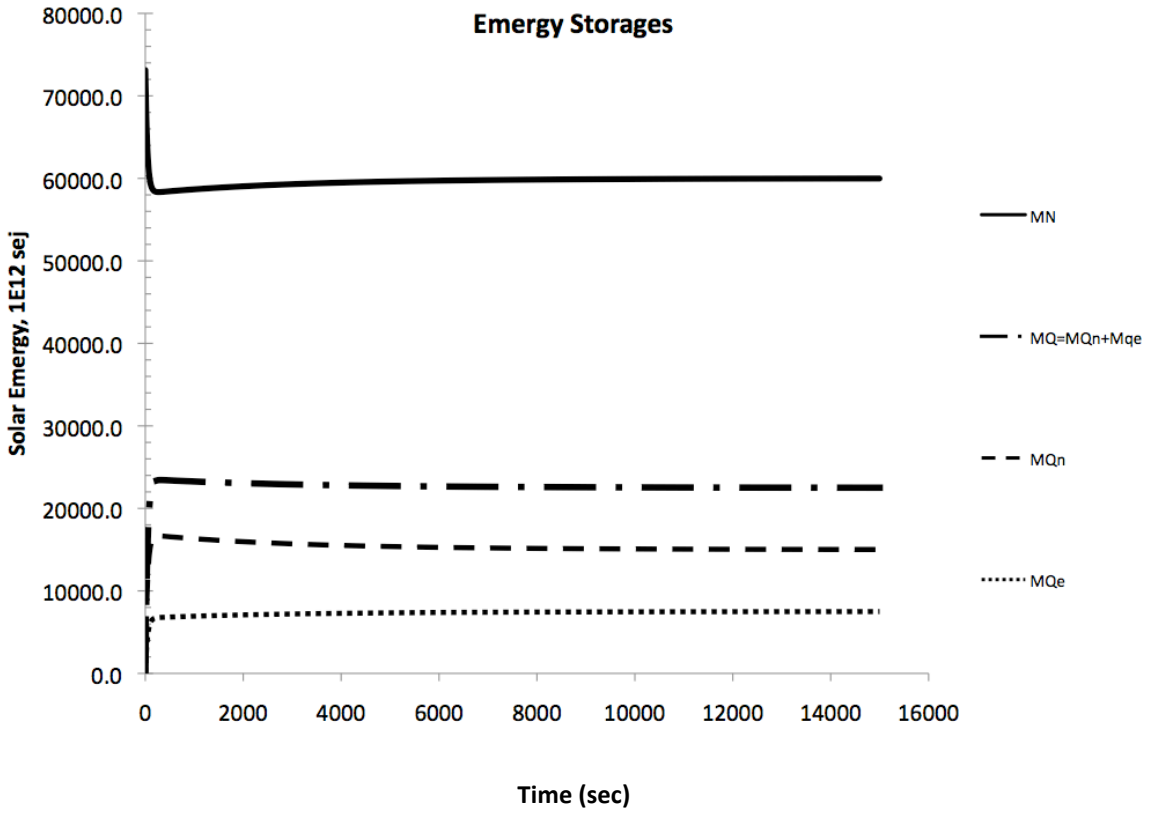

Figure 4.12. Emergy storages in EmCycOpen. Emergy storages reached steady state faster than energy and material storages.

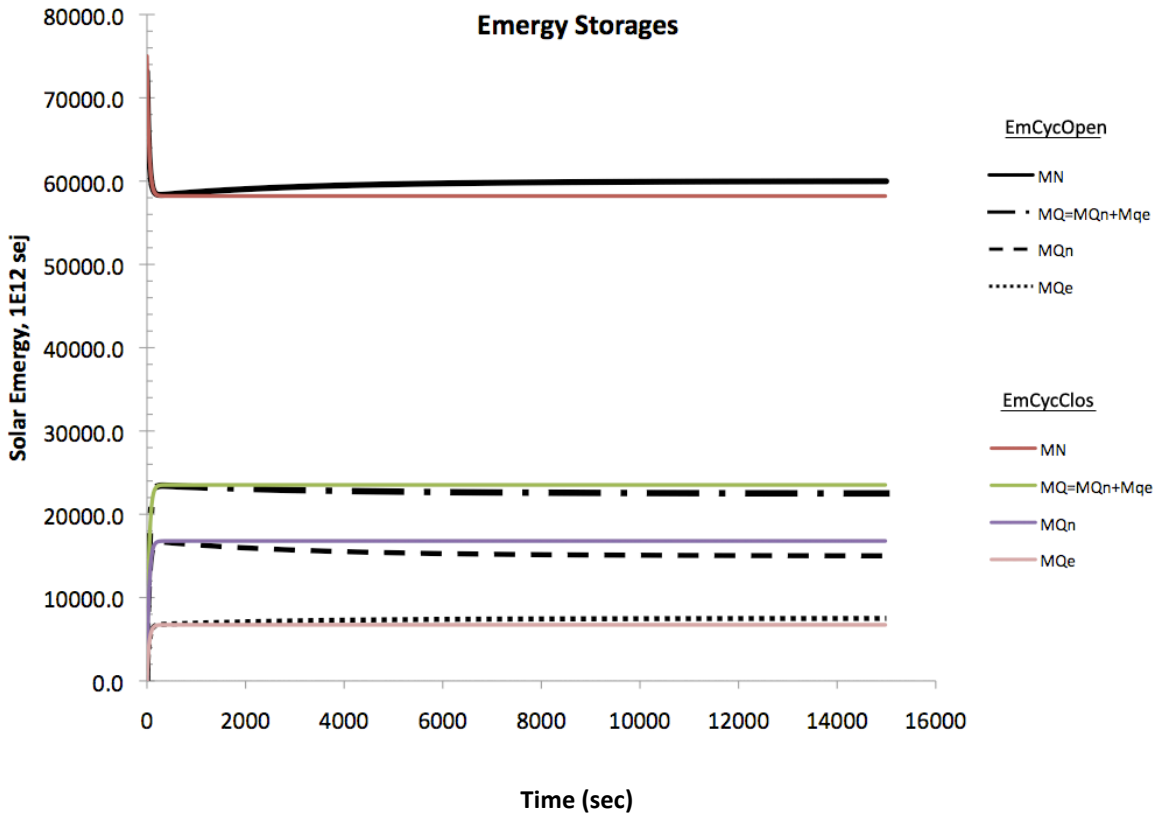

Figure 4.13. EmCycOpen and EmCycClos emergy storages (both calibrated using values from this study). Storages reach steady state in EmCycOpen later than EmCycClos, similar to material and energy storages.

EmCycOpen using the Network Emergy Rule (NER)

Because specific emergy values for internal material flows were evaluated separately for Dynamic Emergy Accounting (DEA) and the Network Emergy Rule (NER), emergy of N was evaluated separately (i.e., M7 and M5 had lower steady state values when calculated using NER than when using DEA (Figure 4.9). Both methods of evaluating internal emergy cycling resulted in similar outcomes, but emergy of low quality material (MN) resulted in a lower steady state values for the NER method (Figure 4.14). In addition, material- and energy-emergy were not tracked separately using the

NER method, so emergy of high quality material (MQ) was calculated using the transformity of Q (TQ) multiplied by the energy of storage Q. This calculation resulted in a slightly lower MQ using NER than when using DEA, a result of a lower material and energy storages, Qn and Qe, respectively (Figure 4.14). These results suggest that by assuming the quality of the cycled material is the same as its destination storage (in this case, storage N), rather than the originating storage (Qn), the stock of emergy in both low quality material (N) and high quality material (Q) may be underestimated over time.

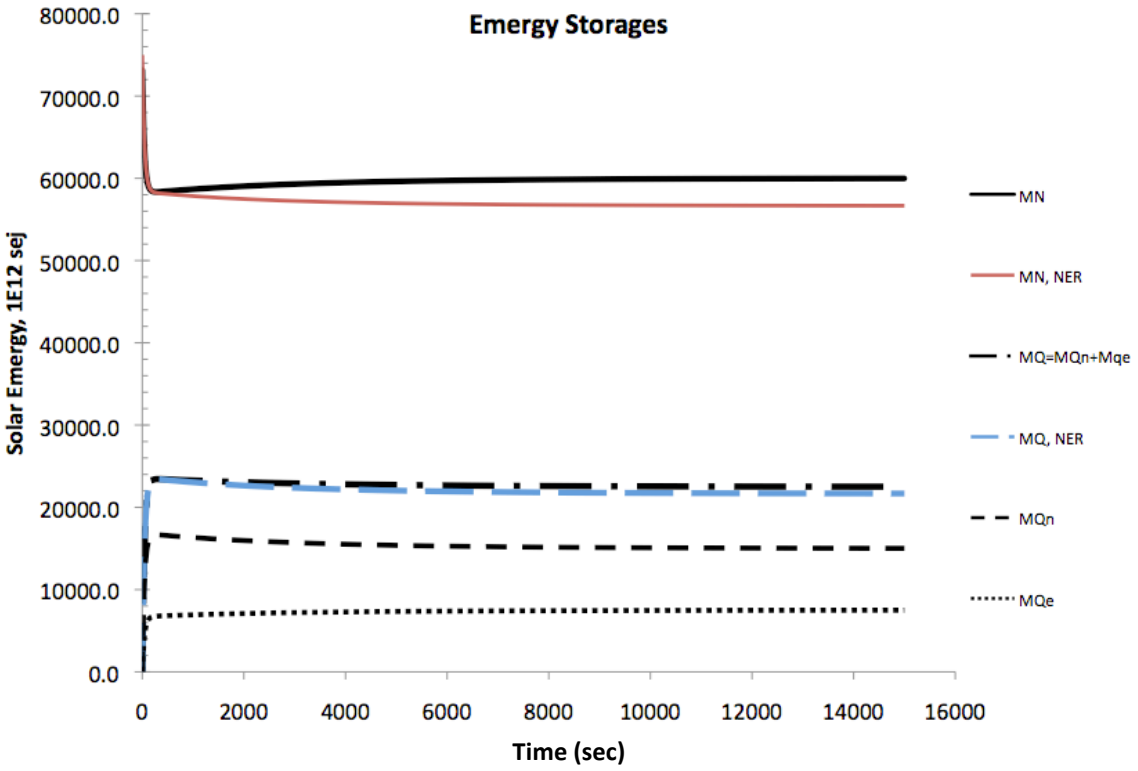

Figure 4.14. Emergy storages of EmCycOpen using both Cohen's Network Emergy Rule (NER) and Tilley's Dynamic Emergy Accounting (DEA) methods. Flows used DEA method of simulation unless noted with "NER." Because emergy of material and emergy of energy were not tracked separately using the NER method, only the emergy of storage Q was simulated in EmCycOpen when using the NER method.

4.4.5. Transformity and Specific Emergy Dynamics

EmCycOpen using Dynamic Environmental Accounting (DEA)

Overall, transformities and specific emergy values approached steady state at a similar rate to flows and storages in EmCycOpen using Dynamic Emergy Accounting rules (Figure 4.15). The highest transformity is for the output energy, J4. This was expected because J4 is very small compared to input energy, J1 and M4, the output emergy, is the same as the input emergy, M1. The high transformity of the outflow reflects the preceding energy transformations resulting in higher quality energy. Specific emergy of Q (σ_Q) has the next highest value (Figure 4.15). This specific emergy is the ratio of the total emergy of Q (MQ) to its material (Qn). The high specific emergy of Q reflects the high quality of material in Q. The transformity of Q (TQ) is lower than the specific emergy of Q (Figure 4.15) because the numerical value of energy is higher than that of material in Q at steady state (1,000 J compared to 750 g). In addition, TQ approached steady state slower than σ_Q because Qe reached steady state faster than Qn. That is, Qe increased faster than Qn initially (Figure 4.10), and MQ was used to calculated both TQ and σ_Q (storages Qe and Qn are in the denominator of these equations, Figure 4.2). Consequently, TQ did not approach steady state as fast as σ_Q. Because the material-emergy that left storage Q (M7 from Qn) was the same as that which entered storage N, the specific emergy of N (σ_N) and the partial specific emergy of Qn ($\rho\sigma_{Qn}$) converge rapidly (Figure 4.15). However, if M7 is calculated using σ_N instead of $\rho\sigma_{Qn}$, the resulting emergy flows are not conserved (i.e., the model is not calibrated for μ7 to have σ_N). This is because the N storage has an initially high σ_N (high initial emergy of N) that quickly converges with $\rho\sigma_{Qn}$, which started low (low initial emergy of Qn).

That is, EmCycOpen would not function properly if the internal material cycle ($\mu 7$) were assigned the specific emergy of its destination storage (σ_N). The lowest transformity is that of the energy-emergy storage, Qe ($\rho\sigma_{Qe}$).

When closed to material inputs and outputs, as in EmCycClos, specific emergy values at steady state increased. As mentioned in previous sections, the increase in accumulation of material when open as in EmCycOpen effectively "diluted" the material-emergy in the high quality storage (Q). This is reflected in the higher specific emergy of Q (σ_Q) and partial specific emergy of Q ($\rho\sigma_{Qn}$) when the system is materially closed. In addition, the specific emergy of N (σ_N) and the transformity of Q (TQ) in EmCycClos were higher than in EmCycOpen. This is due to the same effects of the proportion of material accumulation in storages of EmCycOpen to the energy-emergy accumulation being high. Transformities of J4 and partial transformity of Qe ($\rho\sigma_{Qe}$) did not change the system was closed to material input and output (in EmCycClos).

Again, using the forest ecosystem as an example, when the soil P pool is open to material input and output, the specific emergy of soil P can be expected to decrease. More phosphorus accumulates when open to deposition than when closed (as in EmCycClos). While more energy is used with higher accumulation of phosphorus, the proportion is not high enough to balance out the increased material accumulation. That is, specific emergy of soil P goes down when there is more available in the storage and a non-proportional increase in incoming emergy. In the biomass (Q), the material-emergy has a lower quality (lower $\rho\sigma_{Qn}$) because the material-emergy becomes diluted once it enters the soil P pool, which is accumulating P from deposition. A forest ecosystem that is open to material input and output is does not need to have as high quality material-

emergy as one that is closed to material. This suggests that the material-emergy in a closed system must be preserved at a higher level than in an open system to produce the same quality output (TJ4 in EmCycOpen = TJ4 in EmCycClos).

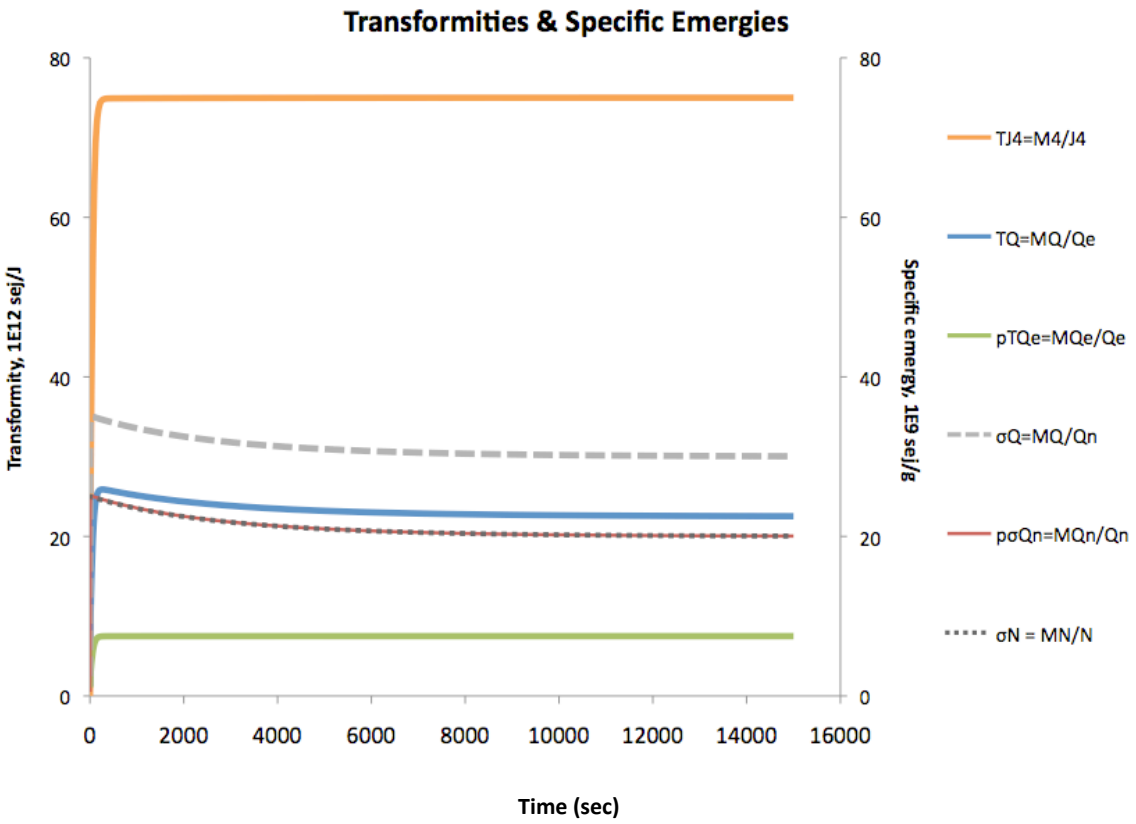

Figure 4.15. Transformity and specific emergy values of EmCycOpen. These relative steady state levels of transformities and specific emergy values were expected. The highest transformity (TJ4) was for the flow of energy from the system (J4), which underwent several transformations from the input energy J1. Specific emergy of N (σ_N) was lower than specific emergy of Q (σ_Q), as expected. Partial transformity of Qn ($\rho\sigma_{Qn}$) and specific emergy of N (σ_N) are both shown on this figure, but share similar values after converging.

4.4.6. Sensitivity Analysis

Results of the sensitivity analysis are presented in the following sections organized by the calibration values that were changed. Response variables that exhibited a change will be shown in figures. Some response variables will be excluded from figures if they are similarly sensitive to changes in calibration values as similar types of response variables. For example, if input material source was changed and all emergy flows changed similarly, only one emergy flow will be presented.

Sensitivity to Energy and Material Sources

In order to assess how the model would change if input energy and material were increased or decreased, the energy source S was doubled and reduced by 20% (in order to maintain other calibration constants, energy source S could not be reduced below 150 J/s) and the input material source, C, was doubled and halved. When input energy (S) was doubled, initial energy flows decreased, but returned to calibration values (Figure 4.16). Because energy flows decreased initially with an increase in S and material flow from Q ($\mu 7$) is controlled by the energy flow, a similar response to increasing S was exhibited in material flow $\mu 7$. Energy, material, and emergy flows and storages likewise exhibited a small change in initial behavior, but reached original calibration levels for steady state. Transformities and specific emergy values showed no change in response to changing S. This shows that EmCycOpen is robust with respect to input energy source S. That is, small changes in S will not affect model behavior significantly. This is because energy flows in EmCycOpen are limited by material cycling.

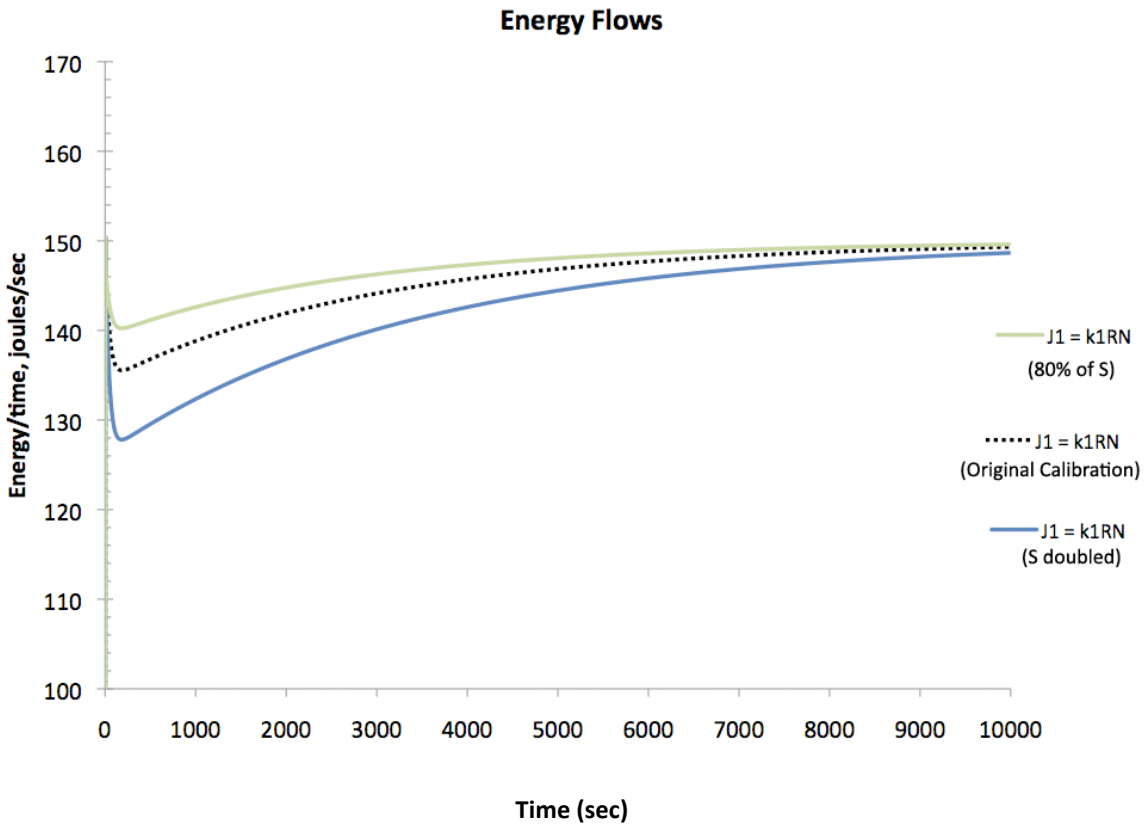

Figure 4.16. Response of J1 to doubling and reducing by 20% input energy source S. All energy flows behaved similarly to J1 with a doubling of energy source resulting in initial decrease of energy flow from original calibration. Reducing input energy S increased energy flow initially. Energy flows eventually reached same calibrated levels as with original S.

The input material source, C, was doubled and halved to assess model sensitivity to changing material input. In order to ensure mass was conserved, the calibration steady state value of the output material flow was changed accordingly. When input material (C) was doubled, initial material flows increased, but returned to calibration values (Figure 4.17). Storage N increased initially with increased C. Consequently, an increase in C,

resulted in increases energy flows J1 and J2 (which is dependent on storage N). Energy, material, and emergy flows and storages likewise exhibited a small change in initial behavior similar to material and energy flows, but reached original calibration levels for steady state. Transformities and specific emergy values showed very low sensitivity to changing C. This shows that EmCycOpen is robust with respect to input material source C. That is, small changes in C will not affect model behavior significantly. Increased material availability is ultimately controlled by energy, but the transient nature of material flows is affected by material availability.

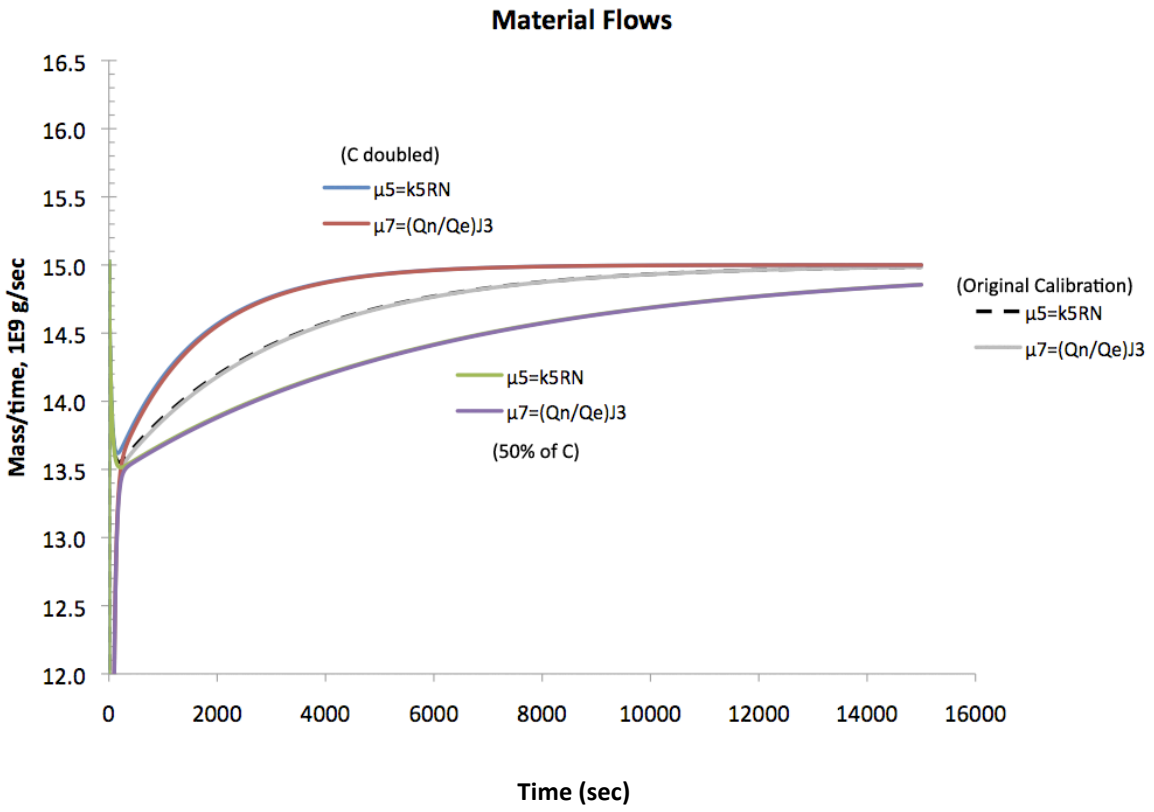

Figure 4.17. Response of μ5 and μ7 to doubling and halving input material source C. Reducing input material C decreased material flow initially. Increasing material input resulted in initial increase of material flows. Material flows eventually reached same calibrated levels as with original C.

Sensitivity to Transformity and Initial Specific Emergy Values

The input energy transformity value (Ts) was doubled and halved to assess model sensitivity to changing input energy quality. When input transformity (Ts) was doubled, steady state energy-emergy (MQe) doubled (Figure 4.18). Similarly, when Ts was halved, steady state value of MQe was half of original calibration. Emergy of Q exhibited an increased equal to the increase in MQe when Ts was doubled (MQn was unaffected). Material and energy flows remained unaffected, as expected. Transformity of output energy (J4) and partial transformity of Qe both doubled and halved accordingly with Ts. The associated change in emergy values with changing input energy transformity Ts shows that EmCycOpen changes in accordance with the incoming emergy. Energy and material response variables remained unchanged, so these behaviors did not change, only the steady state level of emergy response variables changed. Changing Ts will change steady state levels of emergy response variables, so it is important that an appropriate value is used.

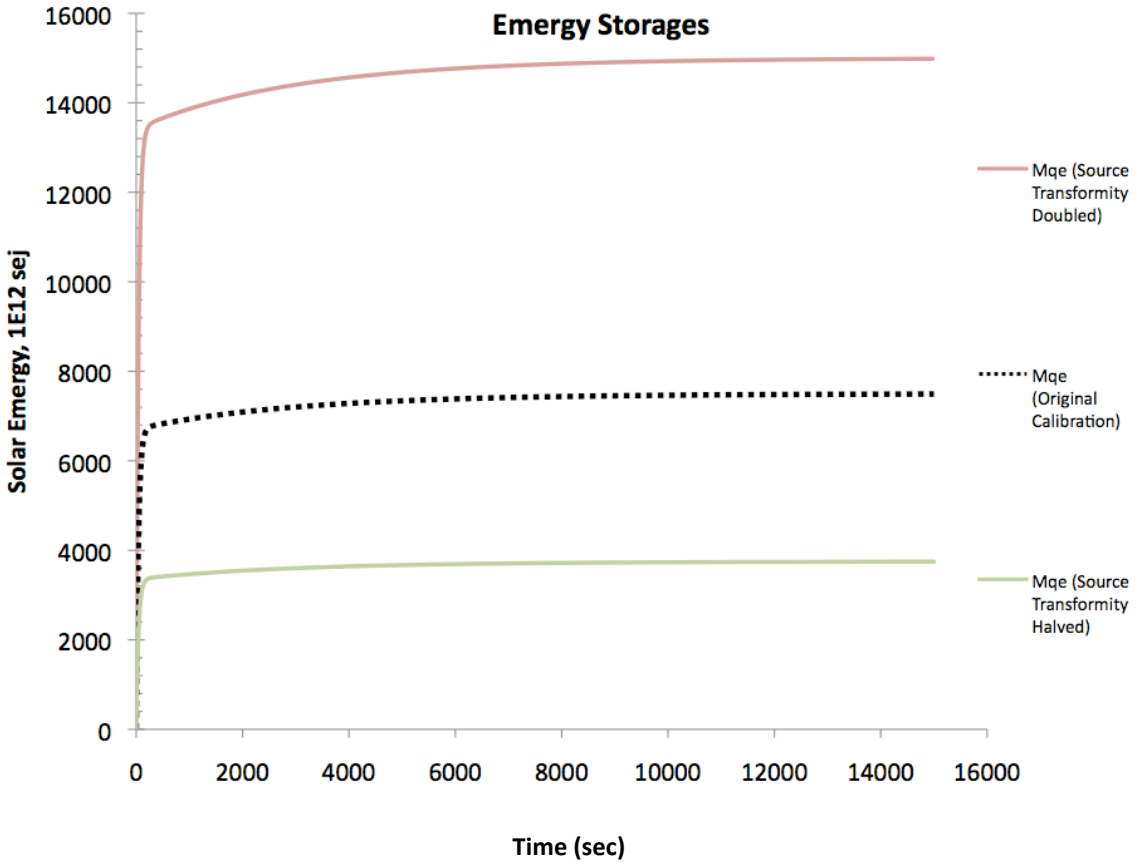

Figure 4.18. Sensitivity to emergy storage of Qe when source transformity is doubled and halved. The energy-emergy accordingly doubled and halved at steady state compared to original calibration.

The initial specific emergy value of N (σ_N) was doubled and halved to assess model sensitivity to changing quality of material N. When σ_N was doubled, steady state emergy of low quality material (MN) doubled (Figure 4.19). Similarly, when σ_N was halved, steady state value of MN was half of original calibration. The steady state value of material-emergy (MQn) also increased proportionally to the to inrease in σ_N. Emergy of Q exhibited an increased equal to the increase in MQn when σ_N was doubled (Qe was unaffected). Material and energy flows remained unaffected, as expected. The associated

changes in emergy response variables with shows that EmCycOpen changes in proportion to the initial specific emergy of N. Energy and material response variables remained unchanged, so these behaviors did not change, only the steady state level of emergy response variables changed. Changing σ_N will change steady state levels of emergy response variables, so it is important that an appropriate value is used.

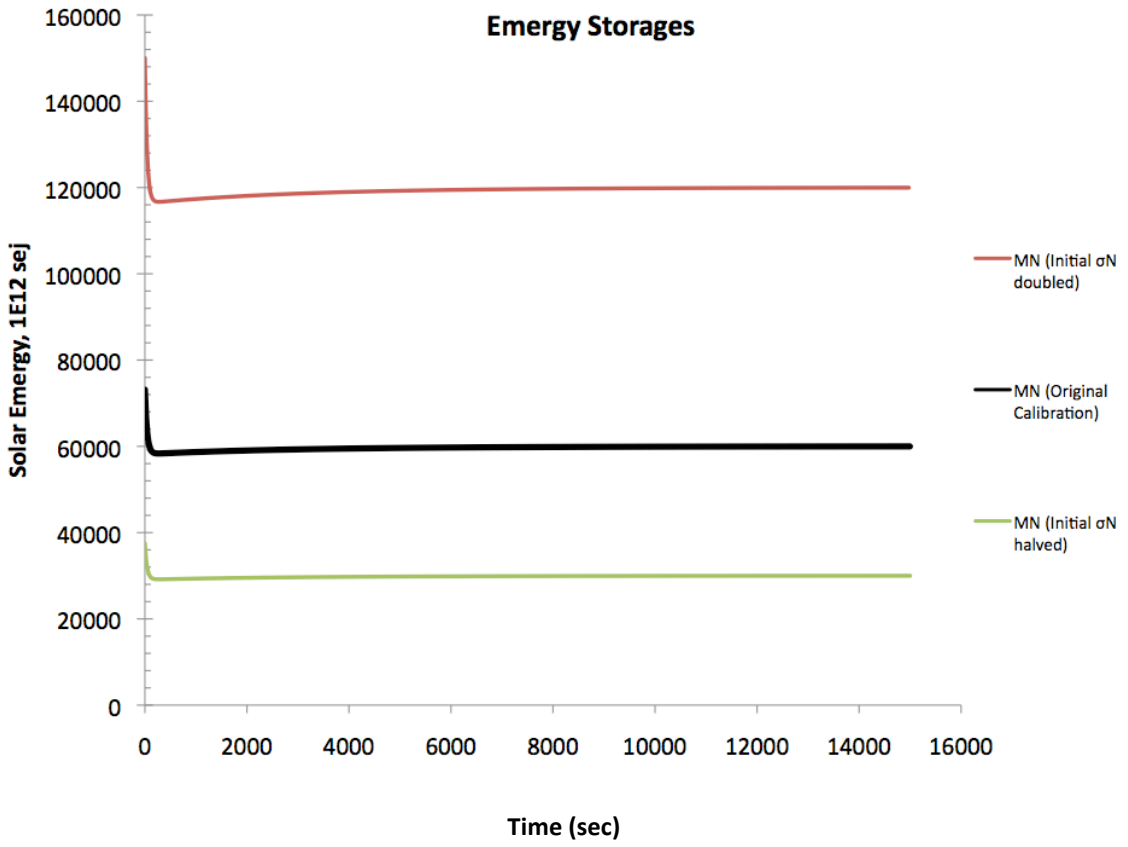

Figure 4.19. Sensitivity to emergy storage of N when low quality material specific emergy (σ_N) is doubled and halved. The emergy of N accordingly doubled and halved at steady state compared to original calibration.

Sensitivity to Initial Values of Storages

The initial value of storages Qe and Qn were doubled and halved. No changes were observed in response variables for these changes. EmCycOpen does not depend heavily on the initial value of these storages.

The initial value of storage N was also doubled and halved. Initial changes in material flows were observed with changes in storage N (Figure 4.20). Material and energy storages increased and decreased initially, but reached original steady state calibration levels eventually. Steady state values of emergy storages and flows and specific emergy values changed proportionately to changes in initial N. This suggests that the initial value of N should be carefully selected in EmCycOpen because it has implications for the steady state conditions of emergy response variables. Storages of material and energy are less affected by the initial value of storage N as they reach original steady state calibration values.

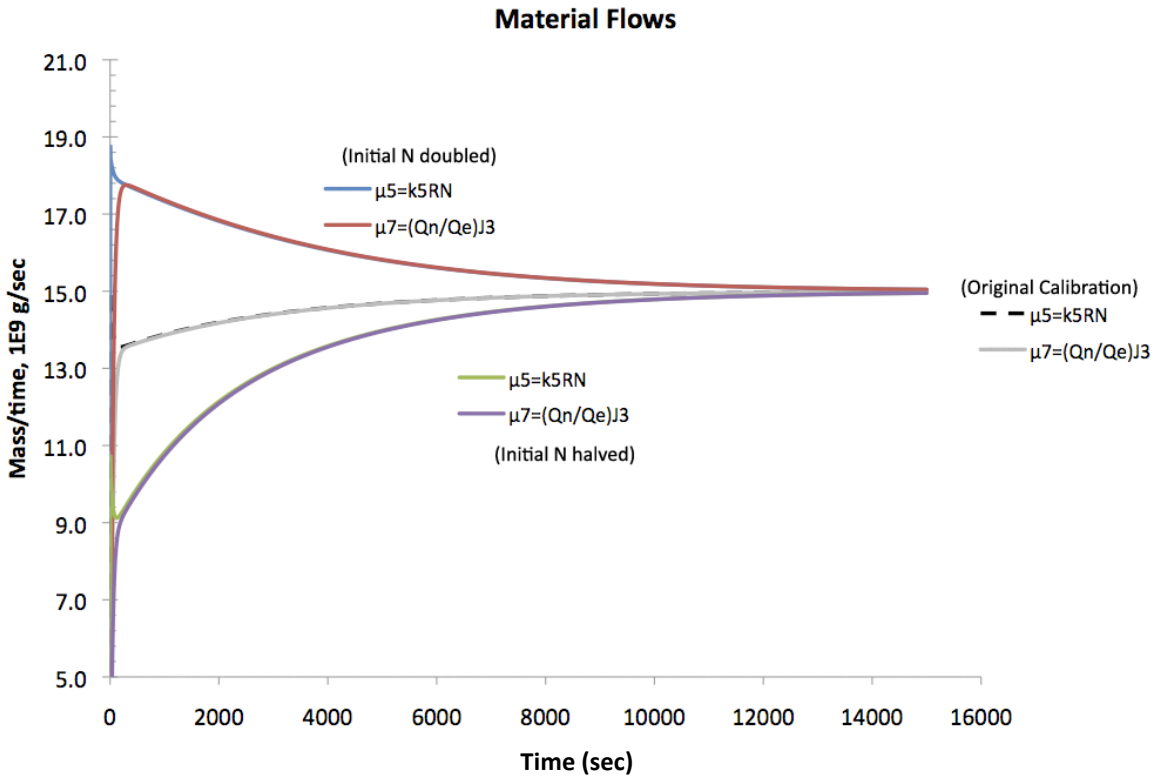

Figure 4.20. Response of μ5 and μ7 to doubling and halving initial value of storage N. Reducing initial N decreased material flow initially. Increasing initial resulted in initial increase of material flows. Material flows eventually reached same calibrated levels as with original initial N.

Sensitivity to Energy and Material Flows

When steady state calibration values of energy flows are doubled and halved, EmCycOpen responds as expected. A proportionate increase in steady state levels is exhibited with the change in energy flow calibration (i.e., 20% increase in J1 calibration corresponds to a 20% increase in steady state value compared to original calibration). The response of material flows in EmCycOpen to changes in energy flows is an initial proportionate change then a gradual approach to original calibration levels for that

material flow. Consequently, emergy response variables are not affected significantly by changing energy flow calibration levels.

Changing internal material flow steady state calibration levels (μ5 and μ7) had several effects. When these material flows were doubled, the response of the steady state level of material flow was to also double (and likewise for halving the calibration level). Storages Qn and Qe also changed proportionately. However, because levels in storage N can be controlled by the dispersal of material, N did not change steady state levels. An increase in internal material flows resulted in an initial decrease in N, but the original calibration level of storage N was eventually reached. However, because emergy of N was affected by the slowed accumulation of material in storage N, the steady state value of the emergy of storage N (MN) decreased when internal material flow increased. Because Qn depends on these material flows (no dispersal), the steady state value was increased with increasing internal material flow. This resulted in an increase in the internal flow of emergy. When material cycles internal to EmCycOpen increase, internal emergy flows and high quality material emergy (MQn) increase. Conversely, the emergy of low quality material N (MN) decreases steady state values.

Summary of Sensitivity Analysis

EmCycOpen responded as expected to changes in calibration and initial parameters. When applying the black box concept to EmCycOpen, changes in calibration parameters do not violate input/output constraints. However, steady state conditions of several internal flows do change in proportion to changes in certain calibration values, as discussed in the previous sub-sections. Thus, it is important to select appropriate

calibration values for these parameters in order to reflect accurate steady state conditions of response variables if EmCycOpen was to be validated using a real system. EmCycOpen is robust regarding all calibration parameters in the sense that changes to steady state conditions of response variables do not occur out of proportion to the changes made to the calibration values.

4.5. Conclusion

The model, EmCycOpen, builds upon Tilley (2011b)'s EmCycClos model that simulates emergy cycling within a system closed to material input and output by adding the input and output of material. Using Dynamic Emergy Accounting rules, EmCycOpen shows that opening the system to material input and output (with no additional emergy) does affect emergy cycling in systems. When open to material input and output, EmCycOpen reached maximum empower for system output similar to previous the model EmCycClos. However, empower of internal cycles decreased to steady state in contrast to system output. When the system was closed to material input and output, as in Tilley's EmCycClos, internal emergy cycles only increased to maximum empower. The implication here is that while maximum empower is reached on a system basis, it is not necessarily reached similarly on internal emergy flows. Still, EmCycOpen agrees with Tilley's EmCycClos in that overall empower of internal flows is higher than system input/output empower, highlighting the importance of Dynamic Emergy Accounting for systems that recycle a significant amount of material.

Additionally, Cohen (2002)'s Network Emergy Rule was evaluated on EmCycOpen to test whether previous emergy simulation that does not track material- and

energy-emergy separately could be used with the revised dynamic emergy accounting framework. It was shown that the Network Emergy Rule, which assigns the specific emergy of the destination storage to cycled material underestimates the quality of the material flow. By tracking material-emergy separately from energy-emergy, Dynamic Emergy Accounting rules allow for a more appropriate specific emergy value, the partial specific emergy to be assigned to the material cycle. This value is more in line with the specific emergy value being derived from the source rather than its destination. This study suggests using the Network Emergy Rule could underestimate the emergy of the material flowing internally. EmCycOpen provides a more accurate accounting of the material-emergy cycling within a system open to material inputs and outputs.

It should be noted that, because EmCycOpen is a model intended to explore the theory of internal emergy cycling, the units should not be a primary concern. If the model were to be validated against a real system, the energy density in storage Q would likely be much higher than currently calibrated (here, energy density is 1.3 J/g, wood biomass has an energy density of about 17,000 J/g). This should be a subject of future work.

Other future work includes building on EmCycOpen by including material outputs from Q that carry emergy. To use the example of the forest ecosystem again, high quality material should be allowed to be exported from the system. This would require splitting M3 and perhaps adding another storage for tracking material- and energy-emergy separately. This will be the subject of future work. In addition, EmCycOpen could be adapted to change the process by which material is concentrated into storage N. Energy from source S may be involved in the concentration of material source C, changing the emergy dynamics of N and consequently creating a competition between

low quality storage N and high quality storage Q for energy source S. Further, material source C does not necessarily need to be absent of emergy. Indeed, it would be more realistic if the source C represents atmospheric deposition of P in a forest ecosystem that some emergy input is included. These changes could improve EmCycOpen to better represent real systems such as the forest ecosystem and will be the subject of future work.

Chapter 5. Conclusion

The three studies in this dissertation were intended to present improvements to the concept of emergy cycling in systems. First, the importance of acknowledging that cycles carry emergy was highlighted. The evaluation of waste flow from production processes into the environment, which reorganizes ecosystems and requires emergy, was presented. A new index for comparison of these systems was developed. Through evaluation of various treatment scenarios, this study found passive treatment systems performed better than active treatment system by using less purchased emergy and more renewable emergy. The calculation of residual emergy discharged to the environment was an important step in recognizing the need to assign emergy to flows of energy and material that have available energy at levels above background. That is, where an environmental gradient between the energy or material flow exists, emergy should be evaluated. When the environment uses energy to process recycled wastes the analytical boundary of the

system should be expanded to include the receiving environment to reflect the true costs of discharging waste that carries emergy.

By expanding the analytical boundary of the system to include the recycled wastes, the emergy associated with the waste flow becomes an internal cycle. In order to better understand emergy allocation to wastes that are cycled internally, three different types of ecosystems that recycle an element critical to production (i.e., phosphorus) were evaluated. Phosphorus cycled similarly in both of the farms, with relatively large inputs and outputs from fertlizers and crop harvest and runoff, respectively. The forest ecosystem had relatively small inputs and outputs of P. All three systems had similar mass flows of recycled P, and did so through similar pathways. The forest recycled P through litterfall, root uptake and death, and root transfer to aboveground biomass. Crops recycled P through root uptake and crop residues left on the fields after harvest. Decisions on emergy allocation were made that assigned all emergy of net primary production to the recycling of phosphorus. Human-managed systems (i.e., farms) required more emergy than the natural system (i.e. a forest) to recycle similar amounts of phosphorus. Emergy flow of internal cycles associated with P was greater than the emergy inputs and outputs associated with P.

Having demonstrated that the emergy associated with a cycled material can be orders of magnitude larger than emergy inputs, the next question was to advance the accounting techniques available for tracking how emergy is recycled. For this a general minimodel of a system recycling emergy associated with a key material was developed based on a prior effort (Tilley 2011b). EmCycOpen simulated the emergy dynamics of a

two-storage system open to material and energy, which expanded the previous model (EmCycClos) that was only open to energy, but not material.

By evaluating the emergy of cycling material in systems, emergy accounting methods were improved. In particular, EmCycOpen provided a foundation for further improvements in simulating the dynamics of internal emergy flows, which can lead to the development of better emergy accounting techniques for systems with large flows of recycled materials. Improving these conceptual models also elucidates significant questions regarding emergy, such as: When a product is destroyed, what happens to its emergy? Does emergy of a product "disappear?"

Possibly one of this study's most important findings was that maximum empower for a system can occur internally rather than externally. In Odum's suggestion for a 4th Law of Thermodynamics, namely that systems self-organize structures and processes to maximize the flow of empower (Tilley and Brown, 2006) there was no clear distinction on where in the system empower should be maximized. However, Tilley relates from personal communications with Odum that he often thought of emergy flow in terms of steady state, rather than dynamics. In a steady state system, emergy flow at each level of the energy hierarchy would be the same, so there was no need to distinguish where within the system empower was measured. Often it was simply assumed that intake empower was the most logical place to measure it. With the advances in simulating the emergy dynamics of inputs, cycles, and outputs demonstrated in this dissertation, we now have a new "intellectual wrinkle" to help us more fully consider what should be the 4th Law of Thermodynamics.

EmCycOpen shows that, even when the system is open to material inputs and outputs (not just energy inputs and outputs as in EmCycClos), the maximum emergy flows were those of the internal cycling material. This is important because it shows that internal emergy cycles, even with the possibility of multiple carriers (material and energy) across system boundaries, carry more emergy flow than the system inputs and outputs. Thus, a recycled product may maintain most of its emergy, even if some of the material leaves the system after it is degraded. The "lost" portion of the product's emergy leaves when the product is no longer usable, but, as shown in EmCycOpen, more emergy remains with the product in its recycle pathway. This is one possibility suggested by EmCycOpen as calibrated in this work. It is important to continue to improve this model and potentially develop it for the intention of representing a real system.

A practical implication of the improved evaluation of the emergy of recycled materials is that, in emergy evaluations, if a product's emergy is composed of material in high proportions, it should be considered as a "loan" to the product's use downstream if that material is to be recycled. For instance, when determining the emergy of a computer, the material- and energy-emergy should be evaluated separately. The computer, after becoming obsolete, will be recycled in a scrap market. This material-emergy remains with the computer. Some of the material re-enters the computer production process as reclaimed precious metals and perhaps reused electronic components. Some material, which has lower value (i.e., lower transformity), is sent to a landfill (i.e., dispersed at low emergy state). In order to represent this particular situation, the EmCycOpen model will need improvement, but the work presented in this dissertation provides a better understanding of how such a model can be constructed. The EmCycOpen model shows

that these internal material cycles can be larger than system inputs and outputs, an important concept regarding emergy theory.

The concepts and models presented in this dissertation have broader impacts. In the face of declining high quality and finite energy resources, decisions regarding their most prudent use for the prosperity of society and nature must be made with sound science. Emergy evaluations reflect resource use on a global scale and improving this systems science improves the accounting techniques emergy analysts use for determining the sustainability of production processes. In particular, this study provides a performance indicator for treatment systems that accounts for the non-renewable energy sources, treatment performance, and residual effects to the environment of these systems. This index can be used to inform community planning. Additionally, the indices presented in the comparisons of forest and agricultural ecosystems suggest emergy cycled within human-dominated systems (in this case farms) may be larger than in natural systems but require more inputs. Systems with material cycles as a significant component seem to also have emergy cycling as a significant component. Previously, emergy was not allocated to internal cycles. The simulations model, EmCycOpen, presented in this dissertation also suggests internal emergy cycles are a significant part of systems with material cycles. The simulation model shows that systems with large internal material cycles relative to their input and output of material also cycle emergy in relatively large amounts. Overall, this work builds on the understanding of how emergy cycles with material within systems, which has implications for the evaluation of a product's emergy density and thus its quality.

APPENDICES

Appendix A

Table A1. Emergy analysis table for *No Treatment* scenario for Acid Mine Drainage. The 11 ha receiving environment was evaluated on a yearly basis with only local, renewable emergy inputs. Significant figures kept for accounting purposes.

#	Item	Unit/yr	Amount Per year	Solar Transformity (sej/unit)	Ref. for Transf.	Solar Emergy (sej/yr) E12
	ENVIRONMENTAL INPUTS TO RECEIVING ENVIRONMENT					
1	Sunlight	J	6.20E+14	1.00E+00	By Definition	620
2	Wind	J	1.73E+11	1.50E+03	Odum 1996	259
3	Rain Chemical Potential	J	5.66E+11	3.06E+04	Odum 1996	17,333
4	Rain Nitrogen	g	2.00E+05	2.41E+10	Brandt-William 2002	4808
5	Rain Phosphorus	g	8.03E+03	2.20E+10	Brandt-Williams 2002	177
6	Rain OM	J	1.92E+09	3.19E+04	Brown and Bardi 2001	61
7	ET	J	5.83E+11	3.06E+04	Odum 1996	17,837
8	*Emergy of Env. Resources*					*17,837*
	MINE DRAINAGE INPUTS FROM SEEPS					
9	MD Chemical Potential	J	1.08E+12	4.85E+04	Odum 1996	52,463
10	MDin Al	g	2.13E+04	1.44E+09	Odum et al. 1987a	31
11	MDin As	g	1.39E+04	1.54E+09	Odum et al. 1987a	21
12	MDin Cd	g	3.87E+03	1.54E+09	Odum et al. 1987a	6
13	MDin Ca	g	1.61E+08	1.68E+09	Odum 1996	270,568

14	MDin Cr	g	4.27E+02	1.54E+09	Odum et al. 1987a	1
15	MDin Cu	g	6.31E+02	3.36E+09	Brown and Ulgiati 2004	2
16	MDin Fe	g	3.90E+07	2.05E+09	Buranakarn 1998	79,989
17	MDin Mg	g	4.40E+07	1.68E+09	Odum 1996	73,959
18	MDin Mn	g	3.31E+05	1.14E+11	Odum 1996	37,755
19	MDin Ni	g	2.07E+05	1.54E+09	Odum et al. 1987a	319
20	MDin Pb	g	1.45E+04	1.54E+09	Odum et al. 1987a	22
21	MDin Zn	g	1.81E+06	7.56E+09	Odum 1996	13,694
22	*Emergy of AMD*					*528,831*
23	**Total Emergy Inputs**					**546,667**
	MINE DRAINAGE AT BACKGROUND LEVELS					
24	MD Chemical Potential	J	1.08E+12	4.85E+04	Odum 1996	52,463
25	Background Al	g	6.73E+04	1.44E+09	Odum et al. 1987a	97
26	Background As	g	0.00E+00	1.54E+09	Odum et al. 1987a	0
27	Background Cd	g	2.50E+02	1.54E+09	Odum et al. 1987a	0
28	Background Ca	g	1.18E+07	1.68E+09	Odum 1996	19,857
29	Background Cr	g	3.90E+02	1.54E+09	Odum et al. 1987a	1
30	Background Cu	g	9.64E+02	3.36E+09	Brown & Ulgiati 2004	3
31	Background Fe	g	1.15E+05	2.05E+09	Brown and Buranakarn 2003	237
32	Background Mg	g	1.14E+06	1.68E+09	Odum 1996	1,918
33	Background Mn	g	4.46E+04	1.14E+11	Odum 1996	5,080
34	Background Ni	g	3.18E+03	1.54E+09	Odum et al. 1987a	5
35	Background Pb	g	6.65E+03	1.54E+09	Odum et al. 1987a	10
36	Background Zn	g	7.29E+03	7.56E+09	Odum 1996	55
37	*Total Emergy of AMD at Reference Site Levels in Receiving Environment*					*79,726*

CALCULATIONS FOR TABLE A1:

	Area of Receiving Env:	69001	m2	Area of Volunteer Wetland =
	AMD Flow	7	L/s	15000 m2
	lifespan:	30	yrs	
1	**SUNLIGHT**			
	mean annual solar radiation	15.8	MJ/m2/day	average in Ottawa Co. (OCS, 2009)
	conversion	3.65E+02	day/yr	
	Solar Energy (J/yr)	(15.8 MJ/m2/day)*(365day/yr)*area		
		3.98E+14	J/yr	
2	**WIND KINETIC ENERGY**			
	mean annual wind speed (OCS for ottawa co.)	3.40E+00	m/s	
	density of air	1.30E+00	kg/m3	
	drag coefficient	1.00E-03		
	area	6.90E+04	m2	
	wind energy=	**1.11E+11**	J/yr	=density*(velocity^3)*drag coefficient*area*3.15e17sec/yr

3	**RAIN CHEMICAL POTENTIAL**			
	annual precip. (OCS)	1.07E+00	m/yr	
	Gibbs Free Energy of rainwater	4.94E+00	J/g	
	chem pot. energy:	**3.63E+11**	=rainfall*gibbs free energy*area	
4	**RAIN NITROGEN**			
	avg. N concentration (Castro et al., 2007)	1.74E+00	mg/L	
	annual precip.	1.07E+03	mm/yr	
	N energy	**1.28E+05**	J	=avg. N conc.*annual precip.*unit conv.*area
5	**RAIN PHOSPHORUS**			
	assumed to be	7.00E-02	mg/L	
	annual precip	1.07E+00	m/yr	
	P energy	**5.15E+03**	J	=avg. conc.*annual precip.*unit conv.*area transformity from Brandt-Williams (2002)
6	**RAIN ORGANIC MATTER**			
	assumed to be	1.00E+00	mg/L	
	energy content	4	kcal/g	
	annual precip	1.066	m/yr	
	OM energy in rain	**1.23E+09**	J	=avg. conc.*annual precip.*unit conv.*area
7	**ET, River and Volunteer Wetland**	1.422	m/yr	river
	agriweather.mesonet.org, miami ET	1.097	m/yr	volunteer wetland
	ET energy	**4.6E+11**	J	=evap*10^6 g/m3 * 4.94 J/g*area
8	**Env. Resources and WW: total emergy of each of these sources is only the largest emergy inflow (ET and ww N, respectively)**			
9	**AMD Chemical Potential**			
	design flow	7	L/s	
	gibbs free energy H2O	5	J/g	
	ww chem pot. energy	**1.1E+12**	=flow*gibbs free energy*1000 g/L * 86400 sec/day * 365 day/yr	
10	**AMD Al**			
	Al concentration	0.097	mg/L	(Nairn, 2009)
	flow	7	L/s	
	AMD Al mass	**2.1E+04**	g/yr	=Al conc*flow/1000 g/mg*86400 s/d * 365 d/yr
11	**ADM As**			
	As concentration	0.0633	mg/L	(Nairn, 2009)
	flow	7	L/s	
	AMD As mass	**1.4E+04**	g/yr	=As conc*flow/1000 g/mg*86400 s/d * 365 d/yr

12	**AMD Cd**			
	Cd conc.	0.018	mg/L	(Nairn, 2009)
	flow	7	L/s	
				=Cd conc*flow/1000
	AMD Cd mass	**3.9E+03**	g/yr	g/mg*86400 s/d * 365 d/yr
13	**AMD Ca**			
	Ca conc.	735.500	mg/L	(Nairn, 2009)
	flow	7	L/s	
				=Ca conc*flow/1000
	AMC Ca mass	**1.6E+08**	g/yr	g/mg*86400 s/d * 365 d/yr
14	**AMD Cr**			
	Cr conc.	0.002	mg/L	(Nairn, 2009)
	flow	7	L/s	
				=Cr conc*flow/1000
	AMD Cr mass	**4.3E+02**	g/yr	g/mg*86400 s/d * 365 d/yr
15	**AMD Cu**			
	Cu conc.	0.003	mg/L	(Nairn, 2009)
	flow	7	L/s	
				=Cu conc*flow/1000
	AMD Cu mass	**6.3E+02**	g/yr	g/mg*86400 s/d * 365 d/yr
16	**AMD Fe**			
	Fe conc.	178.194	mg/L	(Nairn, 2009)
	flow	7	L/s	
				=Fe conc*flow/1000
	AMD Fe mass	**3.9E+07**	g/yr	g/mg*86400 s/d * 365 d/yr
17	**AMD Mg**			
	Mg conc.	201.048	mg/L	(Nairn, 2009)
	flow	7	L/s	
				=Mg conc*flow/1000
	AMD Mg mass	**4.4E+07**	g/yr	g/mg*86400 s/d * 365 d/yr
18	**AMD Mn**			
	Mn conc.	1.512	mg/L	(Nairn, 2009)
	flow	7	L/s	
				=Mn conc*flow/1000
	AMD Mn mass	**3.3E+05**	g/yr	g/mg*86400 s/d * 365 d/yr
19	**AMD Ni**			
	Ni conc.	0.947	mg/L	(Nairn, 2009)
	flow	7	L/s	
				=Ni conc*flow/1000
	AMD Ni mass	**2.1E+05**	g/yr	g/mg*86400 s/d * 365 d/yr
20	**AMD Pb**			
	Pb conc.	0.066	mg/L	(Nairn, 2009)
	flow	7	L/s	
				=Pb conc*flow/1000
	AMD Pb mass	**1.5E+04**	g/yr	g/mg*86400 s/d * 365 d/yr

21	**AMD Zn**			
	Zn conc.	8.273	mg/L	(Nairn, 2009)
	flow	7	L/s	
				=Zn conc*flow/1000
	AMD Zn mass	**1.8E+06**	g/yr	g/mg*86400 s/d * 365 d/yr
22	**Env. Resources and WW: total emergy of each of these sources is only the largest emergy inflow ET and ww N, respectively)**			
23	**TOTAL EMERGY**			
	sum of environmental resources, WW, and total goods and services			
24	**Background Chemical Potential**			
	design flow	7	L/s	
	gibbs free energy	5	J/g	
				=flow*gibbs free energy*1000 g/L * 86400
	ww chem pot. energy	**1.1E+12**	sec/day * 365 day/yr	
25	**Background Al**			
	Al concentration	0.30754709	mg/L	(Nairn, 2009)
	flow	7	L/s	
				=Al conc*flow/1000
	AMD Al mass	**6.7E+04**	g/yr	g/mg*86400 s/d * 365 d/yr
26	**Background As**			(Nairn, 2009)
	As concentration	0.0000	mg/L	
	flow	7	L/s	
				=As conc*flow/1000
	AMD As mass	**0.0E+00**	g/yr	g/mg*86400 s/d * 365 d/yr
27	**Background Cd**			(Nairn, 2009)
	Cd conc.	0.001	mg/L	
	flow	7	L/s	
				=Cd conc*flow/1000
	AMD Cd mass	**2.5E+02**	g/yr	g/mg*86400 s/d * 365 d/yr
28	**Background Ca**			
	Ca conc.	53.978	mg/L	(Nairn, 2009)
	flow	7	L/s	
				=Ca conc*flow/1000
	AMD Ca mass	**1.2E+07**	g/yr	g/mg*86400 s/d * 365 d/yr
29	**Background Cr**			
	Cr conc.	0.001779811	mg/L	(Nairn, 2009)
	flow	7	L/s	
				=Cr conc*flow/1000
	AMD Cr mass	**3.9E+02**	g/yr	g/mg*86400 s/d * 365 d/yr
30	**Background Cu**			
	Cu conc.	0.004400755	mg/L	(Nairn, 2009)
	flow	7	L/s	
				=Cu conc*flow/1000
	AMD Cu mass	**9.6E+02**	g/yr	g/mg*86400 s/d * 365 d/yr

31	**Background Fe**			
	Fe conc.	0.527169353	mg/L	(Nairn, 2009)
	flow	7	L/s	
				=Fe conc*flow/1000
	AMD Fe mass	**1.2E+05**	g/yr	g/mg*86400 s/d * 365 d/yr
32	**Background Mg**			
	Mg conc.	5.214897569	mg/L	(Nairn, 2009)
	flow	7	L/s	
				=Mg conc*flow/1000
	AMD Mg mass	**1.1E+06**	g/yr	g/mg*86400 s/d * 365 d/yr
33	**Background Mn**			
	Mn conc.	0.203497765	mg/L	(Nairn, 2009)
	flow	7	L/s	
				=Mn conc*flow/1000
	AMD Mn mass	**4.5E+04**	g/yr	g/mg*86400 s/d * 365 d/yr
34	**Background Ni**			
	Ni conc.	0.014503796	mg/L	(Nairn, 2009)
	flow	7	L/s	
				=Ni conc*flow/1000
	AMD Ni mass	**3.2E+03**	g/yr	g/mg*86400 s/d * 365 d/yr
35	**Background Pb**			
	Pb conc.	0.030	mg/L	(Nairn, 2009)
	flow	7	L/s	
				=Pb conc*flow/1000
	AMD Pb mass	**6.6E+03**	g/yr	g/mg*86400 s/d * 365 d/yr
36	**Background Zn**			
	Zn conc.	0.033280186	mg/L	(Nairn, 2009)
	flow	7	L/s	
				=Zn conc*flow/1000
	AMD Zn mass	**7.3E+03**	g/yr	g/mg*86400 s/d * 365 d/yr

37 Total Emergy Outputs= effluent outputs

Table A2. Emergy analysis table for *ATS* Scenario for Acid Mine Drainage. This 0.5-ha treatment system was evaluated on a yearly basis with purchased and renewable inputs to the system and receiving environment. The receiving environment was approximately 7.6 ha. Significant figures kept for accounting purposes.

#	Item	Unit/yr	Amount Per year	Solar Transformity (sej/unit)	Ref. for Transf.	Solar Emergy (sej/yr) E12
	ENVIRONMENTAL INPUTS TO TREATMENT SYSTEM					
1a	Sunlight	J	2.88E+13	1.00E+00	By Definition	29
2a	Wind	J	8.06E+09	1.50E+03	Odum 1996	12
3a	Rain Chemical Potential	J	2.63E+10	3.06E+04	Odum 1996	806
4a	Rain Nitrogen	g	9.27E+03	2.41E+10	Brandt-William 2002	224
5a	Rain Phosphorus	g	3.73E+02	2.20E+10	Brandt-Williams 2002	8
6a	Rain OM	J	8.92E+07	3.19E+04	Brown & Bardi 2001	3
7a	ET	J	2.71E+10	3.06E+04	Odum 1996	829
8a	*Emergy of Env. Inputs to System*					*829*
	ENVIRONMENTAL INPUTS TO RECEIVING ENVIRONMENT					
1b	Sunlight	J	2.87E+14	1.00E+00	By Definition	287
2b	Wind	J	8.03E+10	1.50E+03	Odum 1996	120
3b	Rain Chemical Potential	J	2.62E+11	3.06E+04	Odum 1996	8,030
4b	Rain Nitrogen	g	9.24E+04	2.41E+10	Brandt-William 2002	2,227
5b	Rain Phosphorus	g	3.72E+03	2.20E+10	Brandt-Williams 2002	82
6b	Rain OM	J	8.89E+08	3.19E+04	Brown & Bardi 2001	28
7b	ET	J	3.50E+11	3.06E+04	Odum 1996	10,711
8b	*Emergy of Env. Inputs to Rec. Env.*					*10,711*
	INFLUENT MINE DRAINAGE FROM SEEPS					
9	AMD Chemical Potential	J	1.08E+12	4.85E+04	Odum 1996	52,463
10	AMDin Al	g	2.13E+04	1.44E+09	Odum et al. 1987a	31
11	AMDin As	g	1.39E+04	1.54E+09	Odum et al. 1987a	21
12	AMDin Cd	g	3.87E+03	1.54E+09	Odum et al. 1987a	6
13	AMDin Ca	g	1.61E+08	1.68E+09	Odum 1996	270,568
14	AMDin Cr	g	4.27E+02	1.54E+09	Odum et al. 1987a	1
15	AMDin Cu	g	6.31E+02	3.36E+09	Brown & Ulgiati 2004	2
16	AMDin Fe	g	3.90E+07	2.05E+09	Buranakarn 1998	79,989
17	AMDin Mg	g	4.40E+07	1.68E+09	Odum 1996	73,959
18	AMDin Mn	g	3.31E+05	1.14E+11	Odum 1996	37,755
19	AMDin Ni	g	2.07E+05	1.54E+09	Odum et al. 1987a	319
20	AMDin Pb	g	1.45E+04	1.54E+09	Odum et al. 1987a	22
21	AMDin Zn	g	1.81E+06	7.56E+09	Odum 1996	13,694
22	*Emergy of AMD*					*528,831*

	GOODS					
23	Concrete	g	2.51E+08	1.15E+10	Odum 1996	2,889,395
24	PVC	g	1.05E+06	9.90E+09	Buranakarn 1998	10,347
25	Steel	g	1.20E+05	2.99E+09	Odum 1996	359
26	Machinery	g	1.60E+05	1.13E+10	Odum et al 1987b	1,808
27	Pumps	g	1.60E+04	1.10E+10	Arias & Brown 2009	176
28	Lime	g	1.78E+08	1.13E+07	Odum et al 1995	2,013
29	KMnO4	g	3.71E+07	4.97E+09	Brown & Arding 1991	184,529
	PURCHASED SERVICES					
30	Electricity	J	3.65E+10	2.92E+05	Odum 1996	10,670
31	Labor	hrs/ha	2.79E+03	1.06E+12	Odum 1996	2,957
32	*Total Emergy of Goods and Services*					*3,102,253*
	Total Emergy					
33	**Inputs**					**3,641,795**
	EFFLUENT AMD					
34	Effluent Chemical Potential	J	1.07E+12	4.85E+04	Odum 1996	51,783
35	Effluent Al	g	6.65E+04	1.44E+09	Odum et al. 1987a	95
36	Effluent As	g	0.00E+00	1.54E+09	Odum et al. 1987a	0
37	Effluent Cd	g	2.47E+02	1.54E+09	Odum et al. 1987a	0
38	Effluent Ca	g	1.17E+07	1.68E+09	Odum 1996	19,599
39	Effluent Cr	g	3.85E+02	1.54E+09	Odum et al. 1987a	1
40	Effluent Cu	g	9.51E+02	3.36E+09	Brown & Ulgiati 2004	3
41	Effluent Fe	g	1.14E+05	2.05E+09	Buranakarn 1998	234
42	Effluent Mg	g	1.13E+06	1.68E+09	Odum 1996	1,894
43	Effluent Mn	g	4.40E+04	1.14E+11	Odum 1996	5,014
44	Effluent Ni	g	3.13E+03	1.54E+09	Odum et al. 1987a	5
45	Effluent Pb	g	6.56E+03	1.54E+09	Odum et al. 1987a	10
46	Effluent Zn	g	7.19E+03	7.56E+09	Odum 1996	54
47	*Emergy of* Effluent					*78,692*
	MD AT BACKGROUND LEVELS					
48	Background Al	g	1.65E+04	1.44E+09	Odum et al. 1987a	24
49	Background As	g	0.00E+00	1.54E+09	Odum et al. 1987a	0
50	Background Cd	g	0.00E+00	1.54E+09	Odum et al. 1987a	0
51	Background Ca	g	1.59E+08	1.68E+09	Odum 1996	266,425
52	Background Cr	g	3.86E+02	1.54E+09	Odum et al. 1987a	1
53	Background Cu	g	5.53E+02	3.36E+09	Brown &Ulgiati 2004	2
54	Background Fe	g	1.37E+05	2.05E+09	Buranakarn 1998	280
55	Background Mg	g	4.32E+07	1.68E+09	Odum 1996	72,590
56	Background Mn	g	3.10E+05	1.14E+11	Odum 1996	35,345
57	Background Ni	g	8.30E+03	1.54E+09	Odum et al. 1987a	13
58	Background Pb	g	0.00E+00	1.54E+09	Odum et al. 1987a	0
59	Background Zn	g	2.35E+04	7.56E+09	Odum 1996	177
60	*Emergy of MD at Reference Levels*					*374,856*

CALCULATIONS FOR TABLE A2:

			Env. Loading Area (m2)	PTS Area (m2)	
			38959		5000
	area:	43959	m2		
	AMD Flow	7	L/s		
	lifespan:	25	yrs		
1	**SUNLIGHT ATS**				
	mean annual solar radiation	15.8	MJ/m2/day	Average in Ottawa Co. (OCS)	
	conversion	3.65E+02	day/yr		
	Solar Energy (J/yr)	(15.8 MJ/m2/day)*(365day/yr)*area			
		2.88E+13	J/yr		
1b	**SUNLIGHT RIVER**				
	mean annual solar radiation	15.8	MJ/m2/day	Average in Ottawa Co. (OCS)	
	conversion	3.65E+02	day/yr		
	Solar Energy (J/yr)	(15.8 MJ/m2/day)*(365day/yr)*area			
	energy	**2.25E+14**	J/yr		
2a	**WIND KINETIC ENERGY ATS**				
	mean annual wind speed (OCS for ottawa co.)	3.40E+00	m/s		
	density of air	1.30E+00	kg/m3		
	drag coefficient	1.00E-03			
	area	5.00E+03	m2		
	wind energy=	**8.06E+09**	J/yr	=density*(velocity^3)*drag coefficient*area*3.15e17sec/yr	
2b	**WIND KINETIC ENERGY river**				
	mean annual wind speed (OCS for ottawa co.)	3.40E+00	m/s		
	density of air	1.30E+00	kg/m3		
	drag coefficient	1.00E-03			
	area	3.90E+04	m2		
	wind energy=	**6.28E+10**	J/yr	=density*(velocity^3)*drag coefficient*area*3.15e17sec/yr	
3a	**RAIN CHEMICAL POTENTIAL ats**				
	annual precip. (OCS)	1.07E+00	m/yr		
	Gibbs Free Energy of rainwater	4.94E+00	J/g		
	chem pot. energy:	**2.63E+10**	=rainfall*gibbs free energy*area		
3b	**RAIN CHEMICAL POTENTIAL river**				
	annual precip. (weather.com)	1.07E+00	m/yr		
	Gibbs Free Energy of rainwater	4.94E+00	J/g		
	chem pot. energy:	**2.05E+11**	=rainfall*gibbs free energy*area		

4a	**RAIN NITROGEN ATS**			
	avg. N concentration (Castro et al., 2007)	1.74E+00	mg/L	
	annual precip.	1.07E+03	mm/yr	
	N energy	**9.27E+03**	J	
4b	**RAIN NITROGEN river**			
	avg. N concentration (Castro et al., 2007)	1.74E+00	mg/L	
	annual precip.	1.07E+03	mm/yr	
	N energy	**7.23E+04**	J	=avg. N conc.*annual precip.*unit conv.*area
5a	**RAIN PHOSPHORUS ATS**			
	assumed to be	7.00E-02	mg/L	
	annual precip	1.07E+00	m/yr	
	P energy	**3.73E+02**	J	=avg. conc.*annual precip.*unit conv.*area
5b	**RAIN PHOSPHORUS river**			
	assumed to be	7.00E-02	mg/L	
	annual precip	1.07E+00	m/yr	
	P energy	**2.91E+03**	J	=avg. conc.*annual precip.*unit conv.*area transformity from Brandt-Williams (2002)
6a	**RAIN ORGANIC MATTER**			
	assumed to be	1.00E+00	mg/L	
	energy content	4	kcal/g	
	annual precip	1.066	m/yr	
	OM energy in rain	**8.92E+07**	J	=avg. conc.*annual precip.*unit conv.*area
6b	**RAIN ORGANIC MATTER**			
	assumed to be	1.00E+00	mg/L	
	energy content	4	kcal/g	
	annual precip	1.066	m/yr	
	OM energy in rain	**6.95E+08**	J	=avg. conc.*annual precip.*unit conv.*area
7a	**ET, ATS**			
	agriweather.mesonet.org, miami ET	1097	mm/yr	
	ET energy	**2.7E+10**	J	=evap*10^6 g/m3 * 4.94 J/g*area
7b	**ET, Receiving river**			
	agriweather.mesonet.org, miami pan evap.	1422	mm/yr	
	ET energy	**2.7E+11**	J	=evap*10^6 g/m3 * 4.94 J/g*area
8	**Env. Resources and WW: total emergy of each of these sources is only the largest emergy inflow (rain chemical potential and ww N)**			
	9 – 21: Same as Calculations for Table A1			
22	**Env. Resources and WW: total emergy of each of these sources is only the largest emergy inflow (rain chemical potential and ww N)**			

23	**CONCRETE**			
	concrete used	2731	m3	
	concrete density	2300000	g/m3	
	lifetime	25	yrs	
	concrete mass/yr	**2.5E+08**	g	=concrete vol*density/lifetime
24	**PVC**			
	amt	19	m3	
	density	1.4E+03	kg/m3	
	pvc mass/yr	**1045105**	g/yr	=pvc vol.*density*1000g/kg/lifetime
25	**STEEL**			
	amt used	3000000	g	
	steel mass/yr	**120000**	g/yr	=steel mass/lifetime
26	**MACHINERY**			
	machinery mass used	4000000	g	
	machinery mass/yr	**160000**	g/yr	=machinery mass/yr
27	**PUMP**			
	pumps used	400000	g	
	pump mass/yr	**16000**	g/yr	=pump mass/yr
28	**LIME**			
	hydrated lime added	**178133300**	g/yr	
29	**KMnO4**			
	pot perm added	**37128532**	g/yr	
30	**ELECTRICITY**			
	amt. used	**36540000000**	J/yr	
31	**LABOR**			
	labor hours	**2789**	hrs/ha/yr	=crew number*work days/area/*10hrs/day/lifetime
32	**TOTAL EMERGY OF GOODS AND SERVICES**			
	largest of goods and services			
33	**TOTAL EMERGY**			
	sum of environmental resources, WW, and total goods and services			
	EFFLUENT EMERGY IN AMD			
34	**Effluent AMD Chemical Potential**			
	design flow	6.85344	L/s	
	gibbs free energy	5	J/g	
	ww chem pot. energy	**1.1E+12**		=flow*gibbs free energy*1000 g/L * 86400 sec/day * 365 day/yr
35	**Effluent AMD Al**			
	Al concentration	0.076297133	mg/L	
	flow	7	L/s	

	AMD Al mass	**1.6E+04**	g/yr	=Al conc*flow/1000 g/mg*86400 s/d * 365 d/yr
36	**Effluent ADM As**			
	As concentration	0.0000	mg/L	
	flow	7	L/s	
	AMD As mass	**0.0E+00**	g/yr	=As conc*flow/1000 g/mg*86400 s/d * 365 d/yr
37	**Effluent AMD Cd**			
	Cd conc.	0.000	mg/L	
	flow	7	L/s	
	AMD Cd mass	**0.0E+00**	g/yr	=Cd conc*flow/1000 g/mg*86400 s/d * 365 d/yr
38	**Effluent AMD Ca**			
	Ca conc.	733.753	mg/L	
	flow	7	L/s	
	AMD Ca mass	**1.6E+08**	g/yr	=Ca conc*flow/1000 g/mg*86400 s/d * 365 d/yr
39	**Effluent AMD Cr**			
	Cr conc.	0.001786698	mg/L	
	flow	7	L/s	
	AMD Cr mass	**3.9E+02**	g/yr	=Cr conc*flow/1000 g/mg*86400 s/d * 365 d/yr
40	**Effluent AMD Cu**			
	Cu conc.	0.00255806	mg/L	
	flow	7	L/s	
	AMD Cu mass	**5.5E+02**	g/yr	=Cu conc*flow/1000 g/mg*86400 s/d * 365 d/yr
41	**Effluent AMD Fe**			
	Fe conc.	0.63235306	mg/L	
	flow	7	L/s	
	AMD Fe mass	**1.4E+05**	g/yr	=Fe conc*flow/1000 g/mg*86400 s/d * 365 d/yr
42	**Effluent AMD Mg**			
	Mg conc.	199.9189257	mg/L	
	flow	7	L/s	
	AMD Mg mass	**4.3E+07**	g/yr	=Mg conc*flow/1000 g/mg*86400 s/d * 365 d/yr
43	**Effluent AMD Mn**			
	Mn conc.	1.434522649	mg/L	
	flow	7	L/s	
	AMD Mn mass	**3.1E+05**	g/yr	=Mn conc*flow/1000 g/mg*86400 s/d * 365 d/yr
44	**Effluent AMD Ni**			
	Ni conc.	0.038382197	mg/L	
	flow	7	L/s	
	AMD Ni mass	**8.3E+03**	g/yr	=Ni conc*flow/1000 g/mg*86400 s/d * 365 d/yr

45	**Effluent AMD Pb**			
	Pb conc.	0.000	mg/L	
	flow	7	L/s	
	AMD Pb mass	**0.0E+00**	g/yr	=Pb conc*flow/1000 g/mg*86400 s/d * 365 d/yr
46	**Effluent AMD Zn**			
	Zn conc.	0.10853059	mg/L	
	flow	7	L/s	
	AMD Zn mass	**2.3E+04**	g/yr	=Zn conc*flow/1000 g/mg*86400 s/d * 365 d/yr
47	Emergy of Effluent = Sum of effluent terms			

48-60: Same as Calculations for Table A1

Table A3. Emergy analysis table for *PTS* Scenario for Acid Mine Drainage. This 2.7-ha treatment system was evaluated on a yearly basis with purchased and renewable inputs to the system and receiving environment. The receiving environment was approximately 7.5 ha. Significant figures kept for accounting purposes.

#	Item	Unit/yr	Amount Per year	Solar Transformity (sej/unit)	Ref. for Transf.	Solar Emergy (sej/yr) E12
	ENVIRONMENTAL INPUTS TO SYSTEM					
1a	Sunlight	J	1.56E+14	1.00E+00	By Definition	156
2a	Wind	J	4.35E+10	1.50E+03	Odum, 1996	65
3a	Rain Chemical Potential	J	1.42E+11	3.06E+04	Odum 1996	4,351
4a	Rain Nitrogen	g	5.01E+04	2.41E+10	Brandt-William 2002	1,207
5a	Rain Phosphorus	g	2.01E+03	2.20E+10	Brandt-Williams 2002	44
6a	Rain OM	J	4.82E+08	3.19E+04	Brown & Bardi 2001	15
7a	ET	J	1.46E+11	3.06E+04	Odum 1996	4,477
8a	*Emergy of Env. Inputs to System*					*4,477*
	ENVIRONMENTAL INPUTS TO RECEIVING ENVIRONMENT					
1b	Sunlight	J	2.87E+14	1.00E+00	By Definition	287
2b	Wind	J	8.03E+10	1.50E+03	Odum 1996	120
3b	Rain Chemical Potential	J	2.62E+11	3.06E+04	Odum 1996	8,030
4b	Rain Nitrogen	g	9.24E+04	2.41E+10	Brandt-William 2002	2,227
5b	Rain Phosphorus	g	3.72E+03	2.20E+10	Brandt-Williams 2002	82
6b	Rain OM	J	8.89E+08	3.19E+04	Brown & Bardi 2001	28
7b	ET	J	3.50E+11	3.06E+04	Odum 1996	10,711
8b	*Emergy of Env. Inputs to Receiving Env.*					*10,711*
	INFLUENT MINE DRAINAGE FROM SEEPS					
9	AMD Chemical Potential	J	1.08E+12	4.85E+04	Odum 1996	52,463
10	AMDin Al	g	2.13E+04	1.44E+09	Odum et al. 1987a	31
11	AMDin As	g	1.39E+04	1.54E+09	Odum et al. 1987a	21
12	AMDin Cd	g	3.87E+03	1.54E+09	Odum et al. 1987a	6
13	AMDin Ca	g	1.61E+08	1.68E+09	Odum 1996	270,568
14	AMDin Cr	g	4.27E+02	1.54E+09	Odum et al. 1987a	1
15	AMDin Cu	g	6.31E+02	3.36E+09	Brown & Ulgiati 2004	2
16	AMDin Fe	g	3.90E+07	2.05E+09	Buranakarn 1998	79,989
17	AMDin Mg	g	4.40E+07	1.68E+09	Odum 1996	73,959
18	AMDin Mn	g	3.31E+05	1.14E+11	Odum 1996	37,755
19	AMDin Ni	g	2.07E+05	1.54E+09	Odum et al. 1987a	319
20	AMDin Pb	g	1.45E+04	1.54E+09	Odum et al. 1987a	22
21	AMDin Zn	g	1.81E+06	7.56E+09	Odum 1996	13,694
22	*Emergy of MD*					*528,831*

	GOODS					
23	Seedlings	J	4.82E+06	5.80E+04	Odum 1996	0
24	Limestone	g	1.27E+08	2.10E+09	Odum 1996	266,166
25	Geotextile Liner	g	1.57E+05	8.50E+09	Buranakarn 1998	1,335
26	Concrete	g	3.70E+04	1.15E+10	Odum 1996	426
27	PVC	g	2.24E+03	9.90E+09	Buranakarn 1998	22
28	Valves	g	1.36E+05	2.99E+09	Odum 1996	405
29	Agridrains	g	8.80E+04	1.13E+10	Odum et al. 1987b	991
30	Solar Aerator	g	2.75E+04	1.13E+10	Odum et al. 1987b	310
31	Windmill Aerator	g	2.61E+04	1.13E+10	Odum et al. 1987b	294
32	Lumber	g	2.55E+04	1.48E+09	Buranakarn 1998	38
33	Drain/Seep/Inflow Metal Pipes	g	1.52E+04	2.99E+09	Odum 1996	46
34	Compost	J	1.02E+11	3.02E+06	Ortega 1998	307,595
	PURCHASED SERVICES					
35	Construction Labor	hr	1.41E+02	1.06E+12	Odum 1996	149
36	*Total Emergy of Goods and Services*					*577,776*
37	**Total Emergy Inputs**					**1,117,317**
	EFFLUENT AMD					
38	Effluent Chemical Potential	J	1.07E+12	4.85E+04	Odum 1996	51,783
39	Effluent Al	g	1.65E+04	1.44E+09	Odum et al. 1987a	24
40	Effluent Al	g	0.00E+00	1.54E+09	Odum et al. 1987a	0
41	Effluent Al	g	0.00E+00	1.54E+09	Odum et al. 1987a	0
42	Effluent Al	g	1.59E+08	1.68E+09	Odum 1996	266,425
43	Effluent Al	g	3.86E+02	1.54E+09	Odum et al. 1987a	1
44	Effluent Al	g	5.53E+02	3.36E+09	Brown & Ulgiati 2004	2
45	Effluent Al	g	1.37E+05	2.05E+09	Buranakarn 1998	280
46	Effluent Al	g	4.32E+07	1.68E+09	Odum 1996	72,590
47	Effluent Al	g	3.10E+05	1.14E+11	Odum 1996	35,345
48	Effluent Al	g	8.30E+03	1.54E+09	Odum et al. 1987a	13
49	Effluent Al	g	0.00E+00	1.54E+09	Odum et al. 1987a	0
50	Effluent Al	g	2.35E+04	7.56E+09	Odum 1996	177
51	*Emergy of MDout*					*426,639*
	MD AT BACKGROUND LEVELS					
52	Background Al	g	6.65E+04	1.44E+09	Odum et al. 1987a	95
53	Background As	g	0.00E+00	1.54E+09	Odum et al. 1987a	0
54	Background Cd	g	2.47E+02	1.54E+09	Odum et al. 1987a	0
55	Background Ca	g	1.17E+07	1.68E+09	Odum 1996	19,599
56	Background Cr	g	3.85E+02	1.54E+09	Odum et al. 1987a	1
57	Background Cu	g	9.51E+02	3.36E+09	Brown & Ulgiati 2004	3
58	Background Fe	g	1.14E+05	2.05E+09	Buranakarn 1998	234
59	Background Mg	g	1.13E+06	1.68E+09	Odum 1996	1,894
60	Background Mn	g	4.40E+04	1.14E+11	Odum 1996	5,014
61	Background Ni	g	3.13E+03	1.54E+09	Odum et al. 1987a	5
62	Background Pb	g	6.56E+03	1.54E+09	Odum et al. 1987a	10
63	Background Zn	g	7.19E+03	7.56E+09	Odum 1996	54
64	*Emergy of MD at* Background *Levels*					*26,909*

CALCULATIONS FOR TABLE A3:

			Env. Loading Area (m2)	PTS Area (m2)	
			38959		5000
	area:	43959	m2		
	AMD Flow	7	L/s		
	lifespan:	25	yrs		
1	**SUNLIGHT PTS**				
	mean annual solar radiation	15.8	MJ/m2/day	Average in Ottawa Co. (OCS)	
	conversion	3.65E+02	day/yr		
	Solar Energy (J/yr)	(15.8 MJ/m2/day)*(365day/yr)*area			
		2.88E+13	J/yr		
1b	**SUNLIGHT RIVER**				
	mean annual solar radiation	15.8	MJ/m2/day	Average in Ottawa Co. (OCS)	
	conversion	3.65E+02	day/yr		
	Solar Energy (J/yr)	(15.8 MJ/m2/day)*(365day/yr)*area			
	energy	**2.25E+14**	J/yr		
2a	**WIND KINETIC ENERGY PTS**				
	mean annual wind speed (OCS for ottawa co.)	3.40E+00	m/s		
	density of air	1.30E+00	kg/m3		
	drag coefficient	1.00E-03			
	area	5.00E+03	m2		
	wind energy=	**8.06E+09**	J/yr	=density*(velocity^3)*drag coefficient* area*3.15e17sec/yr	
2b	**WIND KINETIC ENERGY river**				
	mean annual wind speed (OCS for ottawa co.)	3.40E+00	m/s		
	density of air	1.30E+00	kg/m3		
	drag coefficient	1.00E-03			
	area	3.90E+04	m2		
	wind energy=	**6.28E+10**	J/yr	=density*(velocity^3)*drag coefficient* area*3.15e17sec/yr	
	RAIN CHEMICAL POTENTIAL				
3a	**pts**				
	annual precip. (OCS)	1.07E+00	m/yr		
	Gibbs Free Energy of rainwater	4.94E+00	J/g		
	chem pot. energy:	**2.63E+10**	=rainfall*gibbs free energy*area		
	RAIN CHEMICAL POTENTIAL				
3b	**river**				
	annual precip. (weather.com)	1.07E+00	m/yr		
	Gibbs Free Energy of rainwater	4.94E+00	J/g		
	chem pot. energy:	**2.05E+11**	=rainfall*gibbs free energy*area		

	RAIN NITROGEN			
4a	**wwtp**			
	avg. N concentration (Castro et al., 2007)	1.74E+00	mg/L	
	annual precip.	1.07E+03	mm/yr	
	N energy	**9.27E+03**	J	
	RAIN NITROGEN			
4b	**river**			
	avg. N concentration (Castro et al., 2007)	1.74E+00	mg/L	
	annual precip.	1.07E+03	mm/yr	
	N energy	**7.23E+04**	J	=avg. N conc.*annual precip.*unit conv. *area
	RAIN PHOSPHORUS			
5a	**wwtp**			
	assumed to be	7.00E-02	mg/L	
	annual precip	1.07E+00	m/yr	
	P energy	**3.73E+02**	J	=avg. conc.*annual precip.*unit conv.* area
	RAIN PHOSPHORUS			
5b	**river**			
	assumed to be	7.00E-02	mg/L	
	annual precip	1.07E+00	m/yr	
	P energy	**2.91E+03**	J	=avg. conc.*annual precip.*unit conv.* area
				transformity from Brandt-Williams (2002)
	RAIN ORGANIC			
6a	**MATTER**			
	assumed to be	1.00E+00	mg/L	
	energy content	4	kcal/g	
	annual precip	1.066	m/yr	
	OM energy in rain	**8.92E+07**	J	=avg. conc.*annual precip.*unit conv.* area
	RAIN ORGANIC			
6b	**MATTER**			
	assumed to be	1.00E+00	mg/L	
	energy content	4	kcal/g	
	annual precip	1.066	m/yr	
	OM energy in rain	**6.95E+08**	J	=avg. conc.*annual precip.*unit conv.* area
7a	**ET, ATS**			
	agriweather.mesonet.org, miami ET	1097	mm/yr	
	ET energy	**2.7E+10**	J	=evap*10^6 g/m3 * 4.94 J/g*area
7b	**ET, Receiving river**			
	agriweather.mesonet.org, miami pan evap.	1422	mm/yr	
	ET energy	**2.7E+11**	J	=evap*10^6 g/m3 * 4.94 J/g*area
8	**Env. Resources and WW: total emergy of each of these sources is only the largest emergy inflow (rain chemical potential and ww N)**			

9 – 21: Same as Calculations for Table A1

Env. Resources and WW: total emergy of each of these sources is only the largest
22 emergy inflow (rain chemical potential and ww N)

23	**SEEDLINGS**			
	Number of plugs	2160	cattail plugs	
	est. dry wt per plug	4	g/plug	
	lifetime	30	yrs	
	seedlings energy	**4.8E+06**	J	=standing biomass/lifetime*1000g/kg*1ha/1000m2* 4kcal/g*4184J/kcal
24	**LIMESTONE**			
	estimated limestone	2261	m3	
	lifetime	30	yr	
	limestone density	1682	kg/m3	
	limestone mass	**1.3E+08**	g	=estimated limestone*limestone density* 1000g/kg/lifetime
25	**GEOMEMBRANE**			
	HDPE	836	m2	
	density	1	g/cm3	
	geomembrane mass	**1.6E+05**	g	=surface area*thickness*100^3* density/lifetime
26	**CONCRETE**			
	concrete amt	0.4914	m3	
	density	2.3E+06	g/m3	
	concrete energy	**3.7E+04**	g	=amount*density/lifetime
27	**PVC**			
	amt	421	m	
	x-sectional area	0.01204	m2	
	density	1.4E+03	kg/m3	
	pvc energy	**2238**	g/yr	=amt*surface area*.25pi*density* 1000g/kg/lifetime
28	**VALVES**			
	number of 6"	12		
	mass per valve	338800	g	
	Valve mass	**135520**	g/yr	=mass of valves/lifetime
29	**AGRIDRAINS**			
	number of agridrains	12		
	mass per agridrain	220000	g	
	agridrain mass	**88000**	g/yr	=mass of agridrains/lifetime
30	**SOLAR AERATOR**			
	mass of solar aerator over lifetime	**27500**	g/yr	=mass of aerator/lifetime

	WINDMILL			
31	**AERATOR**			
	mass of windmill aerator over liftetime	**26107**	g/yr	=mass of aerator/lifetime
32	**LUMBER**			
	Number of 4"X4" at 16'	32		
	Number of 2"X4" at 12'	18	50930.994900	cm3
	grams of lumber	**25465**	g	=volume of lumber*density(0.5 g/cm3)
	DRAIN/SEEP/INFLOW			
33	**PIPES**			
	est. length of pipes	20	m	
	x-sect area	0.00291	m2	
	density	7.850	g/cm3	
	mass of pipes	**15240**	g/yr	=length of pipe*x-sect area* density/lifetime
34	**COMPOST**			
	volume of compost	535	m3	
	density of compost	341.0	kg/m3	typical mushroom compost density
	energy density	4	kcal/g	
	compost energy	**1.E+11**	J/yr	=mass of compost*energy density/lifetime
	CONSTRUCTION			
35	**LABOR**			
	avg crew no.	10		
	work days	114		
	labor hours	**141**	hrs/ha/yr	=crew number*work days/area/* 10hrs/day/lifetime
34	**COMPOST**			
	volume of compost	535	m3	
	density of compost	341.0	kg/m3	typical mushroom compost density
	energy density	4	kcal/g	
	compost energy	**1.E+11**	J/yr	=mass of compost*energy density/lifetime

36 TOTAL EMERGY OF GOODS AND SERVICES

largest of goods and services

37 TOTAL EMERGY INPUTS

sum of environmental resources, WW, and total goods and services

38-64: Same as Calculations for Table A2

Table A4. Emergy Evaluation of No Treatment Scenario for MWW (0.5 MGD, 20 L/s).

Ref. #	Item	Unit/yr	Amount Per year	Solar Transformity (sej/unit)	Ref. for Transf.	Solar Emergy (10^{12} sej/yr)
	Environmental inputs to receiving environment					
1	Sunlight	J	2.87E+16	1.00E+00	A	28,681
2	Wind	J	1.00E+13	1.50E+03	A	14,983
3	Rain Chemical Potential	J	2.25E+13	3.06E+04	A	689,167
4	Rain Nitrogen	g	7.93E+06	2.41E+10	B	191,180
5	Rain Phosphorus	g	3.19E+05	2.20E+10	B	7,021
6	Rain OM	J	7.63E+10	3.19E+04	C	2,434
7	ET	J	1.55E+13	3.06E+04	A	474,386
8	*Emergy of Env. Inputs to Receiving Environment (ENVload)*					*689,167*
	Influent wastewater					
9	WW Chem Potential	J	3.12E+12	3.06E+04	A	95,342
10	WW Nitrogen	g	2.21E+07	7.04E+09	B	155,409
11	WW Phos	g	4.42E+06	3.70E+10	B	163,356
12	WW OM	J	2.64E+12	3.19E+04	C	84,182
13	WW *E. coli*	g	2.11E+13	2.56E+02	D	5,405
14	*Emergy of WW*					*503,695*
15	**Total Emergy Inputs**					**1,192,862**
	Wastewater returned to environment at background levels					
16	Effluent Water Chem Pot.	J	3.12E+12	8.14E+04	A	253,657
17	Background N	g	9.46E+06	1.36E+10	E	128,743
18	Background P	g	3.15E+04	1.51E+09	E	48
19	Background OM	J	3.15E+06	1.05E+05	E	0
20	Background *E. coli*	J	4.22E+08	2.56E+02	D	0
21	**Total Outputs**					**382,448**

A) Odum, 1996; B) Brandt-Williams, 2002; C) Brown & Bardi, 2001; D) Odum, 2002; E) Brown & Arding, 1991

CALCULATIONS FOR TABLE A4

	Area:	411.84	ha	(Environmental receiving area)
	WW flow:	20	L/s	(residential community, population ~5,000; 1/2 mgd)
	ENERGY AND MATERIAL CALCULATIONS:			
1	**SUNLIGHT**			
	mean annual solar radiation	5.3	kWh/m2/day	Average solar energy in MD- http://energy.maryland.gov/facts/renewable/solar.asp
		3.6E+06		
	conversion	6	J/kWh	
	conversion	365	day/yr	
	Solar Energy (J/yr)	(5.3 kWh/m2/day)*(3600000 J/kWh)*(365day/yr)*area		
		2.9E+16	J/yr	
2	**WIND KINETIC ENERGY**			
	mean annual wind speed (NOAA)	4	m/s	
	density of air	1	kg/m3	
	drag coefficient	0		
		411840		
	area	0	m2	
		1.0E+13		=density*(velocity^3)*drag
	wind energy=	**3**	J	coefficient*area*86400 sec/day*365 day/yr
3	**RAIN CHEMICAL POTENTIAL**			
	Chemical potential: annual precip. (weather.com)	1	m/yr	
	Gibbs Free Energy of rainwater	5	J/g	
		2.3E+13		=rainfall*gibbs free energy*area*density of water (10^6
	chem pot. Energy:	**3**	g/m3)	
4	**RAIN NITROGEN:**			
	avg. N concentration (Castro et al., 2007)	2	mg/L	
	annual precip.	1107	mm/yr	
		7.9E+06		=avg. N conc.*annual precip.*unit
	N energy	**6**	g	conv.*area
5	**RAIN PHOSPHORUS**			
	assumed to be	0.07	mg/L	
	annual precip	1	m/yr	
		3.2E+05		
	P energy	**5**	g	=avg. conc.*annual precip.*unit conv.*area
6	**RAIN ORGANIC MATTER**			
	assumed to be	1	mg/L	

	energy content	4	kcal/g	
	annual precip	1	m/yr	
		7.6E+1		
	OM energy in rain	**0**	J	=avg. conc.*annual precip.*unit conv.*area
7	**ET**			
	est. MD mean annual total ET	762	mm/yr	
		1.6E+1		
	ET energy	**3**	J	=evap*10^6 g/m3 * 4.94 J/g*area
8	**Env. Resources and WW: total emergy of each of these sources is only the largest emergy inflow (rain chemical potential and ww N)**			
9	**WW CHEM. POTENTIAL**			
	design flow	20	L/s	
	gibbs free energy	5	J/g	
		3.1E+1		=flow*gibbs free energy*1000 g/L * 86400 sec/day * 365
	ww chem pot. energy	**2**	day/yr	
10	**WW NITROGEN**			
	nitrogen content	35	mg/L	
	flow	20	L/s	
		2.2E+0		=n conc*flow/1000 g/mg*86400 s/d * 365
	WW N energy	**7**	g/yr	d/yr
11	**WW NITROGEN**			
	phos content	7	mg/L	
	flow	20	L/s	
		4.4E+0		=p conc*flow/1000 g/mg*86400 s/d * 365
	WW P energy	**6**	g/yr	d/yr
12	**WW OM**			
	BOD	250	mg/L	
	energy in OM	4	kcal/g	transformity from Jorgensen, Odum, Brown 2004- Emergy and Exergy in Genetic Info
	flow	20	L/s	
		2.6E+1		=BOD*4kcal/g*4184J/kcal*flow/1000
	OM energy	**2**	J/yr	g/mg*86400 s/d * 365 d/yr
13	**WW FIB**			
	cell density	2.E-10	mg-COD/cell	(wet weight of E. coli, 9.6e-13 g) from Principles of Microbial Ecology, TD Brock
		1.0E+0		
	FIB conc. (TC)	7	cells/L	
	energy of biomass	4	kcal/g	
	flow	20	L/s	transformity derived
		2.1E+1		=TC density*TC conc.*energy content of biomass*conversion factor* 1000mg/g*flow*86400s/d*365d/yr * 4184
	FIB conc. Energy	**3**	g/yr	J/kcal

	Env. Resources and WW: total emergy of each of these sources is only the largest			
14	**emergy inflow (rain chemical potential and ww N)**			
15	**TOTAL EMERGY INPUTS**			
	sum of environmental resources, WW, and total goods and services			
16	**CHEMICAL POTENTIAL IN EFFLUENT**			
	gibbs free energy	5	J/g	
		3.1E+1		=flow*gibbs free energy* 1000g/L * 86400
	trt water chem pot.	**2**	J/yr	days*365 d/yr
17	**BACKGROUND N**			
	N in trt water	15	mg/L	
		9.5E+0		
	trted water N	**6**	g/yr	=flow*n conc/1000*86400*365
18	**BACKGROUND P**			
	flow	20	L/s	
	P in trt water	0.05	mg/L	
		3.2E+0		
	trt water P	**4**	g/yr	=flow*p conc/1000*86400*365
	BACKGROUND			
19	**OM**			
	flow	20	L/s	
	BOD	5	mg/L	
		3.2E+0		=flow*BOD/1000*86400sec/day*365day/y
	trt water OM energy	**6**	g/yr	r
	BACKGROUND E			
20	**coli**			
			mg-COD/cell	
	cell density	2.E-10		
		2.0E+0		
	E COLI conc.	2	cells/L	
	energy of biomass	4	kcal/g	
	flow	20	L/s	
				=TC density*TC conc.*energy content of
		4.2E+0		biomass*conversion factor*
	FIB conc. Energy	**8**	g/yr	1000mg/g*flow*86400s/d*365d/yr
	Total Emergy Outputs=sum of WW effluent			
21	**emergy**			

Table A5. Emergy evaluation of WWTP Treatment Scenario (0.5 MGD, 20 L/s).

Ref. #	Item	Unit/yr	Amount Per year	Solar Transformity (sej/unit)	Ref. for Transf.	Solar Emergy (10^{12} sej/yr)
	ENVIRONMENTAL INPUTS TO SYSTEM					
1	Sunlight	J	6.27E+13	1.00E+00	A	63
2	Wind	J	2.19E+10	1.50E+03	A	33
3	Rain Chemical Potential	J	4.92E+10	3.06E+04	A	1,506
4	Rain Nitrogen	g	1.73E+04	2.41E+10	B	418
5	Rain Phosphorus	g	6.97E+02	2.20E+10	B	15
6	Rain OM	J	1.67E+08	3.19E+04	C	5
7	ET	J	3.39E+10	3.06E+04	A	1,037
8	*Emergy of Env. Inputs to System (R)*					*1,506*
	ENVIRONMENTAL INPUTS TO RECEIVING ENVIRONMENT					
9	Sunlight	J	2.51E+16	1.00E+00	A	25,071
10	Wind	J	8.75E+12	1.50E+03	A	13,097
11	Rain Chemical Potential	J	1.97E+13	3.06E+04	A	602,419
12	Rain Nitrogen	g	6.93E+06	2.41E+10	B	167,115
13	Rain Phosphorus	g	2.79E+05	2.20E+10	B	6,137
14	Rain OM	J	6.67E+10	3.19E+04	C	2,128
15	ET	J	1.07E+13	3.06E+04	A	326,514
16	*Emergy of Env. Inputs to Receiving Environment (ENVload)*					*602,419*
	INFLUENT WASTEWATER					
17	WWin Chem Potential	J	3.12E+12	3.06E+04	A	95,342
18	WWin Nitrogen	g	2.21E+07	7.04E+09	B	155,409
19	Wwin Phos	g	4.42E+06	3.70E+10	B	163,356
20	WWin OM	J	2.64E+12	3.19E+04	C	84,182
21	WWin *E. coli*	g	2.11E+13	2.65E+02	D	5,595
22	*Emergy of WWin*					*503,885*
	GOODS					
23	Pumps	g	3.20E+04	1.13E+10	F	362
24	Steel	g	7.60E+06	2.94E+09	G	22,344
25	Concrete	g	1.46E+08	1.15E+10	A	1,684,152
26	PVC	g	1.36E+05	9.86E+09	H	1,337
27	Bricks	g	3.94E+03	3.68E+09	A	15

28	Gravel	g	1.33E+07	2.10E+09	I	27,975
29	Sand	g	2.44E+07	2.13E+09	I	51,866
	PURCHASED SERVICES					
30	Electricity	J	2.16E+12	2.92E+05	A	630,720
31	Operation Labor	$	6.79E+03	6.52E+12	J	44,292
32	*Emergy of Goods and Services (F)*					*2,463,063*
33	**Total Emergy Inputs**					**3,569,366**
	EFFLUENT WASTEWATER					
34	WWout Chem. Potential	J	3.12E+12	3.06E+04	A	95,342
35	WWout N	g	9.46E+06	7.04E+09	B	66,604
36	WWout P	g	1.89E+06	3.70E+10	B	70,010
37	WWout OM	J	3.17E+11	3.19E+04	C	10,102
38	WWout *E. coli*	J	2.11E+07	2.65E+02	D	0
39	*Emergy of WWout*					*242,058*
	WASTEWATER AT BACKGROUND LEVELS					
40	Background N	g	9.46E+06	1.36E+10	E	128,743
41	Background P	g	3.15E+04	1.51E+09	E	48
42	Background OM	J	5.28E+10	1.05E+05	E	5,533
43	Background *E. coli*	J	4.22E+02	2.65E+02	D	0
44	*Total Emergy of WW at background levels (returned to receiving environment)*					*229,665*
45	**Total Outputs**					**242,058**

A) Odum, 1996; B) Brandt-Williams, 2002; C) Brown & Bardi, 2001; D) Odum, 2002; E) Brown & Arding, 1991; F) Odum et al., 1987; G) Odum et al., 1983; H) Buranakarn, 1998; I) McGrane, 1994; J) Vivas, 2004.

CALCULATIONS FOR TABLE A5 (WWTP)

				Env. Loading Area (m2)	Treatment System Area (m2)
				3600000	9000
	Total area:	3.61E+06	m2		
	WW flow:	20	L/s		(residential community, population ~5,000; 1/2 mgd)
	lifespan	25	yrs		
	ENERGY AND MATERIAL CALCULATIONS:				
1-22	**Calculations same as "No Treatment Scenario"**				
23	**PUMPS**				
	#pumps	4.0E+00			
	weight per pump	2.0E+02	kg		
	lifespan of pump	2.5E+01	yrs		
	pump energy	**3.2E+04**	g/yr		=#pumps*mass/lifespan*1000g/kg
24	**STEEL**				
	amount used	1.9E+02	tons		
	lifespan	2.5E+01	yrs		
	steel energy	**7.6E+06**	g/yr		=amt of steel*10^6g/ton/lifespan
25	**CONCRETE**				
	amt used	1.6E+03	m3		
	density	2.3E+06	g/m3		
	lifespan	2.5E+01	yrs		
	concrete energy	**1.5E+08**	g/yr		=amt concrete*density of concrete/lifespan
26	**PVC**				
	amt used	1.0E+03	m		
	min. wall thickness	8.1E-03	m		minimum wall thickness of schedule 80 4" pipe
	radius	5.1E-02	m		
	density	1.4E+03	kg/m3		
	pvc energy	**1.4E+05**	g/yr		=length*x-sect area of pvc wall* density of pvc * 1000g/kg /lifespan
27	**BRICKS**				
	amt used	6.4E+02	m2		assumed to be 10 cm thick
	lifespan	2.5E+01	yrs		
	density	1.5E+03	g/m3		
	brick energy	**3.9E+03**	g/yr		=volume bricks*density/lifespan
28	**GRAVEL**				
	amt used	3.3E+02	m3		
	porosity	4.0E-01			
	gravel density	1.7E+03	kg/m3		
	gravel energy	**1.3E+07**	g/yr		=amt gravel*(1-porosity)*density* 1000g/kg/lifespan

29	**SAND**			
	amt used	3.8E+02	m3	
	density	1.6E+03	kg/m3	
	lifespan	2.5E+01	yrs	
				=amt
	sand energy	**2.4E+07**	g/yr	sand*density*1000g/kg/lifespan
30	**ELECTRICITY**			
	elec. used	5.0E+04	kWh/mo	
	elec. energy	**2.2E+12**	j/yr	=elec. used*12 mo/yr * 3.6e6 j/kWh
31	**LABOR**			
	est. labor cost	**6.8E+03**	$/yr	
32	**TOTAL EMERGY OF GOODS AND SERVICES**			
	largest of goods and services			
33	**TOTAL EMERGY**			
	sum of environmental resources and total goods and services			
34	**CHEMICAL POTENTIAL IN EFFLUENT WATER**			
	flow	2.0E+01	L/s	
	gibbs free energy	4.9E+00	J/g	
				=flow*gibbs free energy* 1000g/L
	trt water chem pot.	**3.1E+12**	J	* 86400 days*365 d/yr
35	**NITROGEN IN EFFLUENT WATER**			
	N content in effluent	1.5E+01	mg/L	
	N mass in effluent	**9.5E+06**	g of N, = N conc.* flow	
36	**PHOSPHORUS IN EFFLUENT WATER**			
	P in trt water	3.0E+00	mg/L	
	trt water P	**1.9E+06**	J	=flow*p conc/1000*86400*365
37	**OM IN EFFLUENT WATER**			
	flow	2.0E+01	L/s	
	BOD	3.0E+01	mg/L	
	trt water OM			=flow*BOD*4kcal/g*4184J/kcal/10
	energy	**3.2E+11**	J	00*86400sec/day*365day/yr
38	**E COLI IN EFFLUENT**			
	cell density	2.0E-10	mg-COD/cell	
	E coli conc.	1.0E+01	cells/L	
	energy of biomass	4.0E+00	kcal/g	
				=TC density*TC conc.*energy content of biomass*conversion factor*
	FIB conc. Energy	**2.1E+07**	J/yr	1000mg/g*flow*86400s/d*365d/yr
39	Total Emergy of WW out= sum of items 26-30			
40-45	**Calculations same as "No Treatment Scenario"**			

Table A6. Emergy evaluation of CTW Treatment Scenario (0.5 MGD, 20 L/s).

Ref. #	Item	Unit/yr	Amount Per year	Solar Transformity (sej/unit)	Ref. for Transf.	Solar Emergy (10^{12} sej/yr)
	ENVIRONMENTAL INPUTS TO SYSTEM					
1	Sunlight	J	2.51E+14	1.00E+00	A	251
2	Wind	J	8.78E+10	1.50E+03	A	131
3	Rain Chemical Potential	J	1.97E+11	3.06E+04	A	6,041
4	Rain Nitrogen	g	6.95E+04	2.41E+10	B	1,676
5	Rain Phosphorus	g	2.80E+03	2.20E+10	B	62
6	Rain OM	J	6.69E+08	3.19E+04	C	21
7	ET	J	1.36E+11	3.06E+04	A	4,158
8	*Emergy of Env. Inputs to system (R)*					*6,041*
	ENVIRONMENTAL INPUTS TO RECEIVING ENVIRONMENT					
9	Sunlight	J	2.47E+16	1.00E+00	A	24,670
10	Wind	J	8.61E+12	1.50E+03	A	12,888
11	Rain Chemical Potential	J	1.94E+13	3.06E+04	A	592,780
12	Rain Nitrogen	g	6.82E+06	2.41E+10	B	164,442
13	Rain Phosphorus	g	2.75E+05	2.20E+10	B	6,039
14	Rain OM	J	6.56E+10	3.19E+04	C	2,094
15	ET	J	1.05E+13	3.06E+04	A	321,290
16	*Emergy of Env. Inputs to Receiving Environment (ENVload)*					*592,780*
	INFLUENT WASTEWATER					
17	WWin Chem Potential	J	3.12E+12	3.06E+04	A	95,342
18	WWin Nitrogen	g	2.21E+07	7.04E+09	B	155,409
19	Wwin Phos	g	4.42E+06	3.70E+10	B	163,356
20	WWin OM	J	2.64E+12	3.19E+04	C	84,182
21	WWin *E. coli*	g	2.11E+13	2.56E+02	D	5,405
22	*Emergy of WWin*					*503,695*
	GOODS					
23	Seedlings	J	2.42E+09	5.80E+04	A	140

24	Gravel	g	3.06E+08	2.10E+09	I	642,627
25	Geomembrane	g	5.73E+05	8.50E+09	H	4,869
26	Concrete	g	1.96E+06	1.15E+10	A	22,516
27	PVC	g	2.23E+03	9.86E+09	H	22
	PURCHASED SERVICES					
28	Electricity	J	8.64E+10	2.92E+05	A	25,229
29	Operation Labor	$	4.59E+03	6.52E+12	J	29,940
30	*Total Emergy of Goods and Services*					*725,344*
31	**Total Emergy Inputs**					**1,821,818**
	EFFLUENT WASTEWATER					
32	WWout Chem. Potential	J	3.12E+12	3.06E+04	A	95,342
33	WWout N	g	9.46E+06	7.04E+09	B	66,604
34	WWout P	g	1.89E+06	3.70E+10	B	70,010
35	WWout OM	J	2.64E+11	3.19E+04	C	8,418
36	WWout *E. coli*	g	4.22E+11	2.56E+02	D	108
37	*Emergy of WWout*					*240,482*
	WASTEWATER AT BACKGROUND LEVELS					
38	Background N	g	9.46E+06	1.36E+10	E	128,743
39	Background P	g	3.15E+04	1.51E+09	E	48
40	Background OM	J	5.28E+10	1.05E+05	E	5,533
41	Background *E. coli*	J	4.22E+02	1.58E+08	D	0
42	*Total Emergy of WW at background levels (returned to receiving environment)*					*229,665*
43	*Total Emergy Outputs*					**240,482**

A) Odum, 1996; B) Brandt-Williams, 2002; C) Brown & Bardi, 2001; D) Odum, 2002; E) Brown & Arding, 1991; F) Odum et al., 1987; G) Odum and Odum, 1983; H) Buranakarn, 1998; I) McGrane, 1994; J) Vivas, 2004.

CALCULATIONS FOR TABLE A6 (CTW)

			Env. Loading Area (m2)	Treatment System Area (m2)
			3542400	36098
	area:	3.6e6	m2	
	WW flow:	20	L/s	(residential community, population ~5,000; 1/2 mgd)
	lifespan:	25	yrs	

1-22 Calculations same as "No Treatment Scenario"

23 SEEDLINGS

10% of stocks-	1000		kg/ha	
area	36098	m2		
lifetime	25			
seedlings energy	**2.4E+09**	J		=0.10*standing biomass*area/lifetime*1000g/kg* 1ha/1000m2*4kcal/g*4184J/kcal

24 Same as calculation from "WWTP Treatment Scenario"

25 GEOMEMBRANE

HDPE	15236	m2	
density	1	g/cm3	
geo energy	**5.7E+05**	g	=surface area*thickness*100^3*density/lifetime

26-37 Same as calculation from "WWTP Treatment Scenario"
38-43 Same as calculation from "WWTP Treatment Scenario"

Appendix B

Table B.1. Maryland Forest emergy analysis

Maryland Forest Emergy Analysis

#	Item	Unit/yr	Amount Per year	Unit Emergy Value (sej/unit)	Ref. for Transf.	Solar Emergy (sej/yr) E12	Aereal Emergy Density (sej/ha/yr) E12
	ENVIRONMENTAL INPUTS TO SYSTEM (R)						
1	Sunlight	J	6.44E+14	1.00E+00	By Definition	644.4	53
2	Wind	J	6.44E+10	1.50E+03	Odum, 1996	96.3	8
3	Rain Chemical Potential	J	8.56E+11	3.10E+04	Odum et al 2000	26,532.8	2,164
4	ET Chemical Potential	J	3.12E+11	5.04E+04	Campbell 2011	15,732.3	1,283
5	Rock Weathering	g	6.00E+05	3.80E+09	Brown and Bardi 2001	2,280.0	186
6	*Emergy of Env. Inputs to System*					*15,732.3*	*1,283*
	NON-RENEWABLE EMERGY INPUTS TO SYSTEM (N)						
7	Net Topsoil Loss	g	7.36E+06	6.25E+04	Odum 1996	0	0.04
	PURCHASED EMERGY INPUTS TO SYSTEM (F)						
8	Diesel	g	1.58E+05	2.83E+09	Bastianoni et al 2009	446.6	36
9	Machinery	g	4.00E+04	1.13E+10	Odum et al. 1987	452.0	37
10	Without Labor and Services					898.6	73.3
11	Skilled Labor	hr	4.00E+02	8.80E+12	Ortega 2000	3,520.0	287
12	Net Income	$	2.86E+02	1.90E+12	Brown and Campbell 2007	542.9	44
13	*Total Purchased Emergy Inputs (excluding Net Income)*					*4,418.6*	*360.4*
	EXPORTS (Y)						
14	Timber	J	1.94E+11	5.04E+04	Brown 2001	9798	799
	Total Exported Emergy					***9798***	***799***

CALCULATIONS FOR TABLE B1: Maryland Forest

		Forest area:	12.26	ha
1 Hectare =	10,000	m2		

1 SUNLIGHT

			Yearly Average Solar Radiation in Baltimore, MD:
mean annual solar radiation	4	kWh/m2/day	http://rredc.nrel.gov/solar/pubs/redbook/PDFs/MD.PDF
conversion	365	day/yr	0 degree tilt, fixed single axis
Solar Energy (J/yr)	Mean Annual Solar Radiation (kWh/m2/day)* (365day/yr)* 10000 m2/ha * 3.6e6 J/kWh * area		
	6.44386E+14	J/yr	
Transformity Source	By definition		

2 WIND KINETIC ENERGY

mean annual wind speed (OCS for ottawa co.)	3.9	m/s	Annual Average (http://rredc.nrel.gov/solar/pubs/redbook/PDFs/MD.PDF)
geostrophic wind velocity	2.34	m/s	geostrophic wind velocity assumed to be 0.6 times observed wind speed
density of air	1.3	kg/m3	
drag coefficient	0.001		
Wind Energy = air density (kg/m3) *((geostropic wind velocity(m/s))^3) * drag coefficient * 10,000 m2 * 3.15e17 seconds/yr * area			
wind energy=	**64400316488**	J/yr	
Transformity Source (corrected to new baseline)	Odum, HT. 1996. Environmental Accounting: Emergy and Environmental Decision-Making. John Wiley and Sons Inc. New York.		

3 RAIN CHEMICAL POTENTIAL

annual precipitation	1.4132	m/yr	Dec. 2010-Nov. 2011: http://www.ncdc.noaa.gov/
Gibbs Free Energy of rainwater	4.94	J/g	
Chemical Potential Energy of Rain = Rainfall (m/yr) * Area * 10,000 m2/ha * Water Density (1000 kg/m3) * Gibbs Free Energy of Rainwater (J/g) * 1000 g/kg			
chem pot. energy:	**8.55896E+11**	J/yr	
Transformity Source (corrected to new baseline)	Odum, HT. 1996. Environmental Accounting: Emergy and Environmental Decision-Making. John Wiley and Sons Inc. New York.		

4 ET

Pan Evaporation	0.859	m/yr	
Kp	0.6	pan coefficient estimated for moderate wind speed and RH, from http://www.fao.org/docrep/X0490E/x0490e00.htm	
ET	0.5154	Allen et al. 1998. Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56	
ET Energy = ET * 1,000,000 g/m3 * 10,000 m2 * 4.94 J/g			

	ET energy	**3.12149E+11**	J/yr	
	Transformity Source (corrected to new baseline)	Odum, HT. 1996. Environmental Accounting: Emergy and Environmental Decision-Making. John Wiley and Sons Inc. New York.		
5	**Rock Weathering**			
	Estimated Amt.	6.00E+05	g/ha/yr	Tilley, 1999 (dissertation)
	Transformity Source: Brown and Bardi, 2001			
6	**Environmental Inputs-**	**Largest emergy input- ET is the amount of incoming rain used by forest**		
7	**Net Topsoil Loss**			
	estimated, tilley coweeta	6.00E+05	g/ha/yr	
		7.36E+06	g/yr	
8	**Diesel Fuel**			
	Amount	50	gal	http://www.dnr.state.md.us/forests/pdfs/westvirginia.pdf
	Mass of Diesel Fuel Used= density * volume			
	Diesel Mass	**157795.4545**	g/yr	7163.913636
	Transformity Source	Bastianoni, S, Campbell, DE, Ridolfi and Pulselli. 2009. The solar transformities of petroleum fuels. Ecological Modelling. 220(1): 40-50.		
9	**Machinery**			
	Tractor, etc.	400	kg	http://www.dnr.state.md.us/forests/pdfs/westvirginia.pdf
	lifetime	10	years	
	grams of machiner	**40000**	g/yr	
	Transformity Source	Odum et al. 1987		
10	**Purchased without labor and services**			
	sum of Fuel and Machinery			
11	**Skilled Labor**			
	Amount	**400**	hrs	http://www.dnr.state.md.us/forests/pdfs/westvirginia.pdf
	Transformity Source	Ortega, E., 2000. Handbook of Emergy Calculations. Laborato´rio de Engenharia Ecolo´gica e Informa´tica Aplicada, Sao Paulo, Brazil,(http://www.unicamp.br/fea/ortega/curso/handbook.htm)		
12	**Net Money**			
	Wages based on rev/exp.	500	USD	http://www.dnr.state.md.us/forests/pdfs/westvirginia.pdf
		21	months	

Net Money=	**285.7142857**	USD/yr	
Transformity Source	Brown, MT and Campbell, ET. 2007. Evaluation of Natural Capital and Environmental Services of US National Forests Using Emergy Synthesis: Final Report. University of Florida Center for Envronmental Policy.		

13 Total Purchased Emergy (excluding net money)

Includes Skilled Labor

23 Timber

weight	14.28571429	tons/yr	http://www.dnr.state.md.us/forests/pdfs/westvirginia.pdf
energy=mass*(15000 j/g)	**1.94397E+11**	J/yr	

Table B.2. Shaw Farm CSA emergy analysis

	Shaw Farm CSA Emergy Analysis						
#	Item	Unit/yr	Amount Per year	Unit Emergy Value (sej/unit)	Ref. for Transf.	Solar Emergy (sej/yr) E12	Aereal Emergy Density (sej/ha/yr) E12
	ENVIRONMENTAL INPUTS TO SYSTEM (R)						
1	Sunlight	J	3.67E+13	1.00E+00	By Definition	36.7	53
2	Wind	J	3.67E+09	1.50E+03	Odum, 1996	5.5	8
3	Rain Chemical Potential	J	4.87E+10	3.10E+04	Odum et al 2000	1,510.4	2,164
4	ET Chemical Potential	J	2.07E+10	5.04E+04	Campbell 2011	1,044.8	1,497
5	Rock Weathering	g	6.00E+05	3.80E+09	Brown and Bardi 2001	2,280.0	0
6	*Emergy of Env. Inputs to System*					*1,044.8*	*1,497*
	NON-RENEWABLE EMERGY INPUTS TO SYSTEM (N)						
7	Net Topsoil Loss	g	4.06E+05	6.25E+04	Odum 1996	0	0
	PURCHASED EMERGY INPUTS TO SYSTEM (F)						
8	Irrigated Water	m3	6.99E+02	8.80E+11	Chen and Chen 2009	615.5	1,516
9	Diesel	g	3.16E+04	2.83E+09	Bastianoni et al 2009	89.3	128
10	Gasoline	g	2.76E+04	2.92E+09	Bastianoni et al 2009	80.6	115
11	N Fertilizer	g	6.00E+04	7.73E+09	Odum 1996	463.8	1,143
12	P Fertilizer	g	4.74E+03	2.99E+10	Odum 1996	141.8	349
13	K Fertilizer	g	3.11E+03	2.92E+09	Odum 1996	9.1	22
14	Seeds	g	3.45E+03	1.11E+09	Brandt-Williams and Fogelberg 2005	3.8	9
15	Electricity	J	6.57E+10	2.69E+05	Odum 1996	17,653.4	25,295
16	Potting Soil	J	1.52E+10	7.40E+04	Brown and Bardi 2001	1,125.9	1,613
17	Composted Manure	g	3.64E+05	1.13E+08	Bastianoni and Marchettini 2000	41.1	101
	Purchased Emergy without labor and services					*20,224.2*	*30,293.5*
18	Skilled Ag. Labor	hr	3.00E+03	8.80E+12	Ortega 2000	26,400.0	37,828
19	Unskilled Ag. Labor	hr	6.84E+02	3.00E+12	Ortega 2000	2,052.0	2,940

20	Net Income	$	4.99E+02	1.90E+12	Brown and Campbell 2007	948.1	1,359
21	*Total Purchased Emergy Inputs (excluding Net Income)*					*48,676.2*	*71,062.2*
	EXPORTS (Y)						
22	potatoes	J	3.60E+08	1.78E+05	Brandt-Williams 2002	64	92
23	squash	J	6.56E+07	2.37E+05	Comar 2001	16	22
24	tomatoes	J	2.42E+06	8.57E+05	Brandt-Williams 2002	2	3
25	lettuce	J	2.75E+06	8.45E+05	Brandt-Williams 2002	2	3
26	cucumber	J	3.47E+06	6.84E+04	Brandt-Williams 2002	0	0
27	beans	J	1.45E+08	1.20E+06	Brandt-Williams 2002	175	250
28	onions	J	8.98E+06	2.37E+05	Comar 2001	2	3
29	kale	J	4.82E+06	2.37E+05	Comar 2001	1	2
30	broccoli	J	6.63E+06	2.37E+05	Comar 2001	2	2
31	turnips	J	2.12E+06	2.37E+05	Comar 2001	1	1
32	carrots	J	1.44E+06	2.37E+05	Comar 2001	0	0
33	beets	J	7.85E+06	2.37E+05	Comar 2001	2	3
34	garlic	J	5.33E+07	2.37E+05	Comar 2001	13	18
35	eggplant	J	4.62E+06	2.37E+05	Comar 2001	1	2
36	basil	J	3.24E+06	2.37E+05	Comar 2001	1	1
37	spinach	J	2.62E+06	2.37E+05	Comar 2001	1	1
38	arugula	J	5.69E+06	2.37E+05	Comar 2001	1	2
39	watermelon	J	3.10E+06	3.81E+04	Brandt-Williams 2002	0	0
40	strawberries	J	2.50E+06	2.37E+05	Comar 2001	1	1
41	bok choi	J	4.83E+05	2.37E+05	Comar 2001	0	0
42	scallions	J	5.32E+06	2.37E+05	Comar 2001	1	2
43	kohlrabi	J	1.37E+06	2.37E+05	Comar 2001	0	0
44	cilantro	J	2.49E+06	2.37E+05	Comar 2001	1	1
45	peppers	J	1.88E+06	7.71E+05	Brandt-Williams 2002	1	2
46	okra	J	2.96E+06	2.37E+05	Comar 2001	1	1
47	swiss chard	J	9.74E+05	2.37E+05	Comar 2001	0	0
48	garlic scapes	J	9.43E+06	2.37E+05	Comar 2001	2	3
49	peas, sugar snap	J	4.43E+06	2.37E+05	Comar 2001	1	2
50	radishes	J	3.59E+05	2.37E+05	Comar 2001	0	0
51	parsnips	J	7.51E+06	2.37E+05	Comar 2001	2	3
52	cabbage	J	2.98E+05	2.71E+05	Brandt-Williams 2002	0	0
53	peas	J	7.19E+06	2.37E+05	Comar 2001	2	2
54	fennel	J	1.27E+06	2.37E+05	Comar 2001	0	0
55	leeks	J	4.24E+06	2.37E+05	Comar 2001	1	1
56	shallots	J	1.62E+06	2.37E+05	Comar 2001	0	1

57	potatoes, new	J	8.45E+06	2.37E+05	Comar 2001	2	3
58	celeniac	J	7.44E+05	2.37E+05	Comar 2001	0	0
59	green garlic	J	5.12E+06	2.37E+05	Comar 2001	1	2
60	rosemary	J	2.08E+07	2.37E+05	Comar 2001	5	7
61	raspberries	J	1.93E+06	2.37E+05	Comar 2001	0	1
62	blackberries	J	1.28E+06	2.37E+05	Comar 2001	0	0
63	yukina savoy	J	3.00E+05	2.71E+05	Brandt-Williams 2002	0	0
64	thyme	J	1.68E+07	2.37E+05	Comar 2001	4	6
65	asian greens	J	2.87E+05	2.37E+05	Comar 2001	0	0
66	radicchio	J	3.16E+05	2.37E+05	Comar 2001	0	0
67	dill	J	1.30E+07	2.37E+05	Comar 2001	3	4
68	peas, snow	J	9.74E+05	2.37E+05	Comar 2001	0	0
69	oregano	J	1.62E+06	2.37E+05	Comar 2001	0	1
70	purslane	J	1.58E+05	2.37E+05	Comar 2001	0	0
	Total Exported Produce					***314***	***450***

	Planted Area	43690	sq ft	0.405893382	ha	4058.933824	m2
	Whole farm	87120	sq ft	0.809371286	ha	8093.712857	m2
	Whole farm minus yard	75120	sq ft	0.697887638	ha	6978.876376	m2
	Buffers, parking, building (whole farm minus parking, yard, buildings)	31430	sq ft	0.291994255	ha	2919.942552	m2
	1 Hectare =	10,000	m2				

1	**SUNLIGHT**			0 degree tilt, fixed single axis
	mean annual solar radiation	4	kWh/m2/day	Yearly Average Solar Radiation in Baltimore, MD:
	conversion	365	day/yr	http://rredc.nrel.gov/solar/pubs/redbook/PDFs/MD.PDF
	Solar Energy (J/yr)	Mean Annual Solar Radiation (kWh/m2/day)* (365day/yr)* 10000 m2/ha * 3.6e6 J/kWh * area		
		3.6681E+13	J/yr	
	Transformity Source	By definition		
2	**WIND KINETIC ENERGY**			
	mean annual wind speed (OCS for ottawa co.)	3.9	m/s	Annual Average (http://rredc.nrel.gov/solar/pubs/redbook/PDFs/MD.PDF)
	geostrophic wind velocity	2.34	m/s	geostrophic wind velocity assumed to be 0.6 times observed wind speed
	density of air	1.3	kg/m3	

	drag coefficient	0.001		
	Wind Energy = air density (kg/m3) *((geostropic wind velocity(m/s))^3) * drag coefficient * 10,000 m2 * 3.15e17 seconds/yr * area			
	wind energy=	**3665920451**	J/yr	
	Transformity Source (corrected to new baseline)	Odum, HT. 1996. Environmental Accounting: Emergy and Environmental Decision-Making. John Wiley and Sons Inc. New York.		
3	**RAIN CHEMICAL POTENTIAL**			
	annual precipitation	1.4132	m/yr	Dec. 2010-Nov. 2011: http://www.ncdc.noaa.gov/
	Gibbs Free Energy of rainwater	4.94	J/g	
	Chemical Potential Energy of Rain = Rainfall (m/yr) * Area * 10,000 m2/ha * Water Density (1000 kg/m3) * Gibbs Free Energy of Rainwater (J/g) * 1000 g/kg			
	chem pot. energy:	**48720987585**	J/yr	
	Transformity Source (corrected to new baseline)	Odum, HT. 1996. Environmental Accounting: Emergy and Environmental Decision-Making. John Wiley and Sons Inc. New York.		
4	**ET**			
	Pan Evaporation	0.859	m/yr	
	Kp	0.7	pan coefficient estimated for moderate wind speed and RH, from http://www.fao.org/docrep/X0490E/x0490e00.htm	
	ET	0.6013	Allen et al. 1998. Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56	
	ET Energy = ET * 1,000,000 g/m3 * 10,000 m2 * 4.94 J/g			
	ET energy	**20730207921**	J/yr	
	Transformity Source (corrected to new baseline)	Odum, HT. 1996. Environmental Accounting: Emergy and Environmental Decision-Making. John Wiley and Sons Inc. New York.		
5	**Rock Weathering**			
	Estimated Amt.	6.00E+05	g/ha/yr	Tilley, 1999 (dissertation)
	Transformity Source: Brown and Bardi, 2001			
6	**Environmental Inputs-**	**Largest emergy input- ET is the amount of incoming rain used by farm**		
7	**Net Topsoil Loss**			
	estimated, tilley coweeta	1.00E+06	g/ha/yr	
		4.06E+05	g/yr	

8	**Irrigated Water**			
	Amount	699.4	m3 water	Shaw Farm Records (Dec 2010-Nov 2011)
	Amount	**699.4**	m3 water	used on planted area
	Transformity Source:	Chen, B, Chen, GQ. 2009. Emergy-based energy and material metabolism of the Yellow River basin. Communications in Nonlinear Science and Numerical Simulation. 14(3): 923-934.		
9	**Diesel Fuel**			
	Amount	10	gal	Shaw Farm Records (CY2011)
	Mass of Diesel Fuel Used=	density * volume		entire farm area (minus yard)
	Diesel Mass	**31559.09091**	g/yr	
	Transformity Source	Bastianoni, S, Campbell, DE, Ridolfi and Pulselli. 2009. The solar transformities of petroleum fuels. Ecological Modelling. 220(1): 40-50.		
10	**Gasoline**			
	Amount	10	gal	Shaw Farm Records (CY2011)
	Mass of Gasoline Used=	energy density * volume		entire farm area (minus yard)
	Gasoline Mass	**27604.54545**	g/yr	
	Transformity Source	Bastianoni, S, Campbell, DE, Ridolfi and Pulselli. 2009. The solar transformities of petroleum fuels. Ecological Modelling. 220(1): 40-50.		
11	**N Fertilizer**			
	Amount	132	lbs	Shaw Farm Records (CY2011)
	Mass Fert. Used	**60000**	g/yr	includes planted area only
	Transformity Source (corrected to new baseline)	Odum, HT. 1996. Environmental Accounting: Emergy and Environmental Decision-Making. John Wiley and Sons Inc. New York.		
12	**P Fertilizer**			
	Amount	10.43	lbs	Shaw Farm Records (CY2011)
	Mass P used	**4740.909091**	g/yr	includes planted area only
	Transformity Source (corrected to new baseline)	Odum, HT. 1996. Environmental Accounting: Emergy and Environmental Decision-Making. John Wiley and Sons Inc. New York.		
13	**K Fertilizer**			
	Amount	6.85	lbs	Shaw Farm Records (CY2011)
	Mass P used	**3113.636364**	g/yr	includes planted area only
	Transformity Source	Odum, HT. 1996. Environmental Accounting: Emergy and Environmental Decision-Making. John Wiley and Sons Inc. New York.		

	(corrected to new baseline)			
14	**Seed**			
	Amount	121.6	oz	Shaw Farm Records (CY2011)
	Mass seed used	**3454.545455**	g/yr	includes planted area only
	Transformity Source	Brandt-Williams, S, Fogelberg, CL. 2005. Nested Comparative Emergy Assessments Using Milk Production as a Case Study. Emergy Conference Proceedings. 3(31): 385-400		
15	**Electricity**			
	Amount	18242.98	kWh	Shaw Farm Records (CY2011)
	Joules of elec. used	**65674728000**	J/yr	entire farm area (minus yard)
	Transformity Source (corrected to new baseline)	Odum, HT. 1996. Environmental Accounting: Emergy and Environmental Decision-Making. John Wiley and Sons Inc. New York.		
16	**Potting Soil**			
	Amount	2000	lbs	Shaw Farm Records (CY2011)
	Joules of PS Used	**15214545455**	J/yr	entire farm area (minus yard)
	Transformity Source	Brown MT, Bardi E. In: Gainesville FI, editor. Folio #3: emergy of global processes. Handbook of emergy evaluation: a compendium of data for emergy computation issued in a series of folios. Gainesville, FL: Center for Environmental Policy, University of Florida; 2001		
17	**Composted Manure**			
	Amount	800	lbs	Shaw Farm Records (CY2011)
	Grams of manure used	**363636.3636**	g/yr	entire farm area (minus yard)
	Transformity Source	Bastianoni, S, Marchettini, N. 2000. The problem of co-production in environmental accounting by emergy analysis. Ecological Modelling. 129: 187-193.		
18	**Skilled Labor**			
	Amount	3000	hrs	Shaw Farm Records (CY2011)
	Transformity Source	Ortega, E., 2000. Handbook of Emergy Calculations. Laborato´rio de Engenharia Ecolo´gica e Informa´tica Aplicada, Sao Paulo, Brazil,(http://www.unicamp.br/fea/ortega/curso/handbook.htm)		
19	**Unskilled Labor**			
	Amount	684	hrs	Shaw Farm Records (CY2011)
	Transformity Source	Ortega, E., 2000. Handbook of Emergy Calculations. Laborato´rio de Engenharia Ecolo´gica e Informa´tica Aplicada, Sao Paulo, Brazil,(http://www.unicamp.br/fea/ortega/curso/handbook.htm)		

20	**Net Money**				
	CSA Fees In, 60 shares at $900	54000	USD	Shaw Farm Records (CY2011)	
	Cost- Wages+Utilities	53501	USD		
	Net Money=	499	USD		
	Transformity Source	Brown, MT and Campbell, ET. 2007. Evaluation of Natural Capital and Environmental Services of US National Forests Using Emergy Synthesis: Final Report. University of Florida Center for Envronmental Policy.			

Purchased Emergy with labor

EXPORTED PRODUCE:

		wt (lbs)	water content	dry wt (g)	energy content (kj/100g)	**energy (J)**
22	potatoes	813.2	75	92409.09091	389.298	**359746742.7**
23	squash	721.8	80	65618.18182	100	**65618181.82**
24	tomatoes	370.1	97	5046.818182	48	**2422472.727**
25	lettuce	288.6	95	6559.090909	41.86	**2745635.455**
26	cucumber	243.5	95	5534.090909	62.79	**3474855.682**
27	beans	179.6	67	26940	539.994	**145474383.6**
28	onions	102.2	89	5110	175.812	**8983993.2**
29	kale	93.8	91	3837.272727	125.58	**4818847.091**
30	broccoli	93.1	89	4655	142.324	**6625182.2**
31	turnips	88.3	94	2408.181818	87.906	**2116936.309**
32	carrots	82.7	92	3007.272727	48	**1443490.909**
33	beets	79.9	88	4358.181818	180.041	**7846514.127**
34	garlic	70.1	70	9559.090909	557.5752	**53299120.25**
35	eggplant	69.3	90	3150	146.51	**4615065**
36	basil	67.9	85	4629.545455	69.9062	**3236339.305**
37	spinach	66.6	91	2724.545455	96.278	**2623137.873**
38	arugula	66.4	85	4527.272727	125.58	**5685349.091**
39	watermelon	63.6	93	2023.636364	153	**3096163.636**
40	strawberries	61.8	91	2528.181818	99	**2502900**
41	bok choi	52.9	96	961.8181818	50.232	**483140.5091**
42	scallions	46.6	85	3177.272727	167.44	**5320025.455**
43	kohlrabi	45	94	1227.272727	111.6266667	**1369963.636**
44	cilantro	43.6	85	2972.727273	83.72	**2488767.273**
45	peppers	38.7	91	1583.181818	119	**1883986.364**
46	okra	33.5	85	2284.090909	129.766	**2963973.409**
47	swiss chard	32	92	1163.636364	83.72	**974196.3636**

48	garlic scapes	30.2	89	1510	624.8220588	**9434813.088**
49	peas, sugar snap	28.3	80	2572.727273	172.3647059	**4434473.797**
50	radishes	28.3	94	771.8181818	46.51111111	**358981.2121**
51	parsnips	27.8	80	2527.272727	297.206	**7511206.182**
52	cabbage	24.1	95	547.7272727	54.418	**298062.2273**
53	peas	22.2	79	2119.090909	339.066	**7185116.782**
54	fennel	21.5	90	977.2727273	129.766	**1268167.727**
55	leeks	21.5	83	1661.363636	255.346	**4242225.591**
56	shallots	20.4	90	927.2727273	175	**1622727.273**
57	potatoes, new	19.1	75	2170.454545	389.298	**8449536.136**
58	celeriac	18.1	92	658.1818182	113.022	**743890.2545**
59	green garlic	16.4	89	820	624.8220588	**5123540.882**
60	rosemary	13.1	65	2084.090909	996.6666667	**20771439.39**
61	raspberries	13	85	886.3636364	217.8081301	**1930572.062**
62	blackberries	11	85	750	170	**1275000**
63	yukina savoy	10.9	94	297.2727273	101.0413793	**300368.4639**
64	thyme	10.6	65	1686.363636	996.6666667	**16807424.24**
65	asian greens	10.4	94	283.6363636	101.0413793	**286590.094**
66	radicchio	10.3	93	327.7272727	96.278	**315529.2636**
67	dill	8.2	65	1304.545455	996.6666667	**13001969.7**
68	peas, snow	6.4	80	581.8181818	167.44	**974196.3636**
69	oregano	5.1	80	463.6363636	348.8333333	**1617318.182**
70	purslane	5.1	90	231.8181818	68.14418605	**157970.6131**
	Totals	1953.090909	kg		225504.541	**1995525226**

Table B.3. Greenway Farm emergy analysis.

	Greenway Farm Emergy Analysis							
#	Item	Unit/yr	Amount Per year		Unit Emergy Value (sej/unit)	Ref. for Transf.	Solar Emergy (sej/yr) E12	Aereal Emergy Density (sej/ha/yr) E12
	ENVIRONMENTAL INPUTS TO SYSTEM ®							
1	Sunlight	J	1.49E+14	5.26E+13	1.00E+00	By Definition	148.8	53
2	Wind	J	1.49E+10	5.25E+09	1.50E+03	Odum, 1996	22.3	8
3	Rain Chemical Potential	J	1.88E+11	6.64E+10	3.10E+04	Odum et al 2000	5,828.8	2,058
4	ET Chemical Potential	J	7.19E+10	2.54E+10	5.04E+04	Campbell 2011	3,622.8	1,279
5	Rock Weathering	g	6.00E+05	2.12E+05	3.80E+09	Brown and Bardi 2001	2,280.0	805
6	*Emergy of Env. Inputs to System*						*3,622.8*	*1,279*
	NON-RENEWABLE EMERGY INPUTS TO SYSTEM (N)							
7	Net Topsoil Loss	g	4.25E+06	1.50E+06	6.25E+04	Odum 1996	0.3	0
	PURCHASED EMERGY INPUTS TO SYSTEM (F)							
8	Irrigated Water	m3	4.83E+03	1.71E+03	8.80E+11	Chen and Chen 2009	4,251.3	1,501
9	Diesel	g	1.89E+06	6.69E+05	2.83E+09	Bastianoni et al 2009	5,358.7	1,892
10	Gasoline	g	1.24E+05	4.39E+04	2.92E+09	Bastianoni et al 2009	362.7	128
11	Electricity	J	2.42E+11	8.55E+10	2.69E+05	Odum 1996	65,099.2	6,433
12	N Fertilizer	g	2.16E+05	7.62E+04	7.73E+09	Odum 1996	1,669.0	589
13	P Fertilizer	g	5.51E+04	1.94E+04	2.99E+10	Odum 1996	1,646.7	581
14	K Fertilizer	g	1.42E+05	5.03E+04	2.92E+09	Odum 1996	415.9	147
15	Lime	g	1.81E+06	6.41E+05	1.68E+09	Brandt-Williams 2002	3,048.1	1,076
16	Seeds	g	8.52E+03	3.01E+03	1.11E+09	Brandt-Williams and Fogelberg 2005	9.5	3

17	Pesticide	g	5.34E+04	1.89E+04	1.48E+10	(Brown and Arding, 199	790.7	279
18	Potting Soil	J	2.85E+09	1.01E+09	7.40E+04	Brown and Bardi 2001	211.1	75
19	Mulch	g	2.27E+06	8.03E+05	2.75E+08	Nelson et al 1998	625.0	221
20	Machinery	g	3.33E+05	1.18E+05	1.13E+10	Odum et al. 1987	3,766.7	1,330
	Without Labor and Services						87,254.6	30,810
21	Skilled Ag. Labor	hr	5.00E+03	1.77E+03	8.80E+12	Ortega 2000	44,000.0	15,537
22	Unskilled Ag. Labor	hr	9.35E+02	3.30E+02	3.00E+12	Ortega 2000	2,805.0	990
23	Net Income	$	1.28E+04	4.51E+03	1.90E+12	Brown and Campbell 2007	24,259.9	8,566
24	*Total Purchased Emergy Inputs (excluding Net Income)*						*134,059.6*	*47,337.4*
	EXPORTS (Y)							
25	Berries	J	1.07E+09	3.78E+08	2.37E+05	Comar 2001	253.6	90
26	Specialty Greens	J	8.59E+07	3.03E+07	2.37E+05	Comar 2001	20.4	7
27	Baby Squash	J	4.55E+07	1.61E+07	2.37E+05	Comar 2001	10.8	4
28	Melons	J	3.41E+07	1.20E+07	3.81E+04	Brandt-Williams 2002	1.3	0
29	Onion	J	2.20E+07	7.77E+06	2.37E+05	Comar 2001	5.2	2
	Total Exported Emergy						***291***	***103***

	Planted Area	7	acres	2.832	ha	28320	m2
	Whole Farm	25	acres	10.12	ha	101200	m2
	1 Hectare =	10,000	m2				

1	**SUNLIGHT**			
	mean annual solar radiation	4	kWh/m2/day	Yearly Average Solar Radiation in Baltimore, MD: http://rredc.nrel.gov/solar/pubs/redbook/PDFs/MD.PDF
	conversion	365	day/yr	0 degree tilt, fixed single axis
	Solar Energy (J/yr)	Mean Annual Solar Radiation (kWh/m2/day)* (365day/yr)* 10000 m2/ha * 3.6e6 J/kWh * area		
		1.4885E+14	J/yr	
	Transformity Source	By definition		
2	**WIND KINETIC ENERGY**			
	mean annual wind speed (OCS for ottawa	3.9	m/s	Annual Average (http://rredc.nrel.gov/solar/pubs/redbook/PDFs/MD.PDF)

co.)

geostrophic wind velocity	2.34	m/s	geostrophic wind velocity assumed to be 0.6 times observed wind speed
density of air	1.3	kg/m3	
drag coefficient	0.001		

Wind Energy = air density (kg/m3) *((geostropic wind velocity(m/s))^3) * drag coefficient * 10,000 m2 * 3.15e17 seconds/yr * area

wind energy=	**14876157936**	J/yr
Transformity Source (corrected to new baseline)	Odum, HT. 1996. Environmental Accounting: Emergy and Environmental Decision-Making. John Wiley and Sons Inc. New York.	

3 RAIN CHEMICAL POTENTIAL

annual precipitation	1.344	m/yr	Dec. 2010-Nov. 2011: http://www.ncdc.noaa.gov/
Gibbs Free Energy of rainwater	4.94	J/g	

Chemical Potential Energy of Rain = Rainfall (m/yr) * Area * 10,000 m2/ha * Water Density (1000 kg/m3) * Gibbs Free Energy of Rainwater (J/g) * 1000 g/kg

chem pot. energy:	**1.88027E+11**	J/yr
Transformity Source (corrected to new baseline)	Odum, HT. 1996. Environmental Accounting: Emergy and Environmental Decision-Making. John Wiley and Sons Inc. New York.	

4 ET

Pan Evaporation	0.734	m/yr	
Kp	0.7	pan coefficient estimated for moderate wind speed and RH, from http://www.fao.org/docrep/X0490E/x0490e00.htm	
ET	0.5138	Allen et al. 1998. Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56	

ET Energy = ET * 1,000,000 g/m3 * 10,000 m2 * 4.94 J/g

ET energy	**71881031040**	J/yr
Transformity Source (corrected to new baseline)	Odum, HT. 1996. Environmental Accounting: Emergy and Environmental Decision-Making. John Wiley and Sons Inc. New York.	

5 Rock Weathering

Estimated Amt.	6.00E+05	g/ha/yr	Tilley, 1999 (dissertation)

Transformity Source: Brown and Bardi, 2001

6 Environmental Inputs- **Largest emergy input- ET is the amount of incoming rain used by farm**

7	**Net Topsoil Loss**			
	estimated, tilley coweeta	1.00E+06	g/ha/yr	
		7.77E+12	g/yr	
8	**Irrigated Water**			
	Estimated for crop type	1705.853659	m3 water/ha	
	Amount used	**4830.977561**	m3 water	used on planted area
	Transformity Source:	Chen, B, Chen, GQ. 2009. Emergy-based energy and material metabolism of the Yellow River basin. Communications in Nonlinear Science and Numerical Simulation. 14(3): 923-934.		
9	**Diesel Fuel**			
	Amount	600	gal	Greenway Worksheet (CY2009)
	Mass of Diesel Fuel Used= density * volume			
	Diesel Mass	**1893545.455**	g/yr	
	Transformity Source	Bastianoni, S, Campbell, DE, Ridolfi and Pulselli. 2009. The solar transformities of petroleum fuels. Ecological Modelling. 220(1): 40-50.		
10	**Gasoline**			
	Amount	45	gal	Greenway Worksheet (CY2009)
	Mass of Gasoline Used= energy density * volume			
	Gasoline Mass	**124220.4545**	g/yr	
	Transformity Source	Bastianoni, S, Campbell, DE, Ridolfi and Pulselli. 2009. The solar transformities of petroleum fuels. Ecological Modelling. 220(1): 40-50.		
11	**Electricity**			
	Amount paid	1700	usd	Greenway Worksheet (CY2009)
	avg price/kwh	0.02527	usd/kwh	use for entire farm (25 acres)
	Joules elec used	**2.42184E+11**	j/yr	
12	**N Fertilizer**			
	Amount	475	lbs	Greenway Worksheet (CY2009)
	Mass Fert. Used	**215909.0909**	g/yr	
	Transformity Source (corrected to new baseline)	Odum, HT. 1996. Environmental Accounting: Emergy and Environmental Decision-Making. John Wiley and Sons Inc. New York.		

13	**P Fertilizer**			
	Amount	121.1619718	lbs	Greenway Worksheet (CY2009)
	Mass P used	**55073.62356**	g/yr	
	Transformity Source (corrected to new baseline)	Odum, HT. 1996. Environmental Accounting: Emergy and Environmental Decision-Making. John Wiley and Sons Inc. New York.		
14	**K Fertilizer**			
	Amount	313.381104	lbs	Greenway Worksheet (CY2009)
	Mass P used	**142445.9564**	g/yr	includes planted area only
	Transformity Source (corrected to new baseline)	Odum, HT. 1996. Environmental Accounting: Emergy and Environmental Decision-Making. John Wiley and Sons Inc. New York.		
15	**Lime**			
	Amount Used	2	tons	
	gram used	**1814369.48**	g/yr	
16	**Seed**			
	Amount	300	oz	Greenway Worksheet (CY2009)
	Mass seed used	**8522.727273**	g/yr	
	Transformity Source	Brandt-Williams, S, Fogelberg, CL. 2005. Nested Comparative Emergy Assessments Using Milk Production as a Case Study. Emergy Conference Proceedings. 3(31): 385-400		
17	**Pesticide**			
	Amount	117.7875	pounds	Greenway Worksheet (CY2009)
	grams used	**53428.41**	g/yr	
	Transformity Source (corrected to new baseline)	(Brown and Arding, 1999)		
18	**Potting Soil**			
	Amount	375	lbs	Greenway Worksheet (CY2009)
	Joules of PS Used	**2852727273**	J/yr	
	Transformity Source	Brown MT, Bardi E. In: Gainesville FI, editor. Folio #3: emergy of global processes. Handbook of emergy evaluation: a compendium of data for emergy computation issued in a series of folios. Gainesville, FI: Center for Environmental Policy, University of Florida; 2001		
19	**Mulch**			

	Amount	5000	lbs	Greenway Worksheet (CY2009)
	Grams of mulch used	**2272727.273**	g/yr	entire farm area (minus yard)
	Transformity Source	Nelson M, Odum HT, Brown MT, Alling A. ‘‘Living off the land’’: resource efficiency of wetland wastewater treatment. Adv Space Res 2001;27:1547–56		
20	**Machinery**			
	Tractor, etc.	5000	kg	Greenway Worksheet (CY2009)
	lifetime	15	years	
	grams of machiner	**333333.3333**	g/yr	
	Transformity Source	Odum et al. 1987		
21	**Skilled Labor**			
	Amount	5000	hrs	Greenway Worksheet (CY2009)
	Transformity Source	Ortega, E., 2000. http://www.unicamp.br/fea/ortega/curso/handbook.htm)		
22	**Unskilled Labor**			
	Amount	935	hrs	Greenway Worksheet (CY2009)
	Transformity Source	Ortega, E., 2000. http://www.unicamp.br/fea/ortega/curso/handbook.htm)		
23	**Net Money**			
				Greenway Worksheet (CY2009)
	Net Money=	12768.35	USD	
	Transformity Source	Brown, MT and Campbell, ET. 2007		

24 *Total Purchased Emergy Inputs (excluding Net Income)*
Purchased with Labor

EXPORTED PRODUCE:

		wt (lbs)	water content	dry wt (g)	energy content (kj/100g)	**energy (J)**
25	Berries	7200	85	490909.0909	218	**1070181818**
26	Specialty Greens	3150	94	85909.09091	100	**85909090.91**
27	Baby Squash	500	80	45454.54545	100	**45454545.45**
28	Melons	700	93	22272.72727	153	**34077272.73**
29	Onion	250	89	12500	176	**22000000**

Table B.4. Calculation of NPP Tranformity for Maryland Forest, Shaw Farm CSA, and Greenway Farm.

Transformity for NPP of forest=			
= emergy of forest NPP/exergy of forest NPP			
emergy=	ET+deep heat+atm dep		
exergy= 14390 kg/ha/yr *1000kg/g*3.5kcal/g*4186J/kcal			
	exergy=	2.10828E+11	J/ha/yr
emergy			
	ET	1.28322E+15	sej/ha/yr
	deep heat*:	7E+14	sej/ha/yr
	atm dep**:	3E+13	sej/ha/yr
	emergy=	2.01322E+15	sej/ha/yr
Trans of NPP in Forest= 9.55E+03 sej/J			
*Tilley, 1999 (table E-1, 100m elevation)			
**Tilley, 1999 (table 9, 30000 g/ha/yr*1e9sej/kg)			

Transformity for NPP of crops at Shaw Farm=			
= emergy of crop NPP/exergy of crop NPP			
emergy=	ET+deep heat+atm dep+purchased		
exergy= farm biomass *1000kg/g*3.5kcal/g*4186J/kcal			
	exergy=	2.36E+11	J/ha/yr
emergy			
	ET	1.49709E+15	sej/ha/yr
	deep heat*:	6.99E+14	sej/ha/yr
	atm dep**:	3E+13	sej/ha/yr
	purchased	3.37535E+15	sej/ha/yr
	emergy=	5.60144E+15	sej/ha/yr
Trans of NPP in Shaw Farm= 2.37E+04 sej/J			
*Tilley, 1999 (table E-1, 100m elevation)			
**Tilley, 1999 (table 9, 30000 g/ha/yr*1e9sej/kg)			

Transformity for NPP of crops at Greenway Farm=		
= emergy of crop NPP/exergy of crop NPP		
emergy=	ET+deep heat+atm dep+purchased	
exergy= farm biomass *1000kg/g*3.5kcal/g*4186J/kcal		
exergy=	3.07E+11	J/ha/yr
emergy		
ET	1.27924E+15	sej/ha/yr
deep heat*:	6.99E+14	sej/ha/yr
atm dep**:	3E+13	sej/ha/yr
purchased	6.41867E+15	sej/ha/yr
emergy=	8.42691E+15	sej/ha/yr
Trans of NPP in Greenway Farm= 2.74E+04 sej/J		

*Tilley, 1999 (table E-1, 100m elevation)
**Tilley, 1999 (table 9, 30000 g/ha/yr*1e9sej/kg)

Table B.5: Calculations of flows and indices for mass and emergy in Table 3.4 for MD Forest, Shaw Farm, and Greenway Farm (both farms had identical calculation methods for each flow and index).

		MD Forest	Shaw and Greenway Farms
Mass Inputs (M_i), g P/ha/yr	=	(Annual Atmospheric Deposition of P + Annual Rock Weathering) ÷ area	(Annual Atmospheric Deposition of P + Annual Rock Weathering + Annual P Fertilizer application) ÷ area
Mass Recycle (M_r), g P/ha/yr	=	(Annual Root Transfer of P) ÷ area	(Annual P left in crop residues) ÷ area
Mass recycle per input, M_r/M_i	=	M_r/M_i	M_r/M_i
Emergy Inputs (Em_i), E9 sej/ha/yr	=	(Annual emergy flow of Atm. Dep + Rock Weathering) ÷ area	(Annual emergy flow of Atm. Dep + Rock Weathering + P Fertilizer) ÷ area
Emergy Recycle (Em_r), E9 sej/ha/yr	=	(Annual emergy flow of For. NPP) ÷ area	(Annual emergy flow of Crop NPP) ÷ area
Emergy recycle per input, Em_r/Em_i	=	Em_r/Em_i	Em_r/Em_i
Specific emergy of recycled mass, Em_r/M_r (E9 sej/g P)	=	Em_r/M_r	Em_r/M_r
Specific emergy of input mass, Em_i/M_i (E9 sej/g P)	=	Em_i/M_i	Em_i/M_i
Recycle Rate (%)	=	$100*M_r/(M_i + M_r)$	$100*M_r/(M_i + M_r)$

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