Perception and Evaluation of Land Management Strategies in Borneo for Novelty and Sustainability

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

This thesis examines subsistence production and state-level government forestry land management strategies as practiced in Sarawak, Malaysia. Subsistence farmers in Rumah Siba Perdu and Sarawak Forestry officials practice different land management strategies, some of which promote novel courses of ecosystem development. Recognizing that there can be notable human impact potential on even lightly-managed tropical forests, the presented research includes interviews and surveys meant to ascertain the importance and impacts of current management. Strategies examined include diverse types of farming such as rice, manioc, peppercorn, and latex, combined rice-manioc-latex production, combined peppercorn-manioc-latex production, combined potential production for all studied species, and Sarawak Forestry-based forest conservation management. Interviews indicated that forestry officials hold strong opinions that farmers often overlook long-term ecosystem integrity and production stability while pursuing short-term economic gains. In contrast, farmers in Rumah Siba recognize the need for conservation, expressing concern regarding poaching and overuse of communal lands. This thesis proposes integrating alternative forest crops into subsistence management strategies to address potential impacts of more intensive management practices. Two agroforested species, sago and breadfruit, are presented as examples to inform mixed-use management approaches in order to rebuild ecosystem structure and restore services provided historically by forests.

In addition, emergy analysis compared and analyzed sustainability of these ten strategies. Fraction Renewable ranged from 0.77 to 0.98 across all strategies, indicating high proportions of renewable energy driving management strategies. Emergy Yield Ratio (EYR) values ranged from 4.42 to 13.34 for current production and from 35.12 to 65.14 for potential strategies. When compared to an EYR of 24.19 for protected areas, this indicates effectiveness in utilizing purchased investments. Environmental Loading Ratio (ELR) values ranged between 0.09 and 0.30 for current farming practices and between 0.02 and 0.03 for potential strategies. Compared to an ELR of 0.04 for protected areas and near zero values for wilderness, most strategies showed minimal environmental stress despite differing strategy outcomes. Emergy Sustainability Index (ESI) values ranged from 14.84 to 155.49 for current farming practices and from 1143.42 to 3819.05 for potential strategies. ESI indicates that potential strategies have high sustainability when compared to 555.00 for protected areas. EYR, ELR, and ESI values were not dependent on land area utilized, but were dependent on purchased resources and non-renewable portions of labor as management intensity increased within a given strategy. Emergy analysis determined that rice production was the most sustainable current agriculture practice, while breadfruit agroforestry was the most sustainable strategy overall.

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Chapter One: Thesis Introduction

Purpose of Thesis

The world's ecosystems are rapidly changing (Chapin et al. 2000; Mascaro et al. 2008; Vitousek et al. 1997). However, this change has become so severe that we have crossed into a new era of human-dominated ecosystems: the Anthropocene (Morse et al. 2014). As a species, humans depend on ecosystems for continued existence, yet have managed to co-opt the majority of ecosystem goods and services for our needs (Ellis et al. 2010; Fisher et al. 2009; Seabrook et al. 2011; Tognetti et al. 2010). Underestimating the impacts of human-oriented ecosystem management practices negatively affects societies, leading to major environmental alterations that may greatly reshape the world as we know it (Hobbs & Harris, 2001; Standish et al. 2012). As consequences of these alterations accumulate over time, affected species may react in newfound ways, dispersing more rapidly or over a greater area than before (Chapin et al. 2000; Ellis et al. 2010; Hobbs et al. 2009; Montoya & Raffaelli 2010). Because human decisions altered underlying ecosystem conditions, these reactions can be described as 'novel' – existing without precedent in historical reference conditions or modern counterparts (Hobbs et al. 2009). Human impacts leading to novel conditions may alter ecosystem functioning and service delivery in biodiverse regions such as tropical forests (Corlett 2012; Lugo 2009; Whitmore 1997; Willis et al. 2010). While these impacts may not be fully understood, there is an increased need to recognize alternative management strategies needed to address novelty and novel ecosystems in these regions (Lugo & Helmer 2004). Understanding the background of current management practices leading to, and continuing during, novel forest development may assist in attuning management to ecosystem capabilities. Novel management including the Iban case discussed in this thesis provides a premise for preferred outcomes partially addressed by adapting current techniques. This work attempts to link these notions by proposing that management in novel tropical forests currently impacted by humans should incorporate agroforestry techniques.

People who live in tropical landscapes often shape their environs (Chazdon et al. 2009b). The work presented in this thesis is one perspective toward including humans as a dependent variable within greater ecosystem functioning. Truly unified socio-ecological work is rare: difficulties exist in defining essential disciplinary components as well as emphasis of their contribution to the final research product. As permitted by the confines of doctoral study, this thesis takes an ecological and management lens within a larger socio-ecological framework, situating discussion within the greater spheres of ecosystem management, natural capital, and novelty. Such work acknowledges that management goals and preferred life ways often conflict between different populations, but examination of said conflict is outside the biophysical scope of this research. Additional work on conflict resolution will be required to enact long-term management recommendations, including those presented in the following chapters. Further, while sustainability as a concept is presented in this thesis, said presentation occurs within a biophysical lens. This thesis does not purport to offer a discourse on traditional notions of sustainable development, within the study region specifically or tropical rainforests in general. Rather, as noted with conflict resolution above, the work presented in this thesis presents a bridge between externalized 'solutions' for human sustainability and those acknowledging human-ecosystem connections. Further socio-political and economic research would augment thesis findings, particularly as they pertain to the case study region.

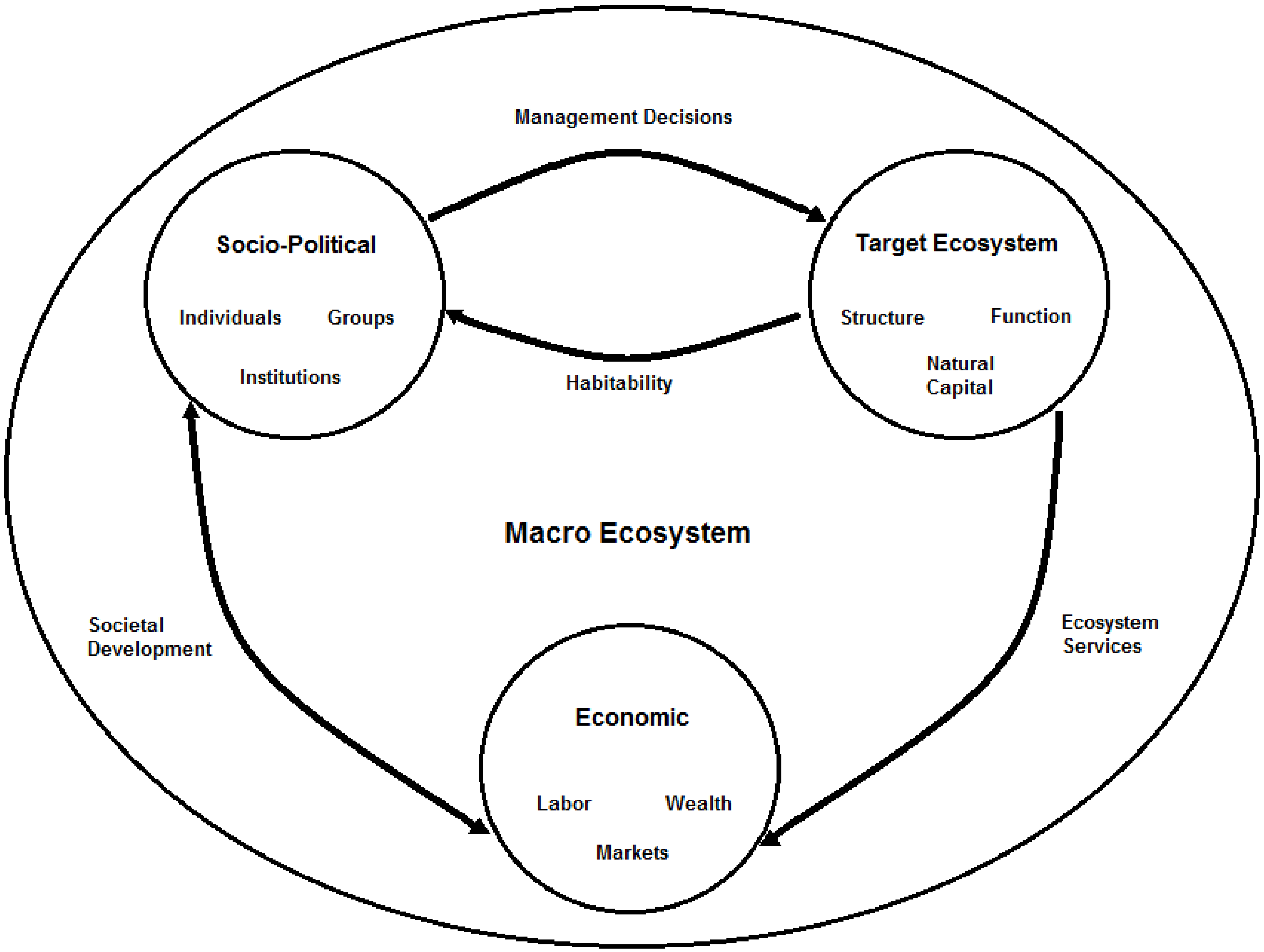

Figure 1. Thesis Macro Ecosystem Research Framing. This thesis presents a biophysical approach to examining the target rainforest ecosystem type, linked to socio-political and economic discourses through management decisions, habitability, and ecosystem services (after Niemeyer 2014).

Research Goals and Objectives

The presented research examines land management strategies and their effects in tropical rainforests of western Borneo. This research included description of current practices, determined production and management outcomes, and examined how management strategies affect biodiversity. The main goals of this research were to assess physical measures of management effectiveness as well as local views and official stances on management practices in high-sensitivity rainforest ecosystems. Objectives for this research include the following:

1. Comparing land manager views of subsistence agriculture and conservation forestry land management strategies;
2. Assessing strategy sustainability through emergy analysis to inform management alterations in Borneo and similar ecoregions of the humid tropics; and
3. Examining the consequences of these management strategies in terms of biodiversity, carbon storage, and livelihood production.

Some authors such as Murcia et al. (2014) label novel management as a means to circumvent restoration. The work presented in the following chapters discusses aspects of current agroforestry-based techniques as an appropriate and potentially efficient management response to novelty in degraded tropical forests. The preceding objectives exist to provide socio-economic background for such a supposition; to compare current conditions with potential management alternatives; and to view both context and comparison in context ecosystem traits and services as well as manager desires. This thesis does not propose that any alternative novel management strategies should be employed where restoration is more appropriate, nor does it propose that novel management should be favored over conservation in any circumstance. While valid and necessary, such discussions are outside the scope of this research and thus excluded hereafter.

Data Acquisition

Research included both quantitative survey questions and open-ended interviews. Study questions assessed current ecosystem conditions, management needs, and study participant desires to provide a baseline for comparison and potential future system alterations. Interviewees included subsistence farmers among indigenous forest-dwelling peoples as well as officials from the state-level government agency Sarawak Forestry. Participant questions ascertained how land management practices currently function, how participants interpret externally-based practices, and how participants understand long-term land management planning in general. Survey questions and resulting discussion attempted to determine overall ecosystem production and also plant species important for resource security and ecosystem services. Interviews explored what ecosystem management techniques are common, including where novel ecosystem management strategies currently exist. Interview questions also attempted to assess interactions between methods utilized by informants and those favored by others, what informants consider 'ideal' management strategies, and where 'ideal' or other management alternatives might better achieve respective strategy goals. Survey and interview data were combined and standardized.

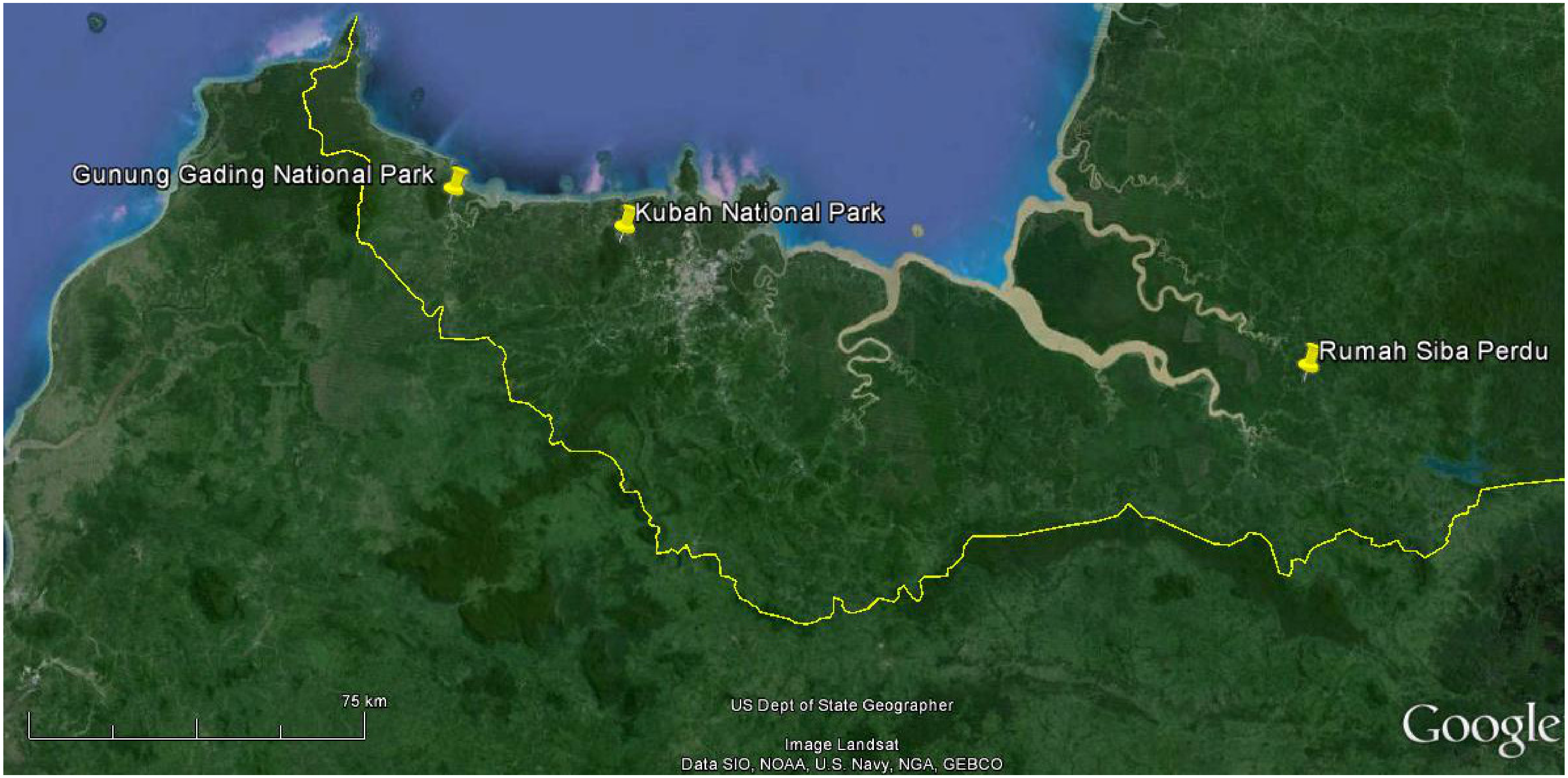

Figure 2. Southwestern Borneo showing study sites in Sarawak, Malaysia (Image courtesy of Google Earth).

Study Strategies and Locations

This research examined various land management strategies in Malaysian Borneo. Specifically, the included case study focused on lowland dipterocarp rainforests in the the southwestern portion of Sarawak. Ease of access, current political stability, and the preliminary recommendations of multiple informants guided study area selection. Varieties of land management strategies are available in tropical regions, and many of these are present in Sarawak. This research examined ten management strategy types. Such strategies include traditional or indigenous subsistence production, cash cropping, and government-based conservation forestry, among others. Areas examined included Kubah National Park, the Matang Wildlife Centre, Gunung Gading National Park, and the indigenous Iban settlement of Rumah Siba Perdu. Kubah NP is located at 1° 36'46 N and 110° 11'48 E, 136 meters elevation while Gunung Gading NP is located at 1° 41'26 N and 109° 50'45 E, 54 meters elevation. Rumah Siba Perdu is located at approximately 1° 20' N and 111° 35' E, elevation 120 meters.

Overview of Thesis

Chapters two, three, and four are all manuscripts developed for submission to peer-reviewed scientific journals. Chapter two presents the need for alternatives in tropical forest management that combine production and restoration. Degraded forests, including those showing increasing degrees of novelty, may benefit from new management techniques. Such techniques may serve to counter human impacts by rebuilding forest structure in ways that benefit services and affected species therein. New management strategies should address the extent of hybrid or novel conditions as well as agro-successional techniques during development. This chapter means to inform the specific discussion and analysis of current Bornean tropical forest management strategies in the following chapters.

Chapter three is a manuscript presenting current management strategies in the study area and interpretations by government forestry officials as well as subsistence and cash crop farmers in indigenous settlements. The chapter presents analysis of interviews regarding management strategies in lowland dipterocarp forests. Physical measures of biodiversity in Borneo are well-documented (Meijaard & Sheil 2007). The main foci of biodiversity conservation in Borneo includes species such as orangutans (*Pongo pygmaeus*), Borneo elephants (*Elephas maximus borneensis*), and other large fauna, as well as a range of flora (Fernando et al. 2003; Nantha & Tisdell 2009; Rabinowitz 1995). However, what qualitative measures of biodiversity mean to human populations, such as perceptions, remains open to discussion. Findings explain how different strategies can lead to conflict, and that opinions held by land managers, population growth, and management techniques influences conflict. Also included are perceptions of management effects on biodiversity conservation and their their effects on carbon storage and livelihoods. Results indicate similar management concerns in both groups, and incorporating new agroforestry-based strategies as a potential compromise.

Chapter four is a manuscript describing the research study site, emergy analysis methods, and principle findings of the emergy analysis. The research results are from emergy interviews conducted in the ethnic Iban community of Rumah Siba Perdu and state-level protected areas of Kubah National Park, Matang Wildlife Centre, and Gunung Gading National Park, Sarawak, Malaysia. The chapter presents analysis of interviews regarding ten management strategies. Interviews determined land area of single-crop and multi-crop combined management strategies for respective land managers; labor performed annually by land managers; purchased resources for strategies; and annual production of respective strategies for upland rice (*Oryza sativa*), manioc (*Manihot esculenta*), peppercorn (*Piper nigrum*), and latex (*Hevea brasiliensis*). Also examined are potential agroforestry-based alternative land management strategies focusing on sago (*Metroxylon sagu*) and breadfruit (*Artocarpus altilis*) production. The manuscript also includes emergy system diagrams, an emergy signature diagram, a calculation example, and additional tables to explain analysis findings.

Chapter five summarizes the research findings within the greater context of novel and tropical forest ecosystem management. The chapter summarizes and reflects upon the research findings as well as recommends future work to augment overall project research. Further, the chapter proposes applicability of Rumah Siba subsistence strategies, suggested agroforestry-based alternatives, and novel tropical forest management strategies on Borneo and in similar ecoregions of the humid tropics. The chapter concludes with an example project employing important assertions and conclusions made in this thesis.

Chapter Two: Literature Foundations

Ecosystems and Humanity

The term “ecosystem” generally refers to interactions of connected energy cycles between and among species that result in changes over a given area (Müller 1997; Odum 1969). Ecosystems also refer to the dynamic complex of biotic communities and abiotic conditions in a given location (Suding 2011). Ecosystems fall under the realm of ecology, the study of interactions that affect organism abundances and distributions (Jelinski et al. 1992). Ecosystems are 'working' examples of environmental processes, self-regulating within certain bounds (Dierssen 2000). Temperature, humidity, topography, altitude, and other biophysical characteristics such as soil communities and vegetation also affect these boundaries (Gray 2005). Interactions as functional units, above or belowground vertical structure, and horizontal dimensions including latitude and longitude can describe ecosystems as well (Gray 2005; Mace et al. 2012). All ecosystems are somewhat influenced by human activities, ranging from minor peripheral effects through complete domination of all processes therein (Clewell & Aronson 2007; Vitousek et al. 1997). Shortsighted ecosystem management choices and high-impact ecosystem alterations such as extensive land clearing and deforestation have negative consequences for ecosystems (Saunders et al. 1991). Further, ecosystem response to change is often unpredictable (Folke et al. 2004), while many human-based ecosystem alterations are difficult or impractical to overturn (Hobbs et al. 2009; Hooper et al. 2005; Hulvey et al. 2013). New and unprecedented conditions require examination of current management practices and well as developing new protocols. The following sections present several topics to assist in framing this thesis with respect to ecosystem management, ecosystem characteristics, and measuring human impacts within ecosystems.

Managing Ecosystems

Ecosystem management is an evolving concept with several interpretations. Preserving ecological integrity, along with specific goals of maintaining population viability, promoting ecosystem distinction, maintaining underlying processes, safeguarding evolutionary potential, and accounting for human use therein, all underlie conventional ecosystem management practices (Grumbine 1994). Such management originates from one of five perspectives: dominant use, multiple use, environmentally-sensitive multiple use, ecosystem-based resource management approaches, and ecoregional management. Dominant use is anthropocentric, focusing on ecosystem production oriented toward human ends such as those in agricultural contexts. “Multiple use”, while similar to “dominant use” in its human focus, attempts to satisfy more than one objective. Though still anthropocentric, the environmentally-sensitive multiple use perspective additionally recognizes environmental limitations beyond multiple use management. Ecosystem-based resource management approaches are ecocentric applications of knowledge gained from scientific study. While the most common management practice, ecosystem-based resource management tends to operate below the ecosystem scale. In contrast, ecoregional management operates at the ecosystem scale while recognizing the need for understanding ecological integrity and more sustainable use (Yaffee 1999). Segregating production and conservation areas is the dominant land use strategy (Scherr & McNeely 2008), with uses classified as natural, production, or urban (Seabrook et al. 2011). Most anthropogenic production falls within dominant use or multiple use, while conservation and restoration goals are in other perspectives (Yaffee 1999). As a result of the command-and-control approach to ecosystem management (Holling & Meffe 1996), anthropocentric and ecocentric goals often conflict (Scherr & McNeely 2008). This conflict is both multi-faceted and value-laden, requiring scrutiny of past techniques and development of new methods to respond to change (Ludwig 2001).

Simultaneous application of both conservation and restoration approaches is often necessary for addressing human impacts on ecosystems (Dobson et al. 1997; Young 2000). Managers focused on conservation-based strategies aim to maintain or promote biodiversity while protecting ecosystems from harm (Soulé 1985). Those utilizing restoration techniques strive to counter the effects of human mismanagement, including species reintroductions or other means to repair degraded conditions (Young 2000). Open-ended restoration emphasizes minimal intervention, relying more on self-organization in response to initial restoration conditions (Hughes et al., 2012). While removing some of the human element from restoration, open-ended restoration is less appropriate in ecosystems heavily influenced by human activities or those dependent on internal processes (Hobbs et al. 2011; Hughes et al. 2012; Standish et al. 2012). Responsive intervention focuses on creating new species habitat in new areas to conserve and restore natural capital, with restoration interventions specifically intended to address the effects of climate change. Interventionist approaches tend to encourage flexibility in achieving restoration goals (Harris et al. 2006). Proactive restoration differs from traditional restoration by allowing more flexibility in species assemblages or overall processes. Ecosystems restored using proactive methods focus on elements that may encourage self-organization toward ecosystem states better suited to changing environmental conditions (Manning et al., 2009). These trajectories range from historical analogs to completely new ecosystem types (Hughes et al. 2012; Jørgensen & Mitsch 2000; Hobbs et al. 2006).

Without complete understanding of how anthropogenic pressures affect secondary succession, conservation and restoration efforts risk misapplication (Tognetti et al. 2010). Restored ecosystems may not replicate reference conditions, or may fail to maintain integrity over time (Funk et al. 2008; Rey Benayas et al. 2009; Suding 2011), requiring interventions beyond restoring historical species assemblages and processes (Hobbs et al. 2011). Restoration should instead focus on establishing ecosystems with future conditions in mind and multiple alternative trajectories to account for unpredictability (Choi 2007). While comparing ecosystem processes requires reference conditions (Simenstad et al. 2006), shifting restoration goals toward ecosystem function may be a more useful alternative in changing circumstances (Palmer et al. 1997). Benchmarks for restoration success should instead focus on ecosystems that contain native species, normal functioning and functional groups required for long term stability, similar community structure and diversity compared to reference conditions, self-sustain breeding populations and underlying ecosystem structure, eliminate potential threats while maintaining resilience, and integrate into their surroundings (Ruiz-Jaen & Aide 2005). Accounting for changing circumstances allows for increased likelihood in meeting restoration objectives and actively counter the effects of human impact (Suding 2011).

Natural Capital and Ecosystem Services

When humans attach value to ecosystem effects, these values refer to ecosystem goods and services that benefit humans and other species (hereafter referred to as ecosystem services) (Costanza et al. 1997; Harris et al. 2006; Hooper et al. 2005). Though formal discussion of ecosystem services has expanded rapidly in the last three decades (Fisher et al. 2009), ecosystem functions typically mean properties or processes within an ecosystem that draw from 'natural capital' stocks to produce ecosystem services (Costanza et al. 1997). Natural capital is the quantity of raw materials or information in an ecosystem, while drawing from natural capital refers to material or information transfers in ecosystems (Mace et al. 2012). Ecosystem functions can produce multiple ecosystem services while multiple functions may be required for producing a single service. Ecosystem structure resulting from numerous biotic and abiotic processes determines ecosystem function and subsequent service production (Fisher et al. 2009).

Ecosystem services usually fall into one of the following categories: provisioning, regulating, supporting, and cultural services (Fisher et al. 2009; Mace et al. 2012). Provisioning services include immediate benefits such as food production, regulating services include background benefits such as carbon storage, supporting services include peripheral benefits such as habitat provision, and cultural services include societal benefits such as scientific discovery. Benefits from ecosystem services include directional benefits to specific locations, omni-directional and benefitting areas in around areas near service production, or in-situ and only providing benefits near service production. An example of a directional benefit is erosion control, while carbon storage is an omni-directional benefit, and soil formation is an in-situ benefit (Fisher et al. 2009).

Humans exploit the environment, manipulating natural capital stores and ecosystem functions through labor inputs and other resources (Costanza et al. 1997; Harris et al. 2006). When altered species composition changes ecosystem structure and natural capital stores, available ecosystem services change as well (Hooper et al. 2005; Montoya & Raffaelli 2010). Ecosystem service decreases result in significant costs to society, especially when combined with the effects of species loss, positive feedback loops, and exceeding environmental tipping points (Chapin et al. 2000; Costanza et al. 1997). Examining the effects of human impact on sensitive ecosystems is one means for understanding novelty and its consequences for delivering existence-supporting ecosystems services.

Novel Ecosystems

Novel ecosystems contain new or uncommon species combinations due in some capacity to human influence (Catford et al. 2012; Hobbs et al. 2006; Montoya & Raffaelli 2010). Influences leading to novelty range from indirect effects of anthropogenic climate change, such as altered growing conditions, to complete or active ecosystem alterations and reorganization (Hobbs et al. 2006; Morse et al. 2014). All future ecosystems may exhibit novel traits, though some suggest this transition process has already occurred (Ellis et al., 2010; Seastedt et al., 2008). Impacted ecosystems can be described as existing on a 'novelty continuum' that ranges from slight alterations of ecosystem trajectories, such as shifting native species dominance, to wholly new ecosystems defined by markedly different species abundances, new species introductions and invasions, or otherwise previously-unknown ecosystem functioning (Hobbs et al. 2006; Mascaro et al. 2008; Montoya & Raffaelli 2010). The resulting ecosystems are 'hybrid' ecosystems, with intermediate levels of biotic and abiotic change beyond historical reference conditions, though not having fully transitioned to novel ecosystems proper (Catford et al., 2012; Hobbs et al., 2009; Tognetti et al., 2010). Even with distinctions between natural and novel ecosystems varying and difficult to define, novel ecosystems cover vast expanses, ultimately resulting in global influence (Johnson 2002; Mascaro et al. 2008; Lugo 2009). However, as explicit boundaries between hybrid and novel ecosystems are often lacking, many authors question scale and severity when discussing novelty (Catford et al. 2012; Hobbs et al. 2006; Mascaro et al. 2012; Standish et al. 2012). These discrepancies lead to three variations in defining the novel ecosystems concept:

1. *All Anthropocene ecosystems are novel.* Acknowledging that human influence affects all current ecosystems, all display at least some novel characteristics (Mascaro et al. 2008). Including hybrid, emerging, and other ecosystems along the novelty continuum, most or all ecosystems are now novel (Seastedt et al. 2008).

2. *Only ecosystems influenced by past human activities are novel.* Past human influence can orient ecosystems toward novel trajectories otherwise not found in any reference or alternative ecosystem state. However, ecosystems that exist only as a result of current intense management are not part of the novelty continuum. Dedicated agriculture or silviculture plots are examples of human-influenced ecosystems excluded from this perspective (Hobbs et al. 2006).

3. *Ecosystems arising out of past management or less-intensive current management are novel.* Decreasing or concluding intense management does not necessarily define an ecosystem as novel or hybrid. However, this interpretation includes restored ecosystems, intentional ecosystems such as agroecological systems, and others with less intensive management than dedicated production ecosystems along the novelty continuum (Doley et al. 2012; Mascaro et al. 2012).

A necessary distinction, the work presented in this thesis exists at the "boundary" between the second and third conceptual variations. Because perspectives vary and contain elements of others, adhering to a rigid framework can be difficult as ecosystems move along the novelty continuum. The case study herein presents a "snapshot" of current management practices that include varying degrees of transition that collectively result in novelty. However, because this transition includes both current intense management as well as ecosystem portions otherwise removed from active human management, actively segregating ecosystem sections may limit the potential of proposed management alternatives. The scale of human impact varies over time as does intensity of impacts in a given location, resulting in mosaics of reference, hybrid, and novel conditions. Acknowledging this increases the potential of alternatives that promote ecosystem functions and services desirable to managers over longer timeframes.

Understanding functional characteristics of novel ecosystems is a necessity when altering and adapting management strategies (Harborne & Mumby 2011; Hulvey et al. 2013). Initial consequences for local diversity are unknown, while ecosystem function may change in response to altered native species abundances and successional patterns (Hulvey et al. 2013; Kueffer et al.

2010; Mascaro et al. 2008). Novel ecosystems dominated by introduced species can replace or become more abundant than native ecosystems in some areas (Lugo 2009; Mascaro et al. 2008; Wilsey et al. 2009). Introduced species therein can coexist, co-dominate with natives, or entirely replace native species as biodiversity alters along the novelty continuum, resulting in ecosystems with no evolutionary precedent (Wilsey et al. 2009). In addition, climate changes affect individual species and their distributions differently, adding to the already-difficult circumstance of predicting changes to species composition, process rates, and ecosystem function in novel contexts (Harborne & Mumby 2011). Further, ecosystems transitioning to novel states present restoration challenges as reference ecosystems themselves may already express novelty (Korb et al. 2012). As a result, novelty often precludes past or current ecosystem management strategies (Hulvey et al. 2013; Seastedt et al. 2008).

Often, there are considerations in ecosystem management that undermine the value of certain ecosystems, their processes, or other factors. These considerations present difficulties in restoring novel ecosystems to reference conditions, especially where barriers to achieving restoration goals exist (Hobbs et al. 2004; Hulvey et al. 2013). Ecological barriers such as positive feedback loops, social barriers such as budgetary limitations, or some combination of barriers are likely to cause apprehension and possibly opposition when managing novelty in ecosystems (Hulvey et al. 2013; Minteer & Collins 2010; Standish et al. 2012). Yet addressing novelty in ecosystems requires careful consideration of possible consequences – we tread new ground in novel ecosystem management (Seastedt et al. 2008; Standish et al. 2012). Even in such circumstances where novel strategies are more compatible with management goals, accounting for novelty in ecosystem management could be misinterpreted as irresponsible or foolhardy (Firn et al. 2010; Hobbs et al., 2004).

Biodiversity

One of the most substantial sources of novelty results from altering ecosystem biodiversity. Biodiversity refers to diversity ranging from genetic to ecosystems scales, and includes spatial distribution, varieties, relative abundance, and interactions in ecosystems (Chapin et al. 2000; Gray 2005; Hooper et al. 2005; Mace et al. 2012). Biodiversity often encompasses both species richness, or the total quantity of species present, and diversity, or more general attributes such as composition and relative abundance (Hooper et al. 2005). Structure, including composition, richness, and evenness, as well as interactions between species attempting to secure available resources, dictates the role of biodiversity in communities and ecosystems (Mascaro et al. 2012). Composition is the spatial distribution of species over a given area, richness is the quantity of present species, and evenness is the abundance of individual species (Chapin et al. 2000; Hooper et al. 2005). Mutualism, competition, predation, and parasitism are examples of species interactions (Hooper et al. 2005), while groups of organisms are known as communities (Odum 1969). Certain species can strongly affect ecosystem function, influencing abiotic and biotic processes (Chapin et al. 2000). However, higher biodiversity can aid in ecosystem disturbance responses by resisting, absorbing, or stabilizing disturbance effects (Fisher et al. 2009; Hooper et al. 2005; Mace et al. 2012). Biodiversity contributes directly to some ecosystem services, while higher biodiversity is required for ecosystem function and service delivery (Hooper et al. 2005). Ecosystems managed with biodiversity as a goal are often advantageous or preferred due to associated aesthetic, cultural, educational, recreational, and religious values (Mace et al. 2012).

All species contribute to ecosystem processes, albeit unequally, with alteration or loss of species therein having potentially dramatic effects (Chapin et al. 2000). Non-native, non-endemic, introduced, alien, and exotic all refer to species that exist outside their natural range (Pyšek & Richardson 2010; Seddon 2010). Non-native species are naturalized or invasive depending on proliferation extent, consequent environmental effects, and interactions with native species (Pyšek & Richardson 2010). For example, non-native species may outcompete natives in an ecosystem where they are introduced (Phillips 1997; Seddon 2010). These non-natives may more readily establish, naturalize, or overtake natives in response to changing environmental conditions, which can greatly impact native species biodiversity and subsequent ecosystem properties (Montoya & Raffaelli 2010). As invasions by ecosystem-dominating non-natives have increased over the last century (Pyšek & Richardson 2010), invasive non-natives are now major community components in modern ecosystems including many areas of conservation priority (Kueffer et al. 2010; Tognetti et al. 2010).

Tropical forests are among the world's most biodiverse ecosystem types (Phillips 1997). Many tropical forests have much greater species richness than other regions, and over half of global species are contained therein (Shulka et al. 1990; Whitmore 1997). While the majority of terrestrial biodiversity hotspots (15 of 25) are in tropical forests (Myers et al. 2000), high amounts of species persist most affected areas (Corlett & Primack 2008). Due to the higher total number of endemic species present, there is a higher likelihood of extinction from human impacts in tropical forests. However, extinctions may not be immediate or noticeable over shorter time frames (Whitmore 1997). Converting forests to other uses and intensifying agriculture compromise biodiversity in tropical forests (Bhagwat et al. 2008). Such alterations may not harm tropical forests overall, but surpassing thresholds may result in degraded ecosystems states (Phillips 1997) that can negatively affect surrounding ecosystems (Parrotta et al. 1997). In some tropical forest contexts, functional changes caused by anthropogenic biodiversity alterations can be detrimental to native species (Mascaro et al. 2012). In others, such changes have marginal or even beneficial effects on native species (Lugo 2004; Lugo & Helmer 2004; Mascaro et al. 2012). As human-mediated effects have accumulated over time, most tropical forests have adjusted, causing a new period of novel tropical forests (Lugo 2009). Such forests can benefit from new management practices influenced by a variety of perspectives (Chazdon 2008; Hulvey et al. 2013). Accounting for both biodiversity restoration and production when restoring degraded forest lands can simultaneously enhance ecosystem functioning, resilience, and livelihoods (Lamb et al. 2005).

Self-organization

Ecosystems are dynamic biological systems but tend to stabilize toward 'mature' or climax communities through the process of self-organization (Barkmann & Windhorst 2000; Fränzle 2000; Odum 1983). Self-organization provides order through spontaneous interaction of ecosystem components, moving ecosystems away from energetic equilibrium with their surroundings (Fränzle 2000; Müller 1997; Odum 1983). Dominant species influence self-organization and ecosystem attributes. Where introduced species dominate, they shift self-organization toward altered ecosystem processes in support of their continued dominance such as novelty (Denslow & Hughes 2004). For example, following agricultural abandonment, introduced species often initiate secondary succession, driving self-organization toward ecosystems that do not resemble those prior to human impact (Mascaro et al. 2008). Such shifts can be sudden and possibly catastrophic, greatly altering ecological resource availability (Rietkerk et al. 2004). Ecosystems self-organizing around exotics and other anthropogenic ecosystems, including those on the novelty spectrum, are thus likely to differ greatly from their historical counterparts (Montoya & Raffaelli 2010).

Complexity

As ecosystems self-organize and develop toward mature or climax states, they tend to become more complex as well (Müller 1997; Odum 1983). Complexity of interactions between species determines population and ecosystem continuity (Montoya & Raffaelli 2010). Ecosystems that have decreased self-organization and resulting complexity, such as those in agricultural contexts, are less likely to provide habitat for establishing species. In contrast, ecosystems that are more complex tend to provide conditions that encourage species establishment (Tscharntke et al. 2005). Increasing species combination complexity may compliment resource use patterns, resulting in further enhancements to other ecosystem processes (Hooper et al. 2005), while complexity altered from within may also affect ecosystem processes (Rietkerk et al. 2004). Further, socio-ecological interactions that surround ecosystems are increasingly complex as well, encouraging management decisions oriented toward maximizing the number of favorable available options (Hulvey et al. 2013; Standish et al. 2012). Goals set by managers affect the potential impacts of management options, and options that meet multiple goals simultaneously maximizes their application suitability (Hulvey et al. 2013). While convenient to interact with ecosystems in this fashion, compromising the ability to return to historical ecosystem states results in new ecosystems with altered functional complexity, requiring alternative management strategies to cope with these newfound conditions (Hulvey et al. 2013; Standish et al. 2012).

Functionality

Combined effects of species interactions, influenced by factors such as self-organization and complexity, result in ecosystem functions (Doney et al. 2012). Functional group diversity, species and population diversity, and species diversity within functional groups are essential for functions in complex ecosystems subject to change (Folke et al. 2004; Hobbs 2004). Functional group diversity refers to types of organisms associated with a specific ecosystem role. Altering functional groups, thus changing how ecosystems function may have severe consequences (Folke et al. 2004). For example, altered functions can vary process rates in ecosystems, affecting natural capital storage and resulting ecosystem service delivery (Hooper et al. 2005; Montoya & Raffaelli 2010). Variety in organism traits, types, and groups within an ecosystem influences functional diversity (Hooper et al. 2005). Further, ecosystem functions are often redundant. Redundancies include real redundancy, where species overlap in their responses to change, as well as more apparent redundancy, where species perform the same function but respond similarly to change (Folke et al. 2004). There are different ways to describe ecosystems, and these characterizations are dynamic. Functions of ecosystems are also dynamic, and can refer to the effects of ecosystem properties or to the compounded effects of ecosystem properties, goods, and services. Ecosystem properties are the quality or quantity of ecosystem resources and process rates (Hooper et al. 2005). Ecosystem functions and properties change in response to new species entering an ecosystem (Denslow & Hughes 2004). In ecosystems influenced by anthropogenic pressure, such changes may mask the effects of other alterations such as climate change (Yakob & Mumby 2010). As in the previous sections, functional changes resulting from human activities can encourage ecosystems to advance along the novelty spectrum (Montoya & Raffaelli 2010), possibly reinforcing the continuity of novel functions.

Resilience

Resilience is the severity of disturbance an ecosystem can absorb prior to reorganizing into an alternative ecosystem state (Holling 1973; Manning et al. 2009). Alternatively, resilience is the speed an ecosystem can return to its previous state following impacts (Groffman et al; 2006; Suding et al. 2004). Resilience is useful for understanding dynamics in socio-ecological systems, as humans are agents of ecosystem change (Folke 2006). Four essential attributes of resilience include resistance, latitude, precariousness, and cross-scale relations. Resistance is how much force is required to move from one ecosystem state to another. Latitude regards the maximum amount of change an ecosystem can endure prior to this transition. Precariousness is how close an ecosystem is to an alternative state. Cross-scale relations refer to the interplay of these factors within the portions of the ecosystem, the ecosystem as a whole, and external influences on the ecosystem (Folke et al. 2004; Suding et al. 2004). Interplay between these attributes affect how likely degraded alternative states will return to a desired pre-disturbance state without intervention, or that intervention may have unintended consequences for resilience (Folke 2006; Suding et al. 2004)

Humans affect resilience through management alterations that can decrease biodiversity and other factors supporting resilience (Folke et al. 2004). Higher biodiversity tends to equate with increased ecosystem resilience (Chapin et al. 2000), enhancing resilience of desired ecosystem states and increasing the likelihood of essential ecosystem service production (Elmqvist et al. 2003). By reorganizing into alternative state dominated by previously rare or infrequent species, some ecosystems can maintain resilience and ecosystem services (Yakob & Mumby 2010). However, decreasing resilience implies adaptability decreases, leading to feedbacks that may affect future resilience regardless of any ecosystem reorganization (Folke 2006). Instead, management can preserve underlying factors that maintain resilience-influencing traits such as biodiversity and self-organization (Elmqvist et al. 2003; Rietkerk et al. 2004), thus promoting. Resilience-based management will be increasingly important as ecosystems respond to human influences, especially those expressing novelty (Elmqvist et al. 2003; Suding et al. 2004).

Disturbance

Disturbance is any alteration of combined ecosystem attributes (Doley et al. 2012). Many ecosystem types are prone to disturbances, resulting in resilient non-equilibrium ecosystem states with difficult to define 'natural' disturbance regimes or species distributions (Spurgel 1991). Disturbances such as fire, wind, and ecosystem fragmentation are major forces behind development, structure, and function in some ecosystem types (Attiwill 1994; Spurgel 1991). Fire encourages change in many terrestrial ecosystems (Clewell & Aronson 2007). Wind-based disturbance is necessary for maintaining some ecosystem types. For example, wind causes tree falls that open forest canopies, benefitting forests by allowing additional light to enter and releasing nutrients while trees decompose (Attiwill 1994). Ecosystem fragments are isolated remnants of native vegetation (Saunders et al. 1991). Ecosystems (and ecosystem fragments) with high diversity of species with different response patterns, life history traits, and functional roles can assist in responding to disturbances (Hooper et al. 2005). Further, human-based disturbances affect almost all ecosystems and the underlying cycles that influence characteristics therein (Bowen et al 2007). Over-exploitation and other disturbances result in negative ecosystem effects, altering courses of ecosystem development and recovery (Bowen et al 2007; Saunders et al. 1991). Chronic or intense disturbance, such as that connected with human activity, facilitates invasion through increased resource availability (Denslow & DeWalt 2008). Management that results in fewer detrimental disturbances is less likely to require outside intervention or guidance toward desired recovery (Doley et al. 2012).

Intensity

Impacts from human influence increase in accordance with management intensity. Ecosystems can continue to function even if intensity increases, but this is less likely as ecosystems degrade (Clewell & Aronson 2007). Conservation may no longer be appropriate in high-intensity contexts, while restoration, repair, reclamation, and reinvention are suitable management alternatives. Restoration can return an ecosystem to historical conditions while repair is oriented toward increasing ecosystem functions and services. Reclamation can employ exotic species while focusing on productivity, while reinvention intends to increase ecosystem function in circumstances where restoring, repairing, or reclaiming may not be appropriate (Seabrook et al. 2011; Weber et al. 2011). Recreating historical species assemblages and ecosystem structure can be difficult, necessitating management that includes both biodiversity and ecosystem services (Mace et al. 2012). Management intensity influences the speed and severity of ecosystem transitions to hybrid or novel states. Rather, focusing on restoring ecosystem function through such combined strategies may be more beneficial in addressing ongoing human population pressures and environmental changes (Lugo & Helmer 2004).

Stability

Ecosystems include equilibrium and non-equilibrium states (Manning et al. 2009). Such alternative states represent possible combinations of ecosystem states and environmental conditions present at given location over time (Suding et al. 2004). Observed stability within known limits, maintenance of feedback mechanisms, and other measures of proposed alternative states support this claim (Scheffer et al. 2001; Seastedt et al. 2008). These states respond to external conditions (Scheffer et al. 2001), while alternate states may be less stable and resilient in response to changing conditions (Seastedt et al. 2008). Several internal and external processes regulate transitions between states (Firn et al. 2010). Even where stability is accepted, dramatic shifts in ecosystem states can occur without any indication or warning, prompting rapid management responses (Hastings & Wysham 2010). Often stable states are oriented toward attractors, or combined ecosystem state and environmental conditions that persist and resurface following disturbances (Suding et al. 2004). For example, positive feedbacks between limited ecosystem resources and consumers therein lead to changes in stability. Consumers in ecosystems respond to available resources, with resulting species dominance oriented toward species best suited to the current stable state (Rietkerk et al. 2004). Severe disturbances, including those caused by humans, can influence transitions to a new ecosystem state (Scheffer et al. 2001). Humans are responsible for most ecosystem transitions to alternative states, with human-induced novelty affirming other alternative states (Folke et al. 2004; Seastedt et al. 2008).

Thresholds

Thresholds are the boundaries between alternative ecosystem states (Folke et al. 2004). Thresholds are 'tipping points' where even seemingly insignificant environmental alterations result in large changes in ecosystem characteristics (Groffman et al. 2006; Suding et al. 2004). Alternative ecosystem states are sometimes difficult to define, with thresholds difficult to define as well (Beisner et al. 2003; Groffman et al. 2006). When disturbed beyond a threshold, functional roles and resilience are essential for ecosystem maintenance. As complexity and reorganization increase, regime shifts may become irreversible (Folke et al. 2004). This realization encourages more focus on regime boundary stability and crossing thresholds (Lansing et al. 2014), especially as threshold-crossing shifts are often unpredictable (Hastings & Wysham 2010). Human activities, such as those resulting in decreased biodiversity or others associated with novelty, often reduce resilience and other factors supporting the current state, increasing the likelihood that an ecosystem will cross a threshold (Groffman et al. 2006). Decreasing biodiversity may not affect ecosystem function or service production, but crossing a threshold may cause drastic reorganization, alternate function, and overall service production (Fisher et al. 2009). Restoring an ecosystem that has crossed a threshold may be impossible without costly interventions (Firn et al. 2010), having profound implications for native species conservation and rebuilding ecosystem functions (Tognetti et al. 2010). As humans influence blurs ecosystem thresholds, more appropriate management efforts may instead guide ecosystem toward desirable alternate states (Firn et al. 2010).

Sustainability

Sustainability is the capacity for persistence or continuity over time (Altieri 1995; Hooper et al. 2005; Torquebiau 1992). In ecosystems, sustainability refers to an ecosystem's innate ability to maintain biodiversity (Altieri 1995), or to replenish utilized resources at rates at least equal to their consumption (Bastianoni et al 2007). In ecosystem management, sustainability can mean meeting changing human needs without upsetting underlying ecosystem characteristics (Torquebiau 1992). Ecosystem management has many elements, some of which are unconnected, that determine resulting sustainability (Torquebiau 1992). Sustainable management goals can include the use of reference conditions, historical data, and other considerations, though these may differ, be inaccurate, incomplete, or otherwise not apply to current conditions (Swetnam et al. 1999). As biodiversity and environments change, ecosystem reactions to disturbance are less likely to be sustainable, thus increasing the probability of ecosystems transitions (Seastedt et al. 2008). Increasing biodiversity to augment ecosystem services by species required for specific ecosystem processes and functions can greatly increase the sustainability of managed ecosystems (Tscharntke et al. 2005). When accounting for novelty and human influence, the work presented in this thesis emphasizes the need for ecosystem managers to focus on these components when developing strategies oriented toward long-term sustainability.

Ecosystems and Energetics

Biological systems persist due to continued energy and information flows (Brown & Ulgiati 1999). One method to determine ecosystem sustainability is examining the efficiency of energy utilization therein (Ness et al. 2007; Sciubba & Ulgiati 2005). However, past energy evaluations did not take into account the effects of self-organization in ecosystems (Jørgensen et al. 2005), whether examined from genetic or whole-system levels (Jørgensen et al. 1995). Where biological systems self-organize toward more diverse, complex, and functional stable states, available energy tends to be used more efficiently (Fränzle 2000; Müller 1997; Odum 1983). Such stable states often organize toward more efficient energy use by both overcoming constraints and emphasizing processes that contribute to productivity (Brown & Ulgiati 1999), often moving a given stable state far from energetic equilibrium with surrounding environs (Weber et al. 1989). In contrast, ecosystems influenced by human activities are often oriented toward alternative states that result in decreased energy use efficiency (Bastianoni et al. 2007). For example, energy flows that alter biomass productivity may in turn alter other ecosystem processes, decreasing overall ecosystem sustainability (Bastianoni et al. 2007; Finn 1976). Because natural capital storage includes materials as well as the energy required for ecosystem processes, any additional energy expended in accumulating natural capital reflects in overall energy use (Bastianoni et al. 2007). Further, energy use and flows within ecosystems differ based on a variety of assumptions, ultimately affecting accuracy in ecosystem-based energy analyses (Odum 2002). Energy quality itself is a controversial topic, resulting in additional uncertainties in any calculations thereafter (Brown & Ulgiati 2004). Equalizing energy qualities for purposes of comparison, such as barrels of oil or solar equivalents, is problematic as such conversion relies on current assumptions that may not apply to energy conversions in the distant past (Ayres 1998). Energy stored in long-term natural capital, such as ecosystem-based energy leading to fossil fuels, is especially troublesome – system boundaries may greatly alter total energy storage over geologic timeframes, affecting resulting analyses (Hau & Bakshi 2003; Hau & Bakshi 2004).

Energy, exergy, and embodied energy analyses are three of many methods to determine the energy needed in converting natural capital to desired services (Bastianoni et al 2007; Brown

& Herendeen 1996; Sciubba & Ulgiati 2005). Energy analysis determines how much energy is required by a system in producing a good or service, but does not focus on optimizing energy nor does it include feedbacks for absorbing or processing waste (Brown & Herendeen 1996). Exergy is available energy within a system (Sciubba 2010), and its analysis concerns maximum possible energy efficiency when a system is in equilibrium with its surroundings (Bastianoni et al. 2007). While exergy analysis focuses on direct inputs to a system, it also includes information contained in ecosystem structure as well (Bastianoni et al. 2007; Bendoricchio & Jørgensen 1997). Emergy analysis determines the values of all resources within a system in terms of how much solar energy they contain, whether they are direct or indirect inputs (Brown & Herendeen 1996). This thesis utilizes emergy, and while often proposed as a more holistic analysis technique, emergy has many criticisms as well (Hau & Bakshi 2004; Odum 1996).

Inconsistencies persist with regard to how emergy is both defined and applied, leading some authors to describe emergy analysis as misleading, inaccurate, contradictory, or even overly simplistic (Bastianoni et al. 2007; Hau & Bakshi 2004; Sciubba 2010). Emergy is also a function of exergy when enlarged system boundaries include more input types (Bastianoni et al. 2007; Hau & Bakshi 2003). In many definitions, emergy is embodied *energy* (Brown and Ulgiati 2004) but may actually be embodied *exergy* when calculated (Sciubba 2010) or both terms may be equivalent in calculation (Hau & Bakshi 2004). Some have noted one of emergy's underlying principles, maximum empower, may be unsubstantiated. Ecosystems can self-organize toward states that maximize emergy use rates, but empower's universal applicability has been described as 'one-dimensional' and not appropriate for complex systems (Ayres 1998). Further, quantifying transformities and allocating between outputs are both problematic. Transformities assume degrees of certainty when converting emergy flow to a given ecosystem service, but may lead to calculation errors such as double-counting when applied universally. Similarly, allocation of emergy to multiple outputs as separate co-products or splits in the same emergy flow may alter final emergy calculations when considering geologic time and other scales (Hau & Bakshi 2004; Odum 1996). In both circumstances, emergy analysis supposedly accounts for all value within a system, not just economic value to humans. However, economic values fluctuate greatly even with similar emergy values, as variations in human value are wholly dependent on context, ultimately detracting from the potential usefulness of emergy in more anthropocentric contexts (Hau & Bakshi 2004). Understanding the basis for such fluctuations is needed for prescribing and enacting appropriate management practices, including those addressing novel conditions.

Chapter Three: Novel Tropical Forests – Seeing the Forest for the Functions of the Trees

Overview

We present an argument for alternative production and restoration management approaches in tropical forest ecosystems. Burgeoning population pressures affect current management decisions in tropical forests, often resulting in degradation and novel characteristics. Recognizing the immense impacts humans have on even lightly-managed tropical forests, a variety of agroforestry techniques can inform mixed-use management, rebuild natural capital, and recover the services provided by historical forest ecosystems. Placed in the context of novelty, the focus of such designs is not only to recover services preferred by local populations, but also services otherwise absent. Emphasis is placed on use of agro-successional techniques developed with ecoregional management, landscape fluidity, and applied historical ecology.

Introduction

All ecosystems show signs of environmental change, almost entirely due to human dominance and mismanagement (Chapin et al. 2000; Vitousek et al. 1997). Destructive land management techniques can result in high rates of ecological degradation and declines in function, compromising ecosystem service delivery (Eastmond & Faust 2006). Management alternatives to utilize ecosystems without compromising their integrity is a global concern, one that requires immediate solutions to provide for the world's rapidly increasing population in times of resource scarcity and climate change (Bhagwat et al. 2008; Parrotta et al. 1997). Tropical forest degradation is one such example of the need for long-term management alternatives. Tropical forests exist in five major regions: Asia, Africa, Madagascar, Central and South America, and Oceania, with each region distinct ecologically and biogeographically (Corlett & Primack 2008). These forests store over 40% of the world's terrestrial carbon, contain over 50% of global biodiversity, and comprise over 60% of all conservation priority hotspots. Further, over 85% of world's poorest people live in tropics (Bhagwat et al. 2008), with human populations increasing significantly faster in tropical regions than global averages (Bhagwat et al. 2008; Corlett & Primack 2008). Most land in tropical regions shows the legacy of human development and resultant degradation. Less than half of primary tropical forests remain, while many areas are significantly degraded (Lamb et al. 1997; Phillips 1997; Vieira et al. 2009). Forest recovery rates vary greatly depending on ecosystem type, natural capital stores, and past management intensity. Generally, forest degradation is more likely as swidden farmers extract resources from fallow or reserved lands, thus extend impact beyond production areas (Phillips 1997; Scherr & McNeely 2008; Vieira et al. 2009).

The most common response to minor degradation following tropical agriculture is fallows, or temporary abandonment periods meant to recover natural capital stores necessary for productivity. Though fallow length may not relate to productivity in shifting cultivation (Mertz et al. 2008), reducing or eliminating fallows can result in severe degradation and decreased natural ecosystem restoration (Parrotta et al. 1997). Instead, permanent abandonment occurs, with no intent of restoring past forests or returning land to production. Permanent abandonment of degraded agricultural land has increased in many tropical regions, and this increase will likely continue (Vieira et al. 2009). As dire as this circumstance sounds, areas in the tropics can naturally revert to secondary forest following abandonment, becoming important as regrowth forests (Parrotta et al. 1997; Bowen et al. 2007). While there can be a desire from landholders, scientists, and policymakers to restore abandoned agricultural areas to primary forest, the process is often hindered by socio-political conflicts and time constraints in tropical contexts (Vieira et al. 2009). One alternative is to consider a more multiuse strategy rather than 'pure' ecological restoration to provide for livelihoods while restoring other services and preventing further degradation to undesired ecosystem states. Such multiuse forests can lead to more emphasis on restoring ecosystem services – rather than all of the biodiversity – and creating a 'novel' ecosystem.

Ecosystem Services and Novelty

Ecosystems services represent an appropriate examination rubric, as the concept exposes the complexities of human-environmental interdependence. While recognized for millennia, formalized definition and discussion of ecosystem services has expanded rapidly in the last three decades (Fisher et al. 2009). Ecosystem functions usually refer to properties or processes, while ecosystems also produce goods and services that benefit humans and other species (Costanza et al. 1997). Ecosystem functions flow from 'natural capital' stocks to complete ecosystem service production. Such flows refer to material or information transfer within an ecosystem, while natural capital refers to the quantity of materials or information in an ecosystem (Mace et al. 2012). Ecosystem functions can result in the production of multiple ecosystem services, while multiple functions may be necessary for production of a single service. Structure or form of an ecosystem, as determined by a combination of biotic and abiotic processes, dictates ecosystem functionality and service production (Costanza et al. 1997). Humans often attach value to the combined effects of ecosystem functions, and these values refer to ecosystem goods and services (Hooper et al. 2005). Decreasing natural capital and ecosystem services threatens continued human existence (Costanza et al. 1997).

The concept of novel ecosystems is a useful examination perspective, as it contextualizes the effects of human influence on ecosystems. Novel ecosystems contain combinations of species that often lack a shared evolutionary history, with non-native species coexisting, co-dominating, or replacing native species during ecosystem development (Wilsey et al. 2009). Given the modified natural vegetation on all permanently inhabited continents, we argue that it is necessary to accept human interactions with ecosystems as a component of their management (Hobbs et al. 2006; Saunders et al. 1991). As there are often no defined boundaries as ecosystems transition to novel states, novelty may be a useful tool in sustaining agricultural production while restoring degraded ecosystems and their services (Catford et al. 2012; Standish et al. 2012). If management no longer has replicate past ecosystems, land managers can utilize new species mixes into novel plant communities that preserve or restore desired ecosystem functions and services. Experimenting with mixes of native and non-native species can allow managers to select more cost-effective means of rebuilding ecosystem structure and natural capital stores, promoting desired ecosystem services. Emphasizing certain ecosystem services at the expense of others could result in creation of functionally-degraded novel ecosystems (Standish et al. 2012; Wilsey et al. 2009). That said, combining production and restoration as well as including novel approaches will be essential to the future of ecosystem management as such multiuse designs may show greater resilience in response to adverse conditions. Multiuse designs may also prove more sustainable, requiring less human maintenance and external inputs such as chemical fertilizers or pesticides to produce desired species (Rayome 2010; Trujillo 1998; Vieira et al. 2009).

Conserving Ideals or Realities?

Conservation may present a net economic loss in many tropical regions, especially if financial and other costs are borne by local peoples (Corlett & Primack 2008). For example, many protected areas exclude native peoples living nearby, though most ecosystems include long-term interaction with human populations. Modern landscapes provide little flexibility in responding to environmental changes, with habitat loss and fragmentation decreasing the likelihood of unassisted species dispersal, especially relevant for species with low adaptive or dispersal capacities (Manning et al. 2009; Walther et al. 2002). Larger preserves are preferable to groups of smaller reserves in the same region, even if the total areas are similar (Corlett & Primack 2008; Odum 1983). Where smaller reserves are the only conservation option, these should be highly interconnected, nearby, or both (Odum 1983). Yet even when properly managed, forest reserves may be unable to protect all of their species (Phillips 1997). Thus, conserving remnant habitats is not enough for conservation; some form of restoration is usually necessary to preserve species affected by human activities (Bowen et al. 2007).

Past tropical forest interventions often focused on one of two options: either maximizing the output of nearby production landscapes, thus decreasing pressure on forest lands while allowing some passive restoration at production-forest boundaries, or more direct restoration techniques. Direct restoration techniques focus on replanting target species, but this requires substantial financial and time investments from project initiation until desired species have established. Recreating the high species diversity and structural complexity associated with climax tropical forests requires meticulous protocols (Lamb et al. 1997; Parrotta et al. 1997). However, many projects restore only certain species under the assumption that others will establish without human intervention. Associated time-lags present difficulties even with intense management and intervention, while natural succession is often slower than human time scales (Corlett & Primack 2008; Vieira et al. 2009; Weber et al. 2011). If managers intend to restore an ecosystem in both biotic structure and ecological function, they will find that approximating impact-free reference conditions is unlikely (Suding 2011). Instead, we argue that more practical courses in heavily-degraded contexts or those with conflicting human pressures should focus on strategies that yield as much ecological structure and function as possible. Misinterpreting how impacted some tropical forests are historically may preclude restoration to past states – they present a moving target, one that humans have and will continue to influence.

Natural biodiversity can be included in agricultural production contexts with neutral or even positive effects on productivity and livelihoods (Scherr & McNeely 2008). We argue that the increasing difficulties associated with complete ecosystem restoration calls for interim strategies to reduce impact on ecosystem structure and function while devising and implementing long-term management practices. Further, these 'eco-agriculture' landscapes can increase the quality of managed areas by interspersing combined production-restoration lands with conserved lands that act as ecological refugia and source habitats (Scherr & McNeely 2008). Eco-agriculture can include agroecology, agroforestry, or agro-succession (Altieri 1995; Bhagwat et al. 2008; McNeely & Schroth 2006; Vieira et al. 2009).

Where production and biodiversity goals meet, increases in multiuse management intensity can further reduce anthropogenic pressures on adjacent natural habitat (Vieira et al. 2009). Because of increasing human pressures, large-scale application of land management efforts that simultaneously restores forest ecosystems and meets the socio-economic requirements of affected populations is necessary in many tropical regions (Parrotta et al. 1997). Many strategies are available to manage secondary forest succession for restoration and production outcomes. Agro-successional restoration is one such technique. By varying and extending interim management periods, agro-successional restoration 'parallels' natural succession, thus benefitting rare or sensitive species. It can also reduce restoration expenditures as multiuse management efficiency gains conserve target species and provide for human livelihoods. Involving producers and local farms in the restoration process can counter many factors contributing to future degradation and losses in biodiversity and ecosystem service delivery (Jose & Gordon 2007; Nair 2006; Vieira et al. 2009).

Managing Ecosystems with Novelty in Mind

Using Hulvey et al.'s (2013) novel ecosystem management framework, managing for novelty requires understanding the extent of changes in an ecosystem, the forces behind those changes, and what forces prevent ecosystem recovery. If an ecosystem has changed, is this change within recognized states or has the ecosystem approached a new threshold? Is the ecosystem in question showing early signs of hybridization and can be restored, is it more hybridized and can allow restoration of only certain traits, or is the ecosystem now fully novel? Identifying the sort of ecosystem that currently exists will influence what management options are most appropriate (Chazdon et al. 2009a; Lamb et al. 2005; Lugo 2009). Understanding previous historical conditions is necessary, as they provide a background for guiding and contextualizing management adaptations. More specifically, identifying barriers to applying past techniques are crucial in future management decisions (Hulvey et al. 2013).

Social and ecological barriers may prevent even the most straight-forward ecosystem management options. Budgetary constraints, differing individual or social norms, and incomplete understanding of the current ecosystem, past management failures, or missing techniques can present social barriers. Examples of social barriers include ethical considerations when attempting to counter invasive species (Lindenmayer et al. 2008), heritage value (Standish et al. 2012), and perceptions of ecosystem 'greenness' (Hobbs et al. 2004). Presence of thresholds preventing return to historical conditions, positive feedback loops driving change toward novelty, interaction accumulation of multiple effects, and disconnections between management scales and underlying causes of change all present ecological barriers. These ecological barriers can include altered post-invasion fire regimes (Denslow & Hughes 2004), composition changes resulting in new ecosystem structure (Lugo 2009), and cumulative human influences at global scales (Morse et al. 2014). However, comprehending if current conditions can be overturned is sometimes vague, encouraging management decisions that account for such uncertainty as well as future conditions (Hulvey et al. 2013).

In ecosystems that have fully transitioned to novel states, we recommend goal-oriented management strategies. Management goals can include supporting native species and biodiversity, supporting or recovering ecosystem functions and services, or new management alternatives that account for modified species assemblages and resulting ecosystem functions. Managing for desired native species and biodiversity suggests removal of threats to natives, ensuring prerequisites for continued native presence, and guidance toward structurally-similar analogues, even if these include non-native species (Hulvey et al. 2013). For example, allowing non-native species to persist in Puerto Rican tropical forests facilitates native species recovery, with such forests providing many similar functions and services as past counterparts (Lugo & Helmer 2004).

Managing to maintain or restore desired ecosystem functions and services has a variety of benefits. Focus on a particular species or process therein may greatly affect overall function and services provided by a novel ecosystem, increasing the effectiveness of novel management

(Costanza et al. 2007; Hooper et al. 2005; Mascaro et al. 2012). New species combinations and subsequent functional responses might require new management techniques, including those that can adapt to changing circumstances. For example, relocating threatened species a subsequent ecosystem response may result in unanticipated peripheral effects, suggesting management that adjusts in response (Minteer & Collins 2010). Regardless of their goals, we suggest that managers should be prudent in developing new strategies and focus on the importance of conservation (Hulvey et al. 2013).

We are in a new era novel tropical forests (Lugo 2009), a consequence of human-driven novel ecosystem increases in the Anthropocene (Morse et al. 2014). As humans continue to impact the environment, decision-making processes affecting nature must adjust accordingly (Hobbs et al. 2006; Noble & Drizo 1997). Severe and often repeated ecosystem structure and function alterations often result in novelty, and by accepting this transition as a possibility, we can adjust management strategies accordingly (Hobbs et al. 2006; Seabrook et al. 2011). Increasingly, managers must be pro-active in the face of ecological uncertainty (Catford et al. 2012; Lugo 2009; Seasteadt et al. 2008). Anticipating local environmental and human populace needs requires employing non-traditional or alternative management strategies in these new conditions (Brockeroff et al. 2008; Doley et al. 2012; Kueffer et al. 2010). But how can managers apply such strategies in ecosystems such as tropical forests?

Applying Novelty in Tropical Forest Restoration

Application of novel ecosystem management must account for the underlying structures, functions, and services that differentiate tropical forests globally. Overuse of pan-tropical agroforestry species presents a situation where established forests may be unable to cope with insults such as pests or disease, especially if genetic material differs little between managed species. However, a combination of ecoregional management, landscape fluidity, and applied historical ecology is promising for maximizing the potential of novel tropical forests developed with agro-successional techniques (Manning et al. 1999; Swetnam et al. 1999; Vieira et al. 2009; Yaffee 1999). Ecoregional management recognizes the distinct ecological and biogeographical differences between similar ecosystem types including phenotypic expression, underlying genetic material, and effects on natural capital stores. Landscape fluidity is the 'ebb and flow' of organisms in a given area over time (Manning et al. 2009), while applied historical ecology is the use of knowledge about the past in ecosystem management (Swetnam et al. 1999). Modern applied historical ecology and paleoecology both support the notion that many tropical landscapes were once ecoagriculture landscapes, and that current 'pristine' areas self-organized after cessation of ecosystem management practices (Bhagwat et al. 2008; Clewell & Aronson 2007).

In many cases, guided reconstruction of forests could equate to the creation of novel forest ecosystems (Chazdon 2008). Interestingly, novel forests are increasing in abundance in unrelated locales such as Hawaii, Puerto Rico, and Florida (Chazdon 2008; Mascaro et al. 2008). Forests restored with nonnatives and wholly constructed novel tropical forests already exist, such as Round Island in Mauritius and Green Mountain of Ascension Island (Hulvey et al. 2013; Wilkinson 2004). Novel tropical forests in Puerto Rico and Seychelles show varying degrees of facilitating native species return based on context-specific management (Kueffer et al. 2010;

Lugo & Helmer 2004). Such novel forests often incorporate high amounts of non-native tree and other species, which can assist in ecosystem restoration and can also benefit native species, providing conditions favorable for colonization, growth, and development (Lugo & Helmer 2004; Mascaro et al. 2008). Using species favorable in agroforestry contexts increases the likelihood of preferred services, as agroforest managers can become active agents in the restoration process.

Agroforestry as a Basis for Novel Forest Structure

Similar to guided reconstruction, the ideal structure for agricultural production systems should mimic natural ecosystems (Scherr & McNeely 2008). By including tree and shade-tolerant understory species such as those utilized in agroforestry (Nair 2006; Scherr & McNeely 2008), agro-successional restoration landscapes can maintain production while restoring rainforest structure in humid tropical contexts. Traditional agroforestry practices promote retention of trees on cleared agriculture land, potentially leading to altered courses of ecosystem regeneration that result in novel ecosystem states (Jose & Gordon 2007; McNeely & Schroth 2006). In addition, agroforestry variants complement other livelihood practices such as field agriculture, hunting, and foraging, potentially decreasing human pressure from each (Nair 2006). Complex agroforestry systems are more supportive of biodiversity than monocrop systems, though they are dependent on nearby natural ecosystems for biodiversity inputs (McNeely & Schroth 2006). Agroforests with high canopy cover and less intensive management have higher richness and similarity to nearby forest reserves than those either with less canopy cover or more intensive management (Bhagwat et al. 2008). Further, agroforestry systems can assist in conserving biodiversity, acting as corridors between nature reserves, providing alternate habitat, and alleviating pressure in conserved areas (Bhagwat et al. 2008; Jose 2009). In some regions, trees have such a prominent place in managed areas that the difference between forest, regenerating fallows, and agroforestry is not immediately apparent (McNeely & Schroth 2006).

Novelty begs the question of "what kind of agroforestry" is an appropriate framework for building a novel ecosystem and delivering desired ecosystem services. These include systems that focus on 'single-tree species, single-crop' strategies, or *taungya*; more sophisticated systems that model agroforestry off of succession to varying degrees, herein referred to as successional agroforestry; and agro-successional restoration. These vary in biodiversity inclusion, management intensity, and overall management intent (Nair 2006). For example, *taungya* systems are simplified multi-crop systems managed for additional food or income while trees grow. Successional agroforestry is more complex than *taungya*, with increasing levels of biodiversity inclusion, ecosystem structure and function, and service delivery as time progresses. Agroforestry, even of the simplified *taungya* variety, appears to be more sustainable when compared to other production-based land management alternatives (Nair 2006; Torquebiau 1992).

Successional agroforestry variants are prominent in humid tropical contexts, potentially allowing for ready acceptance of similar agroforestry-based management techniques such as forest gardens or other more complex agro-successional techniques (Torquebiau 1992; Vieira et al. 2009). Agro-successional restoration extends this complexity by incorporating a variety of eco-agriculture techniques including agroforestry to manage secondary forest succession for multiuse restoration and production outcomes (Jose & Gordon 2007; Nair 2006; Vieira et al. 2009). Production areas near conservation reserves, including heavily-degraded areas and more populous rural areas, can all benefit from application of eco-agriculture in protecting biodiversity and benefits of ecosystem services (Scherr & McNeely 2008). Applying eco-agriculture allows for an emphasis on production while 'easing into' conservation-based landscapes that may include ecosystem service-based novel forests.

Concluding Remarks

It is unclear if novel forests will provide similar ecosystem services to natural forests. Novel forests, however, can repair basic ecosystem services in heavily-impacted areas (Mascaro et al. 2008). This discrepancy underscores the importance of functionality and growth trajectory in species selection and management processes, especially if multi-purpose species respond favorably to management. Novel forests developed through agro-succession with human management in mind have a higher likelihood of producing specific ecosystem services than traditional tropical forest restoration, thus increasing positive perception and ultimately viability. As ecosystem repair is an essential part of human survival due to the extent of human-mediated environmental insults, restoration goals must recognize that ecosystems are dynamic and require new forms of management (Hobbs & Harris 2001). Using novel ecosystem approaches to restore rainforest services in tropical regions will play an important part in maintaining both human societies and the ecosystems that support them in the future.

Chapter Four: Forest Management in Borneo – Contrasting Biodiversity Conservation and Subsistence Practices in Lowland Rainforests of Western Sarawak

Overview

There can be significant differences in how governments and indigenous peoples approach stewardship of natural resources, especially in protected areas that allow for extraction, either by tacit failure to enforce regulations or explicit legal permission. Within that framework, we analyzed and compared strategies employed by Sarawak Government forestry officials in Kubah and Gunung Gading National Parks and those of subsistence and cash crop farmers in the Iban settlement of Rumah Siba Perdu. All areas contain managed lowland dipterocarp rainforests, the majority ecosystem type on Borneo, yet differ in management strategies and goals. We found that differences in strategic priorities have led to conflict, and that conflict may become exacerbated with increasing pressure from human population growth (at 2% a year among ethnic Iban), lucrative export markets, and ecological disturbances from local impacts of anthropogenic climate change. Based on interview results, we found that forestry officials had a strong opinion that farmers often overlook long-term ecosystem integrity and production stability while pursuing short-term economic gains. In contrast, farmers in Rumah Siba Perdu recognize the need for conservation, expressing concern regarding poaching and overuse of communal lands. Acceptance of alternative crop and management strategies by Iban and other subsistence farmers may circumvent negative perspectives held by government officials. Strategies such as multiuse ecosystems focusing on agroforested tree species are one such means for coping with increasing human populations and future environmental conditions by including biodiversity conservation and increasing carbon storage while providing for livelihoods.

Introduction

Governing organizations and local communities often differ on how to define and implement long-term management priorities (Cortner et al. 1998; Davis & Wali 1994; Sodhi et al. 2011; Szaro et al. 1998). Those who manage resources, protected areas, and settled areas must address numerous cultural, social, political, economic, and environmental issues simultaneously to meet management goals sustainably (Robinson 2010). Conflict can arise where strategies originate externally, exclude local input, or emphasize factors that may be of marginal importance to affected peoples (Cortner et al. 1998; Davis & Wali 1994; Szaro et al. 1998). Such strategies can include regional conservation or production quotas (Woinarski 2009), exotic timber plantations (Osemeobo 1988), or payments for environmental services (Sommerville et al. 2010). For example, overemphasizing short-term production practices can cause declines in other ecosystem services and severe environmental degradation, thus compromising long-term ecological integrity (Eastmond & Faust 2006; Finer et al. 2008; Raudsepp-Hearne et al. 2010; Reyes et al. 2005; Waylen et al. 2010). This type of scenario is a mistake repeated globally and throughout history, so examining how to avoid deforestation (as part of the larger issue of land use conversion to agriculture) is an important and generalizable topic in environment and resource management (Bowen et al. 2007; Brockeroff et al. 2008; Tscharntke et al. 2005).

While relevant to many ecoregions, deforestation has a particularly strong impact in the tropics (Brown & Lugo 1982; Phillips 1997; Shulka et al. 1990). External and internal economic and sometimes social incentives to harvest forests and convert to agriculture compound this ecological risk (Davis & Wali 1994; Edwards et al. 2013; Henley 2011; Noble & Drizo 1997). Rainforests represent 85% of the total deforested area in tropical regions, with logging and conversions to agriculture a high proportion of this deforestation-based loss (Bhagwat et al. 2008; Whitmore 1997). Globally, forests declined 3% between 1990 and 2005, with over 1% loss annually in some tropical regions (Bhagwat et al. 2008; FAO 2007). Expressing deforestation at a national level glosses over specific changes, as averaged rates may mask biodiversity loss, microclimate alterations, or indirect impacts such those associated with logging (FAO 2007; Noble & Drizo 1997; Whitmore 1997). Logging, the first step in forest-based land use conversions, includes not only the physical removal of trees, but also peripheral effects such as road building, soil compaction, forest fragmentation, and other consequences such as extinction of undiscovered species (Corlett & Primack 2008; Whitmore 1997).

Most agriculture-based forest loss in the tropics stems from subsistence agriculture. This is often some form of swidden agriculture, which facilitates species colonization from nearby areas, including exotic and undesirable species (Corlett & Primack 2008). When properly maintained, recovery from swidden agriculture is similar to other kinds of intense disturbance (Attiwill 1994), with many areas naturally reverting to secondary forest as areas are abandoned and anthropogenic pressure decreases (Parrotta et al. 1997). Nonetheless, any subsistence agriculture can harm soil fertility and other ecosystem services supporting production if not carefully managed. This often leads to abandonment, commonly referred to 'fallow' periods, yet these are not the managed fallow rotations found in proper swidden agroecosystems. These abandoned lands will likely follow successional trajectories dominated by undesired exotic species that will alter soil and water cycles as well as being difficult to remove, hindering a return to production or redevelopment of species-rich and native-dominated landscapes. Where fallow periods are inadequate due to population and related land use pressures, subsistence and swidden agriculture can result in severe ecosystem degradation requiring drastic ecological restoration efforts (Parrotta et al. 1997; Phillips 1997; Vieira et al. 2009).

On the island of Borneo, forest removal or repurposing are major factors in deforestation and biodiversity loss (Fitzherbert et al. 2008; Henley 2011; Nantha & Tisdell 2009). Specific actions can include decreased fallow periods (Lawrence, 2005), increased fertilizer use (Mertz et al. 2008), and uncontrolled burns (Langner et al. 2007). Repurposing land to cash crops or biofuel plantations decreases ecological functions of Bornean forests, compromising ecosystem integrity and services (Edwards et al. 2013; Giam et al. 2011; Lee-Cruz et al. 2013; Tanaka et al. 2009). Integrity refers to an ecosystem's ability to maintain self-organization and stability (Barkmann & Windhorst 2000). Ecosystem services are the result of ecological functions that benefit humans and other species such as food production or soil regeneration (Costanza et al. 1997; Fisher et al. 2009). These are important concepts and allow researchers and managers to understand the relative need for intervention.

In Malaysian Borneo, forest conversion to palm plantations in Sabah reduces local ecological integrity (Edwards et al. 2013; Lee-Cruz et al. 2013). In Sarawak, logging and cash cropping practices are becoming more prevalent, negatively affecting ecological integrity and ecosystem services (de Neergaard et al. 2008; Jinggut et al. 2012; Tanaka et al. 2009). Because of higher-impact management techniques that include extensive chemical use, increasing peppercorn has a greater environmental effect than upland rice or other short-term production techniques (de Neergaard et al. 2008; Tanaka et al. 2009). In contrast, smallholder latex rubber production in Sarawak showed soil characteristics similar to secondary forests (Tanaka et al. 2009). Increasing the perceived value of unsustainable management practices including peppercorn and latex results in a circumstance where conflicting conservation, restoration, and production goals are compounded and difficult to remedy (Fitzherbert et al. 2008; Nantha & Tisdell 2009).

New policies and protocols to circumvent unsustainable management practices is both ideal and necessary. These approaches take time and may not reverse the damage that already exists (Parrotta et al. 1997; Rey Benayas et al. 2009). New long-term management strategies must reduce impacts on ecosystem structure and function in the interim. Managers need to recognize that abandoned agricultural lands can regain ecological and commercial value in the form of secondary forests containing native species and non-invasive species originating elsewhere (Bowen et al 2007; Chazdon et al. 2009a). Crossing the threshold from unaffected ecosystems into ones that are mostly human dominated should cause us to rethink ecosystem definitions and management plans if we intend to restore, repair, or reinvent ecosystems (Morse et al. 2014; Seabrook et al. 2011; Suding 2011). Managers will find that idealized restoration is improbable; we argue that managers should instead plan for more plausible trajectories that yield as much ecological structure and function as possible. In regions like Borneo, structural restoration may not be the most suitable option due to misconceptions of how some forest structures self-organized or what managers can expect from intervention changes. Expectations of unaltered ecosystem states and functions can differ from historical realities or even future possible responses to extreme disturbances. For example, many presumed unaffected tropical forests in Borneo and elsewhere self-organize after cessation of ecosystem management practices (Bhagwat et al. 2008; Clewell & Aronson 2007; Sheil et al. 2012). Yet most tropical forest restoration tends toward recreating species diversity and structural complexity, or maximizing production potential in rehabilitated areas, thus potentially ignoring that baselines may derive from human-influenced reference conditions (Lamb et al. 1997; Parrotta et al. 1997; Sheil et al. 2012).

Acknowledgement of this transition and the human agent driving it allows for the guiding of forest reconstruction efforts toward more practical forest ecosystems (Chazdon 2008). Using species appropriate for direct management, such as agroforested species, increases the likelihood of desired forest restoration and development, as managers can become active agents in the restoration process (Bhagwat et al. 2008; Mascaro et al. 2008). Managed production systems should closely mimic the structure of native ecosystems, and in most tropical contexts, these would equate to multiuse forests (Scherr & McNeely 2008). In Borneo and elsewhere, multiuse forests may represent a cost-effective solution for guiding regrowth and restoring services of heavily-degraded forests (Plieninger & Gaertner 2011). In many degraded areas, multiuse forests can provide a variety of ecosystem services by repairing forest structure and associated ecosystem functions (Mascaro et al. 2008; Plieninger & Gaertner 2011).

Study Site Description

Situated southeast of the Asian continental landmass, the island of Borneo is home to many endemic flora and fauna as well as a variety of ecosystem types including tropical forest. Divided between Malaysia, Indonesia, and Brunei, Borneo is subject to differing government policies that result in unique environmental management practices. This research focuses on the southwestern portion of Sarawak, a state in Malaysia that has only 3% of its intact forests under protection, with these areas having only 72% forest cover (Bryan et al. 2013). Though having a low growth rate across the state, Sarawak has a large population. However, some populations are increasing much greater than others, a cause for concern as many of these subsist in marginal conditions and sensitive ecosystems (Gov. of Malaysia 2011; 2015).

Sarawak is ethnically-diverse, with many indigenous populations living throughout the state (Sutlive & Sutlive 2001). Many indigenous peoples have extensively modified their local environments, including forest repurposing, field agriculture, and animal husbandry that led to changes like higher nutrient soils via fertilization and degradation of soils and loss of biodiversity and production potential (Barker & Richards 2013; Dounias & Froment 2011; Sheil et al. 2012). As in much of the tropics and sub-tropics, there is a need for ecosystem management strategies that can lessen any additional pressures. The need for sustainability is especially relevant as market-driven external pressures increase and current management strategies respond and intensify (Bhagwat et al. 2008; Corlett & Primack 2008; Geldman et al. 2014).

The Iban people are descendants of populations indigenous to the region. Their settlements dot the border between Sarawak and the Indonesian province of West Kalimantan (Eilenberg 2011; Sutlive & Sutlive 2001), many of which are growing over 2% annually (Gov. of Malaysia 2011; 2015). The Iban practice forms of subsistence land management similar to those of their ancestors (Ichikawa 2007; Sutlive 1978; Sutlive & Sutlive 2001). As in many indigenous cultures, the local people do not emphasize maintaining historical management regardless of its effectiveness. This allows Iban to adapt management in response to changes such as new crop species, government pressure, and shifts in the availability of outside employment (de Neergaard et al 2008; Cramb & Sujang 2011; Lansing et al. 2014; Tanaka et al 2009). Over the past few decades, many Iban land managers have been unable to fully respond to Sarawak law and policy changes that restrict traditional land uses, even where communities chose to diversify production and income sources (Cramb & Sujang 2011; Gov. of Malaysia 2011; 2015). Subsistence hunting, gathering, and farming practices are falling out of favor, while logging, cash crops, and ecotourism are increasing (Ichikawa 2007; Oshima 1999). Because these land management strategies are becoming more popular, the potential for environmental degradation increases as population rates surpass state averages, strategies intensify and become more attuned to global markets (de Neergaard et al. 2008; Gov. of Malaysia 2011; 2015; Tanaka et al 2009). Shifting from subsistence strategies to more intensive farming and ecotourism present an opportunity to examine the characteristics pertinent to long-term environmental sustainability (Crumb 2007; de Neergaard et al. 2008).

Methods

Interview Scope and Sample Demographics

We conducted interviews with land managers in western Sarawak, Malaysia in April 2013 (Figure 3). This included interviews with senior protected areas managers in Kubah and Gunung Gading national parks as well as land managers in the Iban traditional settlement of Rumah Siba Perdu. The Sarawak Forestry Corporation, a state-level government agency tasked with managing protected areas in Sarawak, operates both national parks. Interviews with protected areas managers were in English and conducted orally. All study participants chose to remain anonymous. Sarawak Forestry land managers self-identified as ethnic Iban and ranged between 36 and 48 years old. Informants noted a lack of available female interviewees in positions of authority regarding forest management. This gender discrepancy may have resulted in some response bias but speculation thereof is outside the scope of this research.

Rumah Siba Perdu is one of many indigenous communities in Sarawak accorded native customary rights for its lands, though several court decisions have called into question whether such rights are inalienable (Bulan 2006). It was unclear if Native Area Land or a Native Communal Reserve status has been granted by the Malaysian government, but participants referred to their community as a 'reservation' during the interview process. Commonly referred to as Rumah Siba (Perdu indicates the current leader), the community contains 80 people in thirteen families. Of these, approximately 40 residents were under the age of 18. Seventeen land managers were available for interviews including the son of the village leader as well as several village elders. A translator was present as all Rumah Siba participants spoke Iban only. Participants chose to remain anonymous, with interviews conducted in a group setting. Assessing literacy or education levels was not part of this study. Interviewees in Rumah Siba were all male and between 38 and 72 years old. In Rumah Siba, few women participated in land management activities beyond garden plots, indicating potential for male-oriented bias in results.

Figure 3. Island of Borneo. Equatorial case study region is shown in orange.

Interview Process and Instruments

Potential study sites were of the dipterocarp forest type, as it is the majority forest type on the island (WWF 2015). Study site selection favored locations subject to different management conditions such as conservation forestry or production. Sites accessible by road were preferred to assist in potential follow-up interviews as necessary. Bako, Maludam, and Talang-Satang national parks do not contain mostly lowland dipterocarp forest, while Tajong Datu National Park and its associated Sanmussan Wildlife Sanctuary were only accessible by boat.

Of five potential study villages, we chose Rumah Siba as our study location by a process of elimination – the local peoples and ours. Three villages were in close proximity to selected park areas, but relied almost exclusively on ecotourism income and did not manage forests in any fashion. The change reflects rapid change in Iban traditional culture, one that is rapidly fading or constrained and marketed as part of the growing ecotourism sector (Zeppel 1997). Contacted households in the community of Maludam, 72 km west of Rumah Siba, declined prescreening questions. Interview attempts with three nongovernmental conservation organization officials as well as managers of pineapple, papaya, and mahogany plantations in western Sarawak were unsuccessful. Only managers affiliated with Sarawak Forestry or residing in Rumah Siba agreed to interviews. While affected landscapes span a variety of management practices, comprehension and resulting discussion apply only to the available techniques.

A combination of oral surveys and open-ended interviews helped to understand the qualitative views of study participants. Participants discussed how their land management practices currently function, how they interpret externally-based practices, and how they understand long-term land management planning in general. Surveys attempted to determine which plant species were important for resource security and ecosystem services. Further, surveys determined total land areas of different management strategies, labor performed annually by land managers, necessary purchased resources, and annual production for upland rice, manioc, peppercorn, and latex rubber for comparison.

Open-ended interview techniques attempted to clarify primary informant responses to survey questions as well as individual and collective opinions on management. This included what ecosystem management techniques were the norm, how their management practices interact with methods favored by others and where alternative management strategies might succeed. Recognizing that land management in Borneo is experiencing transitions similar to other tropical ecosystems (Lansing et al. 2014; Rayome 2010), surveys and interviews provided a baseline for comparison of these changes as well as future alterations.

Results and Discussion

Kubah National Park & Matang Wildlife Centre Experienced Different Impacts

Kubah National Park spans 2230 ha, with a two-hectare boundary serving as a buffer for nearby farming communities according to the interviewed official. Over 95% of the park is in unmanaged primary or secondary forest over a century old. Kapur (*Dryobalanops aromatica*), bintangor (*Calophyllum* spp.), and other endemic trees define much of the forest structure, which spans several dipterocarp forest types. The remainder is managed trails and biodiversity gardens including a palmetum and a frog pond. While Sarawak Forestry employs many land managers, few were able to discuss park management in detail and only one available to speak at liberty about long-term impacts. The informant noted most labor in the park is devoted to trail and boundary maintenance, with patrols, minor tree planting, and removal of harmful species also performed. Hand labor is the primary choice for completing park duties, with tools such machetes and parang knives primarily used, though labor also includes chain saws when needed. There are few invasive non-native species in the park. Where non-natives are present, spread is minimal and controlled.

Managers emphasize community-based natural resource management in and around Kubah, but the combined effects of local practices were excessive. The interviewed official stated that poor land management adjacent to the park encourages encroachment into the buffer zone and illegal park use. Intended to replicate limited-use management policies that existed for decades prior to park establishment, locals may enter park lands to cut trees for domestic use or sale by limited-issue permits. However, certain species have been subject to intense illegal logging pressure in the attempt to circumvent these regulations.

Removing high-value belian trees (*Eusideroxylon zwageri*) has presented a problem in recent years despite logging and export bans in Sarawak and nearby West Kalimantan in Indonesia. Hunting and trapping by nearby communities reduces animal populations. This effect is severe where Kubah borders farming communities or during poor fruiting periods. According to the official, observed declines in animal populations, including primates, small mammals, and birds, may relate to deforestation and hunting pressure near park boundaries. Human impacts have led to several new species discoveries, a peripheral effect of negative disturbances intended to extract resources for human subsistence and livelihoods rather than altruistic scientific discovery. Species including hornbills (*Buceros* spp. and related) and giant squirrels (*Ratufa affinis*) have recovered in recent years, but orangutans can only be found in isolated patches deep within the forest. As in much of Sarawak, Borneo elephants and Borneo rhinoceros are locally extinct from human pressures including overhunting and nearby habitat loss. The official also noted Sarawak Forestry is also concerned with overuse of the park for nearby village subsistence activities.

Matang Wildlife Centre operates as an outdoor zoo and rehabilitation facility on the outer reaches of Kubah National Park. While functioning as a separate Sarawak Forestry entity, Matang has similar grounds management as Kubah NP. However, due to its smaller size and more frequent use, the manager indicated Matang does not experience similar pressures from farming communities as in Kubah NP. Food and illegal sale constitute flora removal in isolated circumstances, but grounds tend not to experience much impact from illegal logging or gathering. All fauna within Matang is semi-wild and many of these animals can no longer function in the wild due to debilitating injuries or behavioral issues. However, even with several high-value species present in the facility, staff generally do not perceive nearby farming communities as detrimental to their operations. Instead, Matang relies on nearby development to encourage tourists and funding.

Gunung Gading National Park Experiences Fewer Pressures

Gunung Gading National Park covers 4106 hectares, designated primarily for conserving rare species such as rafflesia (*Rafflesia tuan-mudae*). Though larger than its neighbor to the southeast, interviewed officials indicated similarity to Kubah NP in having multiple dipterocarp forest types and many uncommon species. Government management from Sarawak Forestry is also comparable, with most labor geared toward trail and boundary maintenance as well as guided Rafflesia tours. Border patrols are less frequent than in Kubah – much of Gunung Gading is easily accessible by road, allowing foresters to assess park boundaries by vehicle. Labor is mostly by hand as in Kubah NP, while harmful or invasive species are typically not found within the park because the park has not been subject to intense management pressures.

Community-based natural resource management is encouraged by forest managers near park borders, a necessity given the park's proximity to cities and farming communities. If not managed in this manner, farmer encroachment would most likely overwhelm Gunung Gading NP managers through farmer-forester conflicts such as poaching. Several facilities managed by Sarawak Forestry have community co-operatives within protected area boundaries, but interviewed officials emphasized that this practice is not present in Gunung Gading NP or Kubah NP, contradicting the statements of the Kubah NP official. Removal of any species from all Kubah and Gunung Gading NP grounds is illegal; this also contradicts the official at Kubah NP. Regardless, issues with illegal timber felling and poaching were almost non-existent in the park, in part due to proximity of nearby cities and livelihood sources that lessen the need to poach or participate in illegal logging or gathering.

Officials described flora populations in Gunung Gading NP as thriving, but most large fauna were locally extinct, including orangutans and several feline species. One official indicated high productivity and biodiversity in the park could sustain viable populations of reintroduced native species. Current local extinctions are a legacy of the Japanese occupation in WWII and Communist rebellions during the 1950s and 1960s, where combatants routinely slaughtered animals for food (Eilenberg 2011; Sutlive & Sutlive, 2001). Officials expressed concern that biodiversity and production management goals could conflict with any species reintroductions. In areas of more intense production, such as on the fringes of Gunung Gading NP, reintroductions could compromise livelihoods as populations expand and extend ranges to park boundaries and beyond. For example, Bornean elephants are known to frequent palm oil plantations near forests (English et al. 2014) while Sumatran rhinos in Sabah respond negatively to land conversions (Rabinowitz 1995), thus potentially limiting land management choices. Further, both officials viewed reintroductions as negative for biodiversity not only due to potential farmer-forester conflict, but also by inviting external poaching. While conserving current faunal biodiversity is a priority for Sarawak Forestry, the prospect of poachers expanding beyond target species, including flora, is a major constraint to species reintroductions and ecosystem restoration.

Rumah Siba Perdu

Many indigenous Iban practice livelihood production and hunting activities for local use as well as cash crops and forest products destined for export. The indigenous Iban of Rumah Siba Perdu live in a traditional settlement on reservation lands, subsisting as small-scale swidden and cash crop farmers. Subsistence crops in Rumah Siba include upland rice (*Oryza sativa*), manioc (*Manihot esculenta*), and vegetables for home consumption. Refined white rice is the primary staple while also serving as a minor cash crop, grown in monoculture clearings near the main village. Manioc is grown in small plots scattered about the village outskirts, while small gardens (>10 m^2) produce various horticultural crops. Extensive gathering, hunting, trapping, and fishing practices compliment production between farming and husbandry activities. According to interviewees, hunting and gathering are more enjoyable, and informants indicated both activities are preferred over production.

As in many Iban settlements, informants indicated that nine farmers in Rumah Siba chose to discontinue upland rice farming over the past five years, instead preferring artisanal peppercorn (*Piper nigrum*) and small-scale latex (*Hevea brasiliensis*) agroforestry (Ichikawa 2007; Tanaka et al. 2009). Both are profitable cash crops grown for export, with peppercorns geared toward tourists and latex maintained as an insurance crop. Further, chemical inputs in peppercorn farming supplant much of the labor required in upland rice plots, opening up more time for other pursuits. As farmers transition from upland rice farming to artisanal peppercorn, this newfound leisure time instead goes toward activities that contribute to household livelihoods. Informants suggested that hunting, gathering, and related wild harvests may surpass reproductive capacity as peppercorn farming and associated leisure time increase.

Upland rice agriculture is relatively low-impact, using hand labor, short-duration burns, and unmanaged fallow periods (de Neergaard et al. 2008). Erosion tends to be minimal while rice fields are maturing, with residues often left in fields post-harvest, further contributing to erosion control and facilitating regrowth from the soil intact seed pool. In contrast, peppercorn and latex production includes outdoor power equipment, extensive chemical use, and removal of forest cover according to farmers. Peppercorn farming is unfavorable for maintenance of endemic flora and fauna, even with inclusion of fruit species in multi-year peppercorn plots (de Neergaard et al. 2008; Jinggut et al. 2012; Ichikawa 2007). Latex production may support similar soil fertility and structure as secondary forests, but reduces biodiversity and plant density and this ultimately affects productivity and thus maintenance potential for non-target species (Ichikawa 2007; Tanaka et al. 2009). Reducing the use of both peppercorn and latex based strategies boosts ecosystem services such as biodiversity and soil maintenance in Borneo forests (de Neergaard et al. 2008; Edwards et al. 2013; Jinggut et al. 2012).

Similar to the responses from Sarawak Forestry officials, all Iban land managers in Rumah Siba agreed that overuse and poaching are a major concern on community lands. Informants indicated this overharvesting is already occurring, including poaching from outside the community. This observation corroborates views of Sarawak Forestry officials regarding overharvest by communities near protected areas. Land managers described many faunal species as locally extinct, while noting decreases in others over the past decade. For example, three land managers indicated they no longer hunt barking deer as the most recent sighting was three months prior. Of particular note is the absence of hornbills, a species recovering in both parks, as well as any felid sightings.

Rumah Siba land managers agreed that poachers could expand activities through the open boundaries of communal lands. This is of particular concern as populations of profitable species such as pangolin (*Manis javanica*) decreased according to several participants, as were those of several snake and bird species. One interviewee cited evidence of sun bear (*Helarctos malayanus euryspilus*) poaching near the southern border. Sun bear populations are in decline across Southeast Asia, particularly troublesome as Bornean subspecies faces endangered status. This negative trend will most likely continue as human pressures increase (Fredriksson et al. 2008). Overall, land managers expressed distress in coping with direct effects of poaching as well as associated consequences on managed ecosystems.

Comparing Management Strategy Impacts on Biodiversity Conservation

Biodiversity conservation strategies differ greatly between Sarawak Forestry land managers and producers in Rumah Siba. All Sarawak Forestry informants indicated that both parks are oriented toward conserving endemic species with no production-related activities. According to land managers in Rumah Siba, their strategies compartmentalize production and conservation for wild harvest. Lowland forests often contain several hundred tree species over a given hectare, many of which are multi-use and endemic to the island. Because highly-diverse dipterocarps dominate rather than legumes (WWF 2015), land managers can combine indigenous practices with other techniques for conservation and production needs in multiuse strategies.

Plants like rafflesias, orchids, and cycads have biological and livelihood value, as do conserved timber species. Adoption of latex agroforestry as well as cultivation of manioc and peppercorn indicates the willingness of villagers to explore new crop species, perennials, and those with less labor and greater agricultural productivity than rice. Given that most village farming activities are oriented toward either production or eventual purchase of a primary staple crop, opportunities exist for diversifying production. Indeed, this research supports past work indicating Iban land managers as flexible in farming choices, and are often willing to experiment with new species and markets (Crumb 1993; Wadley & Mertz 2005; Tanaka et al. 2009).

In Rumah Siba, starch-producing trees such as sago (*Metroxylon sagu*) and breadfruit (*Artocarpus altilis*) are alternatives to rice. Both are well-documented agroforested species with high yields and low maintenance requirements. Further, both are regionally-native and non-invasive. Sago has a history of favorable production in Iban villages, while breadfruit often surpasses subsistence yields of upland rice (BI 2014; Flach 1997). Allowing multiuse regrowth to develop around such crops while including species of conservation interest presents a circumstance that meets the goals of both conservationists and farmers. Multiuse forests can augment other starch production strategies, such as increasing genetic diversity or incorporating associated indigenous ecological knowledge from upland landraces utilized elsewhere in Sarawak (Thomson et al. 2009).

Even high-impact production like peppercorn has the potential to increase biological conservation; for example, of nine peppercorn farmers in Rumah Siba, eight include fruit trees in peppercorn plots as a part of combined production-fallow restoration strategies. The direct impacts of erosion and fertilizer runoff decrease as growing timber or other high value endemic species absorb excess nutrients while also providing habitat for impacted fauna (de Neergard et al. 2008; Jinggut et al. 2012; Ichikawa 2007). Elsewhere, similar management alterations have been positive for forest ecosystem structure and overall ecological integrity (Harvey & Gonzalez Villalobos 2007; Rayome 2010; Salafsky 1993; Wang & Young 2003)

All interviewed Sarawak Forestry officials noted while forests could potentially support breeding populations of large fauna, hunting pressures would quickly negate any reintroduction attempts. Even where hunting and poaching pressures are lower – such as in Gunung Gading NP

– wariness by government informants precluded the more immediate needs of threatened animals. For example, all remaining Sumatran rhino populations face extinction. While currently existing in Malaysia and Indonesia, countries with differing environmental management and conservation policies, those on Borneo could benefit from additional habitat (Rabinowitz 1995) such as that found in Sarawak Forestry protected areas.

Fortunately for conservation objectives, indigenous settlement preferences for wild game do not necessarily preclude native species reintroductions. Land managers in Rumah Siba were explicitly concerned about poaching and overharvest, though hunting occurs on reservation lands includes a variety of game species. In areas where community-based natural resource management is encouraged, those engaged in the practice can become active opposition to illegal wildlife trade while maintaining traditional hunting. This is compatible with expressed Sarawak Forestry biodiversity management goals, and is similar to other faunal successes in tropical rainforest conservation management (Andam et al. 2010; Harvey & Gonzalez Villalobos 2007; Salafsky 1993).

Forest Management, Carbon Storage, and Livelihoods

Tropical trees sequester vast quantities of carbon, both aboveground in trunks and branches as well as below in root systems (EPA 2010). Further, tropical forest soils also hold significant amounts of carbon in living organisms such as arbuscular mycorrhizae as well as decomposed organic matter pools (Rillig et al. 2001; Sombroek et al. 1993). Sequestration differs from carbon capture and storage, where carbon is removed from the atmosphere by artificial means and relocated to geological formations or deep ocean storage outside of the global carbon cycle (ECO 2011). Estimates of total carbon stored in biomass vary in response to growth conditions, with more fertile areas often showing greater aboveground storage than less fertile areas, which are instead oriented toward rooting mass (Kenzo et al. 2015). Removing forest cover and associated conversions to production-based management are major sources of unfavorable carbon balances, with poor management choices compromising the process of storing atmospheric carbon dioxide in living biomass and surrounding environs (EPA 2010). For example, establishing and operating palm oil plantations is an important driver of carbon emissions in Southeast Asia (Fitzherbert et al. 2008). More ecologically-appropriate management activities such as reforestation and ecosystem service restoration can help to reduce carbon loss (Albrecht & Kandji 2003; Chazdon 2008; EPA 2010).

Carbon sequestration presents an interesting contrast between protected, impacted, and recovering areas in Bornean tropical forest ecosystems. Specifically, addressing the need to sequester carbon relates to many factors including biodiversity restoration, but can conflict with others such as livelihoods. Some Iban villages participate in the logging industry, thus actively detracting from local carbon sequestration (Oshima 1999), while land use conversions from forest cover to field agriculture negatively affect carbon sequestration in most ecosystem types (FAO 2015). These land use changes are significant sources of released carbon in Borneo (Hashimotio et al. 2000), estimated at close to 50% of aboveground losses (Berry et al. 2010). While estimates of carbon stocks in Bornean dipterocarp forests have yet to be standardized (Basuki et al. 2009), any loss is significant as such forests may potentially hold more carbon in aboveground biomass than other tropical forest types (Kenzo et al. 2015). Further, while rapid and likely persisting as secondary forests mature (1.4 Mg C ha^{-1} yr^{-1} recovering vs. 0.28 Mg C ha^{-1} yr^{-1} mature), post-logging carbon accumulation cannot offset deforestation losses without intervention (Berry et al. 2010). Regardless of the significance of carbon reabsorption (Hashimotio et al. 2000), more research into the supporting value of carbon sequestration is needed in recovering and further-managed tropical landscapes such as agroforestry (Chazdon et al. 2009b; Schoeneberger 2009; Steffan-Dewenter et al. 2007).

In Sarawak, lands overseen by government forestry officials often consist of lightly-managed mature forests, with many areas containing over a thousand trees per hectare exceeding 10 cm diameter at breast height. In contrast, indigenous villages such as Rumah Siba view forests as a resource necessarily altered for local needs. As with biodiversity, carbon storage may benefit from alternative management practices combining production with conservation and restoration such as multiuse regrowth agroforests. For example, villagers in Rumah Siba and elsewhere often participate in latex rubber agroforestry (Ichikawa 2007; Tanaka et al. 2009). Agroforests can serve as carbon sinks in tropical regions, storing carbon in tree trunks for the duration of plot productivity (Albrecht & Kandji 2003). It is reasonable to assume that multiuse tropical forests developing around agroforested species will store carbon similarly to those managed exclusively for agroforested species alone. This is particularly relevant if forest structure develops around rapidly-growing trees or other woody species that also store carbon such as sago and breadfruit. Further, conserved timber species such as kapur, bintangor, and belian can be included in multiuse agroforests as well as other valuable endemics.

An appropriate subsistence technique in areas of high forest cover (Padoch & Pinedo-Vasquez 2010; Zeigler et al. 2011), swidden agriculture can have a variety of detrimental environmental effects, especially on carbon storage (Amorim et al. 2014; Kotto-Same et al. 1997). Cutting and burning existing vegetation in preparation for crop species decreases carbon storage. While releasing nutrients in vegetable matter for use by crops, controlled burns risk excess carbon release as duration, intensity, and fuel load increases (Pelletier et al. 2012; Thomaz et al. 2014). This is particularly problematic if combustion intensity releases stored soil carbon, or if fires spread to peat swamps or other areas of concentrated high-carbon fuel, thus significantly contributing to global carbon emissions (Permadi & Oanh 2013; Toriyama et al. 2014). Land managers in Rumah Siba insisted that because their high-intensity fires burn over small areas and are often self-extinguishing, they were easily controlled and thus not detrimental. Yet with no means to restrict spread or intensity should fires burn uncontrollably, this explanation ignores the potential for increased forest wildfires on Borneo as a result of climate change (Herawati & Santoso 2011). Decreasing the need for such practices, particularly burning, reduces the potential for carbon release in managed ecosystems, especially if viable or complementary alternatives to swidden agriculture exist (Albrecht & Kandji 2003; Amorim et al. 2014; Kotto-Same et al. 1997).

Conclusion and the Need for Multiuse Forest Management

Human management of ecosystems affects all resulting functions and services such as such as biodiversity and carbon storage. Tropical land management often takes many forms, and desires of interested parties may be a source of conflict, especially near protected areas or designated indigenous reserves. Government forestry officials may manage landscapes for biodiversity conservation and ecotourism-based income, but often exclude subsistence livelihood activities in protected areas. Human activities affected parks prior to protected area designations. While some impacts may have been detrimental to ecosystems, excluding local indigenous peoples potentially promotes distrust and resentment on both sides. Instead, including perspectives from local populations, especially those near protected areas, is necessary. Whether this includes piecemeal subsistence activities in Sarawak Forestry lands or larger-scale conservation and restoration-production planning, local input may provide benefits for long-term ecological integrity on a regional scale.

In areas managed by Sarawak Forestry, the primary focus is to keep standing forest healthy for biodiversity, tourism, and possible timber extraction. Management is state-wide, with little focus on reforestation, ecosystem restoration, or mixed-use landscapes. There is some disagreement of legality and authority of mixed-use on lands near settlements and farms, as major goals include keeping farmer encroachment and deforestation at bay. Despite management for flora species, illegal logging occurs in many protected areas. In addition to habitat losses from logging, poaching also exists, and affects many fauna species. While orangutan populations remain in some areas, there have been no elephant or rhino for close to a century as a result of overhunting and external pressures. Combined, these factors result in negative perceptions of alternatives to government management protocols. A focus on export-based management allows for a variety of products to enter subsistence farming villages such as diesel for generators and manufactured goods. Importing rice allows land conversions to peppercorn production, thus increasing potential profits and quality of life. However, management for short-term gains, including high fertilizer and biocide use in peppercorn production, results in decreased ecological integrity and fewer ecosystem services. Cumulative management effects ultimately decide the stability and sustainability of human societies.

Strategies such as those presented by multiuse agroforestry are a promising alternative to meet multi-faceted needs of biodiversity conservation, ecosystem restoration, and livelihoods production. Farming communities such as Rumah Siba have embraced agroforested species including latex rubber, poising them for ready acceptance of other profitable species. As climates alter and markets respond, societies will need to make changes that ranging from small-scale adaptations at the individual level to the complete re-envisioning of human societies. Openness to new crop species and management techniques will assist in coping with potentially chaotic futures, thus affecting the survival of all species and ecosystems.

Chapter Five: Emergy Analysis of Traditional, Local, and State-level Forestry Land Management Strategies in Western Sarawak, Island of Borneo

Overview

Land managers in Sarawak practice a variety of strategies for managing lowland dipterocarp forests. Strategies employed by subsistence managers focus on local production, short-term cash crops, and extraction forestry. In contrast, state-level protected areas foresters manage for conservation forestry and ecotourism. Emergy analysis determined sustainability for ten management strategies. This involved determining renewable, non-renewable, and purchased inputs to management strategies and strategy yields. These inputs assisted in calculating the following emergy indices: the Fraction Renewable Index, the Emergy Yield Ratio (EYR), Environmental Loading Ratio (ELR), and the Emergy Sustainability Index (ESI). Fraction Renewable ranged from 0.77 to 0.98 across all strategies, indicating high proportions of renewable energy driving management strategies. EYR values ranged from 4.42 to 13.34 for current production and from 35.12 to 65.14 for potential strategies. When compared to an EYR of 24.19 for protected areas, this indicates how effectively a strategy utilized purchased investments. ELR values ranged between 0.09 and 0.30 for current farming practices and between 0.02 and 0.03 for potential strategies. Compared to an ELR of 0.04 for protected areas and near zero values for wilderness, these strategies showed minimal environmental stress despite differing strategy outcomes. ESI values ranged from 14.84 to 155.49 for current farming practices and from 1143.42 to 3819.05 for potential strategies. As ESI is the proportion of emergy yield to environmental loading, potential strategies have high sustainability when compared to 555.00 for protected areas. EYR, ELR, and ESI values were not dependent on land area utilized, but were dependent on purchased resources and non-renewable portions of labor as management intensity increased within a given strategy. Emergy analysis determined that subsistence rice production was more sustainable than any cash cropping in current management practices, while breadfruit agroforestry-based management was the most sustainable production method, followed closely by sago starch agroforestry. These strategies were not only the most sustainable production method, but also more sustainable than protected areas management.

Introduction

Humans exploit the environment, manipulating natural capital stores and ecosystem functions through labor inputs and other resources. Limited environmental resources, dwindling concentrated energy supplies, and decreasing ecosystem services present a difficult challenge in sustaining an ever-increasing world population as future climates become more unpredictable (IPCC 2014). One way to address this challenge is evaluating environmental management sustainability to maximize production while minimizing resource utilization and environmental degradation. While economic analysis can quantify the monetary value of such alterations, underestimating or externalizing ecosystem service contributions can misinform policy and management (Brown & Ulgiati 1999; Lefroy and Rydberg 2003; Ulgiati et al. 1994). Researchers have long identified the need for approaches that quantify environmental and economic inputs, and select for systems that meet future human and environmental requirements in a sustainable fashion (Brown & Ulgiati 1999; Odum 1996; Lefroy and Rydberg 2003).

Management alternatives using larger percentages of renewable energy must be developed and employed as they are more likely to increase management sustainability than those driven by fossil fuel and other non-renewable inputs (Lefroy and Rydberg 2003; Rayome 2010). An appropriate and innovative means for addressing this is the application of multiuse agroforestry management strategies that utilize new techniques to meet both production and conservation goals while capitalizing on the effects of human-mediated regrowth. Agroforestry concerns woody species managed for production beyond lumber or fuelwood. Encouraging multiuse applications beyond production allows agroforestry managers to oversee other ecosystem aspects in addition to target species (Nair 2006; Scherr & McNeely 2008).

On this premise, we posited that an effective measure of sustainability in determining how to apply multiuse agroforestry ecosystems is emergy analysis. Emergy examines the total energy necessary for an ecosystem to produce a given output, or how sustainably a desired outcome arises (Odum 1996). Emergy evaluation assumes that resource contributions are proportional to available energy, and that this energy is in a form necessary for accessing those resources (Brown and Herendeen 1996). Emergy analysis can be useful in comparing management effects and assisting in decision making processes. Emergy evaluation is practical for evaluating resource utilization, productivity, and sustainability of a management strategy as it considers all components therein based on how much solar energy they contain, or embodied solar energy. Embodied solar emergy serves as a common foundation in emergy analysis, with embodied solar emjoules, or solar emjoules (sej), serving as the unit of measurement. Solar emergy calculation multiplies units of energy by emergy per energy ratios (transformities), units of mass by emergy per mass ratios, and dollars by emergy per dollar ratios. This conversion process is necessary to standardize different energy qualities (i.e. more concentrated forms of energy) as well as non-energy measurement units to the single unit of solar emjoules for ease of analysis and comparison. Previous studies (i.e. Odum 1996) have calculated emergy unit values for a variety of resources, products, services, and renewable energies as well as quantifying solar emjoule requirements for production of individual components. Emergy evaluation can quantify environmental and economic contributions required for primary production. These quantified contributions can then be compared using solar emjoules as the common basis, circumventing some of the potential for bias based on currency or market fluctuations. Because of this common basis, emergy analysis quantifies environmental and economic resources while attempting to determine the real value of nature to humanity (Odum 1988).

We chose to contrast land management strategies in lowland dipterocarp rainforests of western Borneo as our case study to test the effectiveness of emergy analysis in comparing emergy use efficiency. This forest ecosystem type is unique in tropical contexts as forest structure is not comprised of leguminous trees, but dipterocarps endemic to the island and found nowhere else on earth (WWF 2015). Borneo is also ethnically-diverse, with many indigenous populations spread about the island. Many of these populations colonize sensitive ecosystems and yet still live in poverty (Gov. of Malaysia 2011). While population densities and growth rates are low for much of the island, groups such as the Iban are experiencing marked increases by over 2% annually in some areas (Gov. of Malaysia 2011; 2015). This regional coupling of socio-ecological degradation means there is a need to solve problems of ecological degradation and poor living conditions concurrently, requiring alternative ecosystem management strategies that can lessen any additional pressures.

As opposed to those living in cities, Iban who live in traditional communities practice rainforest ecosystem management methods that include production and hunting activities for local use as well as cash crops and forest products destined for export (Sutlive & Sutlive 2001). Changes occurring within Iban strategies, such as adopting new crops and management techniques, present a rare opportunity to examine how emergy can measure how changes to subsistence management affect characteristics pertinent to agroecosystem stability and output. This is true of changes affecting overall farming methodology, land areas devoted to different strategies, and labor, time, and other resources invested in crop management.

In contrast to indigenous peoples like the Iban, government-level forestry officials often manage landscapes for biodiversity conservation and ecotourism-based income, but exclude any indigenous hunting, gathering, or subsistence livelihood activities in protected areas (Oshima 1999; Sutlive & Sutlive 2001). Because production and conservation strategies differ and can lead to conflict, identification of more sustainable land management strategies is relevant as population increases accelerate in both the tropics and Southeast Asia (Bhagwat et al. 2008; Corlett & Primack 2008; Geldman et al. 2014).

This study describes an emergy evaluation conducted as part of a larger project examining subsistence, cash crop, and protected areas management strategies on the island of Borneo. Areas examined include the Iban settlement of Rumah Siba Perdu, and protected areas in Kubah National Park, Matang Wildlife Centre, and Gunung Gading National Park in western Sarawak, Malaysia. Emergy evaluation quantitatively examined strategies, emphasizing how different management strategies and end goals affect ecosystem dynamics and integrity. Procedures including transformities and calculations followed Odum (1996). Emergy analysis has been used to evaluate sustainability for land management strategies in areas such as Australia, Belize, and Sweden (Lefroy and Rydberg 2003; Rayome 2010; Rydberg and Jansen 2002). Because it is applicable in a wide variety of contexts, emergy analysis can be a useful lens to compare management effects and assist in decision making processes. As such, primary objectives of this emergy analysis were the following:

1. Determine how different aspects of subsistence production and protected areas management influence sustainability as determined by emergy analysis;

2. Determine energetic costs and consequences of cash crops and alternative production strategies on production efficiency;
3. Determine how findings can inform incorporation of multiuse alternative management strategies in Borneo and similar high-sensitivity ecoregions of the humid tropics.

Methods

Interview Design and Study Process

We conducted interviews with subsistence, cash crop, and protected area managers in western Sarawak, Malaysia in April 2013. The interview process included land managers in the ethnic Iban community of Rumah Siba Perdu as well as protected areas managers in Kubah and Gunung Gading national parks. Interview questions are available in the Appendix. Commonly referred to as Rumah Siba, the community has a population of 80 people living in 13 families. Of these residents, approximately 40 were minors and excluded from the potential sample pool. Seventeen land managers volunteered to participate including several village elders and the son of the village leader. Rumah Siba informants spoke Iban only, with interviews conducted in English via translator assistance. This study did not assess literacy or education levels as variables; we focused the limited time participants had available to key questions about management practices. All interview responses were anonymous and collected in a group setting at the participants' request. Interviewees self-identified as land managers and ranged from 38 to 72 years old. No female Iban land managers were involved in this study; few women in Rumah Siba participate in land management activities beyond small-scale horticulture.

Protected area interviewees were all employees of the Sarawak Forestry Corporation, a state-level government forest management agency. These included senior management officials at Kubah and Gunung Gading National Parks and the Matang Wildlife Centre. Interviews were verbal as all participants spoke fluent in English. As in Rumah Siba, all protected areas managers chose to remain anonymous. Sarawak Forestry protected areas land managers ranged from 36 to 48 years old, and identified as ethnically Iban. Both park wardens indicated no women were in positions of authority at either park, limiting participants to males. Interviews were designed to determine land area of management strategies, labor performed annually by land managers, necessary purchased resources, and annual subsistence or cash crop production for upland rice (*Oryza sativa*), manioc (*Manihot esculenta*), peppercorn (*Piper nigrum*), and latex (*Hevea brasiliensis*).

Rice and manioc are staple starch crops, with the former meant for human consumption and the latter as animal feed. Peppercorn and latex are cash crops destined for export markets. In addition, two agroforestry-based strategies served as alternatives for comparison to upland rice cultivation. These included sago (*Metroxylon sagu*) and breadfruit (*Artocarpus altilis*) managed for subsistence starch production. Both are tree-based subsistence starch crops, with the former native to Borneo and the latter originating in nearby islands (BI 2014; Flach 1997). Sago has a long history of providing sustenance to indigenous peoples on Sarawak, including cultures closely related to the Iban. The crop also has low maintenance requirements, excellent yields relative to soil conditions, and year-round availability of starch-filled trunks (Flach 1997). Breadfruit, naturalized in most regions where it will grow, is also known for ease of production and and high yields, often rivaling other staple crops including rice (BI 2014; Table 1).

Table 1. Strategy names, composition, and products extracted from Iban management of Rumah Siba Perdu and surrounds, Sarawak, Malaysia

Strategy	Description	Strategy Origin	Managers	Purpose	Dominant Species Type	Products
Rice	Rice monoculture	Traditional	8	Production	Herbaceous grass	Upland rice
Manioc	Manioc plots	Local	17	Production	Woody shrub	Manioc, fruits, wild foods
Peppercorn	Peppercorn polyculture	Local	9	Production	Herbaceous vine	Peppercorn, fruits, wild foods
Latex	Latex plots	Local	17	Production	Woody tree	Latex, wild foods
R / M / L	Rice, manioc, latex	Mixed	(17)	Production	Herbaceous	Upland rice, manioc, latex, fruits, wild foods
P / M / L	Peppercorn, manioc, latex	Mixed	(17)	Production	Herbaceous	Peppercorn, manioc, latex, fruits, wild foods
Combined	All production combined	Mixed	(17)	Production	Herbaceous/woody	Upland rice, peppercorn, manioc, latex, fruits, wild foods
Sago	Sago agroforestry	Local	(17)	Fallow/production	Woody tree	Sago starch, fruits, fuelwood, lumber, wild foods
Breadfruit	Breadfruit agroforestry	Local	(17)	Fallow/production	Woody tree	Breadfruit, fruits, fuelwood, lumber, wild foods
Forest Mgmt	Mature forest management	Traditional	(17)	Fallow/production	Woody tree	Fuelwood, lumber, materials, wild foods, medicinals

Notes

Not all stages produce products evaluated in the current study, while all stages produce unexamined products. Parentheses indicate production potential for area.

Calculating Emergy Inputs to Management Strategies

Calculating the following three inputs to a system strategy is necessary for emergy analyses: total renewable, total non-renewable, and total purchased. Emergy analysis requires these measures as a basis for computing impact and sustainability indices. Total renewable (R) measures all inputs originating within individual strategies and within timeframes accessible to strategy processes. In most land management strategies, this includes the combination of sun, rain, and wind inputs as well as renewable portions of unpaid or volunteer labor. Total non-renewable (N) measures inputs originating from within strategies but outside timeframes accessible to system processes. In examined areas, this includes net erosion or topsoil loss including and beyond background rates. Total purchased (F) measures inputs originating entirely outside management strategies. This includes all manufactured goods such as tools, fertilizers, fuels, and biocides as well as the non-renewable portions of unpaid and volunteer labor, and all purchased labor. Yield (Y) measures the combined effect of these inputs, calculated as the sum of R, N, and F (Ulgiati and Brown 1998). However, accurately quantifying yield in subsistence livelihood strategies is somewhat problematic as subsistence strategies often produce multiple products beyond target crops. Specifically, difficulty exists in using upland rice production to estimate yield for combined, multi-species strategies (Rayome 2010). Combining production strategy choices for rice, manioc, peppercorn, and latex served to compare individual strategies and protected areas management while establishing standards for sago and breadfruit agroforestry-based alternatives.

Calculating Emergy Indices for Management Strategies

Once the necessary inputs were calculated, emergy analysis indices allowed interpretation of strategy sustainability. Emergy analysis indices include the Fraction Renewable Index, the Emergy Yield Ratio, the Environmental Loading Ratio, and the Emergy Sustainability Index. Fraction Renewable Index measures the reliance on renewable energy as a portion of total system energy input (Odum 1996). This measure is the ratio of all renewable input to all strategy yields. The Emergy Yield Ratio (EYR) compares how closely associated net emergy leaving a strategy is to emergy imported in the form of purchased resources and exported emergy. EYR also compares how effective non-renewable resources are in capturing renewable resources, or the ratio of total yields to total purchased inputs for a given strategy. It answers the question of 'what do we get?' from using limited resources such as fossil fuels. The Environmental Loading Ratio (ELR) indicates ecosystem stress as by comparing combined purchased and non-renewable resources to renewable resources, and is a direct inverse of the Fraction Renewable Index (Ulgiati and Brown 1998). The Emergy Sustainability Index (ESI) measures strategy productivity as a function of ecosystem stress (Brown and Ulgiati 1999). ESI is the ratio of the EYR to the total ELR, or how much benefit comes from overall strategy processes (Ulgiati and Brown 1998; see also Appendix). These four indices are defining facets of emergy analysis, as calculation of each provides a different aspect of sustainability. Further, they normalize management impact in ways that allow for common comparison between markedly different products, processes, and ecosystems.

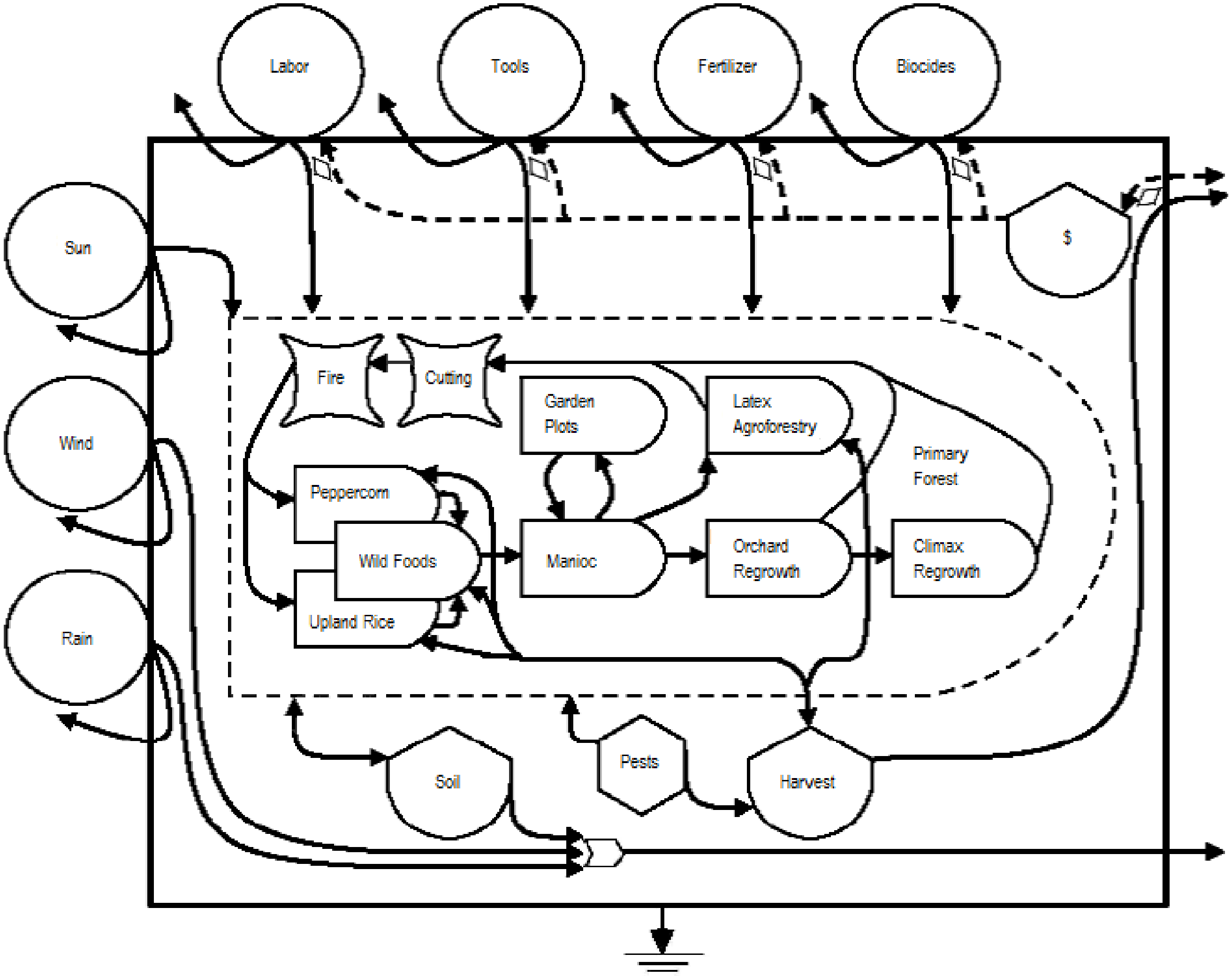

Figure 4. Full System diagram of all Iban land management strategies as practiced in Rumah Siba Perdu, Sarawak, Malaysia (after Odum 1996).

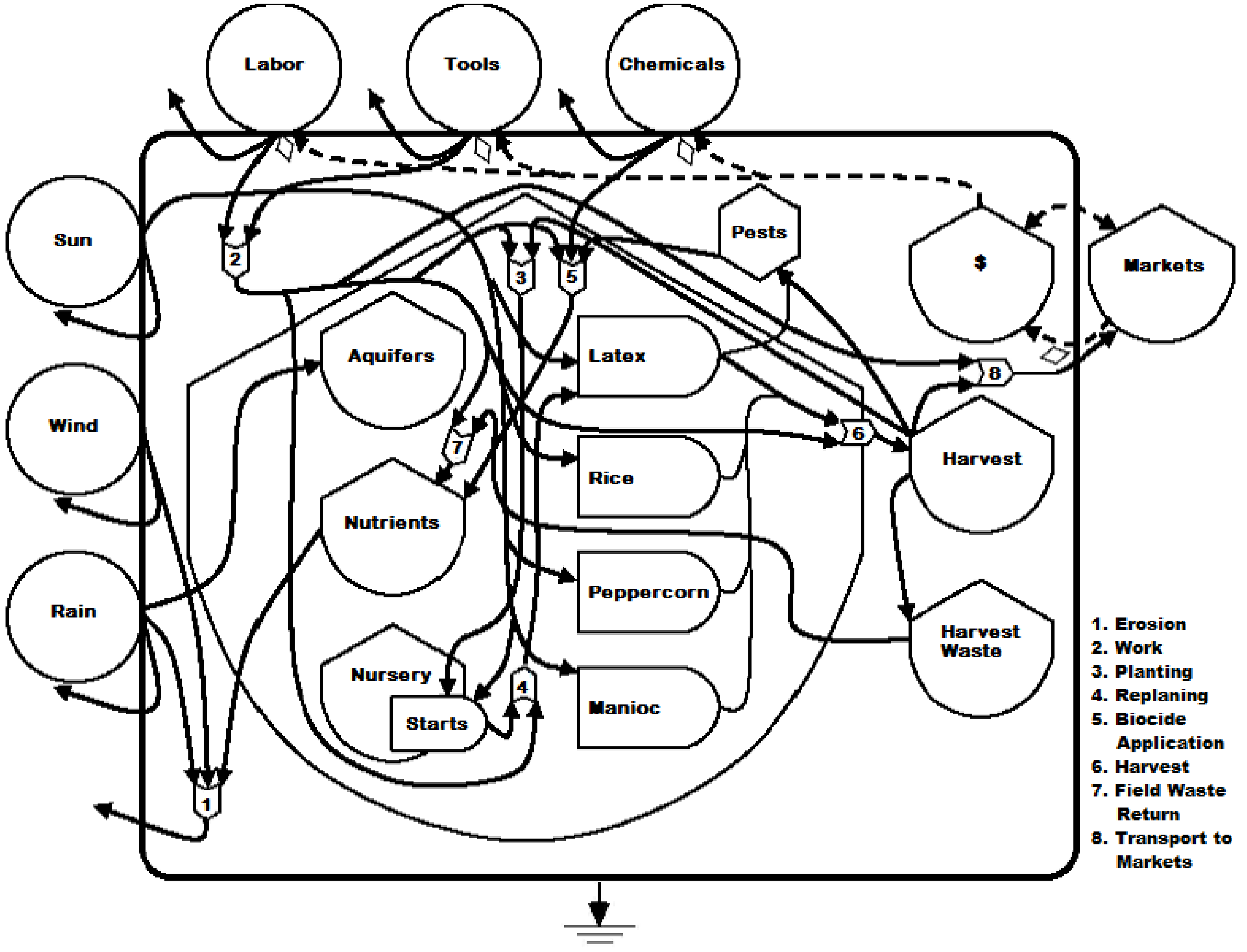

Figure 5. Simplified strategy diagram of all Iban land management as practiced in Rumah Siba Perdu, Sarawak, Malaysia (after Odum 1996).

Table 2. Emergy Evaluation of Combined Production.

193.80 hectares *Combined*

Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY* (sej/unit)	Solar EMERGY (E13 sej/yr)	Solar EMERGY/area (E13 sej/ha/yr)
RENEWABLE INPUTS (R)						
1	Sun	J	2.84E+13	1.00E+00	2.84	0.015
2	Rain	J	3.74E+13	1.80E+04	67310.91	347.32
3	Wind	J	1.74E+11	1.50E+03	26.11	0.13
4	Labor (renewable)	hr	4.78E+04	6.99E+12	33431.35	172.50
					100742.26	519.83
NONRENEWABLE INPUTS (N)						
5	Net Topsoil Loss	J	6.32E+10	6.25E+04	394.95	2.04
					394.95	2.04
PURCHASED INPUTS (F)						
6	Labor (nonrenewable)	hr	14286	6.99E+12	9985.99	51.53
7	Hand Tools	US$	1.17E+03	3.33E+13	3890.49	20.07
8	Power Tools	US$	1.61E+03	3.33E+13	5344.65	27.58
9	Fuel	L	2.73E+02	6.60E+04	0.00	0.00
10	Fertilizer	g	4.50E+03	1.99E+09	0.90	0.00
10	Herbicide	L	1.06E+05	8.88E+09	93.72	0.48
11	Pesticide	L	2.70E+01	8.88E+09	0.02	0.00
					19315.77	99.67
TOTAL INPUTS					120452.97	621.53
EXPORTS						
12	Rice	J	1.46E+12			0.00
13	Manioc	J	1.68E+11			0.00
14	Peppercorn	J	2.70E+07			0.00
15	Latex	J	2.85E+10			0.00

Results

Forest Management Strategies Have Differing Outcomes

None of the land managers we interviewed in Rumah Siba or protected areas grew all of the popular local species (Table 1). Rather, land managers were in favor of upland rice or peppercorn, but not both. Eight practiced rice-latex-manioc swidden strategies, while nine favored peppercorn over rice in their combined swidden strategies. All strategies practiced in Rumah Siba produced manioc and latex, indicating the importance of these species. In contrast, no protected areas produced any crops analyzed in this study. While assessed, inconsistencies forced the omission of any combined garden or fruit tree species data. Peppercorn was the most common production strategy in terms of area, while latex agroforestry was the least. The majority of land cover was not in combined production and regrowth fallow areas but unmanaged forested areas. This is important as large expanses of forest facilitate regrowth and soil recovery in swidden agriculture (Parrotta et al. 1997).

In Rumah Siba strategies, regrowth utilizes herbaceous annuals and perennials with minor inclusion of woody species. The majority of harvested species in forested areas are either animals or woody perennials, requiring less intensive management and greater land areas than annual or short-term production. This is similar to strategies practiced by Sarawak Forestry land managers in nearby national parks where government management focuses on maintenance of current flora and fauna populations. However, because Rumah Siba lands are communal and have open boundaries, land managers expressed difficulty in estimating area utilized outside of direct production. This necessitated inclusion of national parks management data as a proxy for mature forests on Rumah Siba lands. For example, labor focused toward ecotourism-based activities in parks such as trail building is similar to stalking desired game, while removal of undesired or poisonous species is similar to gathering processes. Subsistence livelihoods had similar effects as high natural predation, poaching, and illegal forest product removal in protected areas.

Preparing Interview Data for Emergy Analysis Calculations

A full strategy diagram shows primary constituents and interactions of all Rumah Siba land management strategies (Figure 4), with a separate diagram for the production species level (Figure 5). The appendix shows all renewable, non-renewable, and purchased resource inputs as identified from interview data, with Table 2 showing an example for combined species production. Annual inputs to each strategy are in raw units, with resulting values determined through transformities necessary for converting to solar emjoules. Areas are in solar emjoules per hectare per year (sej ha^{-1} yr^{-1}) for ease of comparison. Detailed references and calculations for emergy unit values are included in the appendix. All climatological renewable emergy flows are by-products of coupled processes, with the largest renewable emergy flow serving to approximate total renewable emergy flow in all strategies. If renewable emergy flows combine into a single source-flow, the renewable portions of emergy flows affect results more than by those stemming from management. This causes precision errors in sustainability indices and can result in miscalculations that favor less sustainable management strategies (Odum 1996; Lefroy and Rydberg 2003). Errors present further difficulties in ecosystems where renewable flows are closely connected and can result in positive-feedback loops, such as those affected by seasonal monsoons or ENSO conditions including Borneo (CEPF 2014; WWF 2015). Compounding errors and miscalculations can ultimately undermine conclusions drawn from sustainability indices.

Using methods from production-based emergy studies and country data from the National Environmental Accounting Database (NEAD 2014; Panzieri et al. 2002; Ulgiati et al. 1994), households in Malaysia were determined to have renewable emergy supporting labor at 12% and non-renewable 88%. However, Malaysia is a rapidly-industrializing country with a high urban population, increasing urban population density, and ready access to fossil fuel resources (Gov. of Malaysia 2011, 2015; NEAD 2014). As such, national averages do not accurately represent the rural-dwelling subsistence producers and thus an exaggerated baseline for emergy analysis calculations. While few emergy studies exist for subsistence production in Southeast Asia, the examined strategies are similar to those in Central American rainforest ecosystems. All calculations used respective renewable and non-renewable emergy supporting labor figures of 77% and 23% (Trujillo 1998; Rayome 2010). Odum (1996) was the baseline for emergy calculations in this study.

Renewable Resources in Management Strategies

Combining emergy analysis calculation data allowed calculation of emergy analysis indices (Hong-fang et al. 2003; Table 3). Calculation data indicated manioc had the greatest amount of renewable emergy inputs (9.98E15 sej ha-1 yr-1) due in part to family labor (6.51E15 sej ha-1 yr-1; Table 3). Despite having perennial growth and small land areas, manioc is labor-intensive – replanting starts occurs during harvest, increasing workload. In all other strategies, the greatest renewable input was precipitation. Seeds and plant starts were not included as a renewable input in our study because the majority of these inputs do not originate outside greater management areas. For example, sago comes from one of several trunks that sprout from a single root mass (FAO 2006; Flach 1997). Informants indicated that production areas, fallows, and forests have a higher likelihood of contributing their own seed inputs on a biennial basis. This was due to a combination of seed and propagule saving, short-term herbaceous and perennial species, lightly-managed agroforestry, and natural regeneration processes (Figure 4). These shift more labor and time investments to renewable processes as opposed to emphasizing non-renewable and purchased chemicals and seed inputs (Table 3).

Table 3. Emergy indices for Rumah Siba Perdu land management strategies were calculated by aggregating strategy data.

Strategy	Yield (E13 sej/ha/yr)	Total Renewable (E13 sej/ha/yr)	Total Non-renewable (E13 sej/ha/yr)	Total Purchased (E13 sej/ha/yr)	Fraction Renewable	Emergy Yield Ratio (EYR)	Environmental Loading Ratio (ELR)	Emergy Sustainability Index (ESI)
	Y	R	N	F	=R/Y	=Y/F	=(F+N)/R	=EYR/ELR
Upland rice	5.13E+02	4.72E+02	2.09E+00	3.84E+01	0.9210	13.34	0.09	155.49
Manioc	1.20E+03	9.98E+02	2.09E+00	1.95E+02	0.8348	6.12	0.20	30.90
Peppercorn	6.01E+02	4.63E+02	2.09E+00	1.36E+02	0.7704	4.42	0.30	14.84
Latex	7.29E+02	6.40E+02	5.23E-01	8.85E+01	0.8778	8.23	0.14	59.17
R + M + L	5.81E+02	5.24E+02	2.04E+00	5.44E+01	0.9027	10.67	0.11	99.00
P + M + L	6.58E+02	5.16E+02	2.04E+00	1.40E+02	0.7843	4.70	0.28	17.10
Combined	6.22E+02	5.20E+02	2.04E+00	9.97E+01	0.8364	6.24	0.20	31.87
Sago	3.93E+02	3.81E+02	5.23E-01	1.12E+01	0.9702	35.12	0.03	1143.42
Breadfruit	3.69E+02	3.62E+02	5.23E-01	5.66E+00	0.9832	65.14	0.02	3819.05
Mature forest	3.62E+02	3.47E+02	1.57E-01	1.50E+01	0.9582	24.19	0.04	555.00

Erosion Drives Non-renewable Resource Flows

Soil erosion was the only non-renewable resource flow for all strategies. Soil resource pools replenish outside of timeframes accessible to management processes, with any soil stability reductions (i.e. erosion) difficult to curtail. However, erosion decreases inversely to plant cover density and detritus layer thickness. Both cover and detritus are more likely to accumulate in longer-term strategies, including fallows and agroforestry. The erosion rate decreases as time progresses, and will be less in lightly-managed primary and secondary mature forests. Annual upland rice had a 0.4 t ha^{-1} yr^{-1} erosion rate. Manioc and peppercorn also shared this rate through final harvest some three to four years after initial establishment. Interplanted species tend to dominate only after maturity during fallows, and do not generally cycle enough organic matter to affect soil erosion until this occurs. Agroforested latex, sago, and breadfruit had a rate of 0.1 t ha^{-1} yr^{-1} regardless of species; less-impacted protected forest areas eroded at a rate of 0.03 t ha^{-1} yr^{-1} (Pimentel et al. 1987; Bruijnzeel 2004). The rate for all strategies combined defaulted to that affecting the majority of land cover, 0.4 t ha^{-1} yr^{-1}, to prevent double-counting (Table 3).

Tools, Chemicals, and Labor as Purchased Resources

Six purchased resources were present in Rumah Siba production strategies: hand tools, small power tools, fuel, fertilizers, herbicides, pesticides, and labor. Hand tools and labor were present in agroforestry alternatives, while hand tools, power tools, and labor were present in protected areas management. The relatively low average percentages of non-renewable resources supporting labor in Rumah Siba, agroforestry-based alternatives, and nearby parks (23%) resulted in a lower input of non-renewable emergy for labor to support individual strategies (Table 3). Total labor per strategy varied slightly, though when combined with other factors, did not adversely affect overall emergy sustainability. The greatest labor input was for manioc, 1.94E15 sej ha^{-1} yr^{-1}, and the least was in breadfruit, 4.48E13 sej ha^{-1} yr^{-1}, related to overall area in a given strategy and strategy management intensity, including what tools support labor therein.

Interviews revealed that all land managers in Rumah Siba employ only family members and unpaid local volunteers. The community hires minimal labor to transport agricultural products for sale, but this paid labor does not assist in production or other subsistence activities. This contrasts with what park managers in Kubah and Gunung Gading revealed during interviews. Management in both parks originates almost exclusively from paid Sarawak Forestry employee labor. Volunteers do contribute to both parks, including those paying for internship opportunities at the Matang Wildlife Centre, but this input is minimal and does not greatly affect overall labor according to officials.

On a crop species basis, total labor varied greatly. Land managers in Rumah Siba noted the most work occurs in peppercorn, yet amount of labor was less than in other currently-practiced production strategies, 1.15E15 sej ha^{-1} yr^{-1}. Mature forest management had the least amount of labor of current management, 7.84E13 sej ha^{-1} yr^{-1}. The emergy contributed by tools, which included both hand tools and small-engine outdoor power equipment, was greater than an order of magnitude less than labor input for a given strategy (Figures 4 and 5; Table 3). Fuel, fertilizer, herbicide, and pesticide inputs contributed similarly to emergy values (Figures 4 and 5;

Table 3). Due to their relative ease in establishment, low maintenance requirements, and consistent productivity, both sago and breadfruit will have fewer labor requirements than latex agroforestry or any other production strategy, even when accounting for chemical inputs and associated labor per cultivated rice area equivalent. Paid labor contributed little in most areas, even in protected areas, due in part to large expanses and low-intensity management of Sarawak Forestry offsetting paid labor impacts.

Yields and Emergy Transformities Undervalue Total Production

All land managers employed a combination of strategies that produced at least three of the examined products. These included either in a varying proportions of rice, latex, and manioc or of peppercorn, latex, and manioc. Interestingly, though strategies were in transition, no manager produced both rice and peppercorn on their lands. However, while no managers produced all measured species, all strategies produce yields beyond those quantified. The chosen method of combining species to approximate production yield underestimates output through undercounting yields of polyculture production, entirely bypassing yields of other species. For example, while fruit trees exist in peppercorn plots, production is erratic as plants mature and harvested only as needed for home consumption. Combining production yield for all species presents a more accurate representation of management efficiency, resulting in a transformity of 1.65E12 sej J^{-1}. In contrast, relying on rice yield alone results in a transformity of 1.46E12 sej J^{-1}. These four products formed the study basis due to prevalence in Rumah Siba interviewee production strategies as well as uncertainty in providing accurate responses to questions of other yields from all study participants, resulting in comparing common strategy output characteristics.

Conservative yield estimates for multiuse sago and breadfruit agroforestry strategies were favorable. Target agroforested species yields as equivalents of upland rice output yields suggested respective transformities of 3.09E12 sej J^{-1} for both strategies. Like manioc, both sago and breadfruit contain much higher proportions of water when harvested than rice, requiring adjustment for moisture when contrasting yield and available energy. Energy and moisture fluctuations during harvest processing and cooking tend to provide this correction (BI 2014; FAO 2006; Flach 1997; USDA 2014). We caution that transformity evaluations only exist for strategies producing a measured product. Within that constraint, peppercorn production resulted in the lowest transformity at 2.70E07 sej J^{-1}, while combining rice, manioc, and latex resulted in the highest transformity, 2.29E12 sej J^{-1}, partially due to the contrasting majority crop energy contents (2.51 kcal g^{-1} in peppercorn opposed to 3.60 kcal g^{-1} in rice) as well as the higher proportion of purchased inputs in the latter (USDA 2014; Table 1).

Emergy Analysis Indices for Strategies

The Fraction Renewable Index revealed that strategies with multiple crop species had at least 78.43% renewable inputs, while individual crop strategies had at least 77.04% renewable inputs. All strategies combined used the greatest percentage of renewable inputs, 83.64%, while a peppercorn, manioc, latex combination used the fewest (Table 3). Breadfruit used the greatest percentage of renewable inputs, 98.32%, while peppercorn used the least, 77.04%. The Emergy

Yield Ratio varied some among combined strategy types, being greatest for rice, manioc, and latex (10.67) and least for peppercorn, manioc, and latex (4.70). EYR varied for individual strategies, ranging from 65.14 in breadfruit agroforestry to 4.42 in peppercorn. Environmental Loading Ratio values varied for combined production as well as individual crop strategies. The ELR was greatest for peppercorn, manioc, and latex (0.28) and least for rice, manioc, and latex (0.11), while greatest for peppercorn (0.30) and least for breadfruit (0.02). The Emergy Sustainability Index ranged from 99.00 to 17.10 for combined strategies that respectively excluded peppercorn and rice, and from 3819.05 for breadfruit to 14.84 for peppercorn production alone.

Discussion

Inputs to Different Management Strategies

Calculation of all four emergy analysis indices allowed all energy input comparison on a common basis. This is essential for contrasting Iban subsistence and cash crop strategies with other types of production and management. One index value might capture factors not inherent in another, allowing for more informed decision making processes. Environmental management strategies relying on fossil fuel inputs often result in high productivity. This productivity comes at a cost, as fossil fuel inputs often have negative effects from resource procurement and environmental degradation. In contrast, subsistence strategies rely on greater inputs of renewable resources, including environmental inputs such as solar, wind, and rain originating outside of managed areas. Volunteer labor within strategies enhanced renewable inputs to agricultural practices. As workers consume many strategy products, energy therein returns to agriculture in the form of hand labor.

Emergy supporting labor represented the largest amount of purchased resources for strategies. Both proposed agroforested strategies tend to be more sustainable than annual-managed or otherwise short-term strategies in Rumah Siba and surrounds. This discrepancy is important because efficiency is lost when utilizing more intense management strategies. For example, Rumah Siba subsistence strategies used approximately 233 h of human labor to produce one hectare of rice, nearly ten times the labor/ha rice production for mechanized production in the US (Pimentel & Pimentel 2007). In strategies oriented toward multi-year harvest products (such as peppercorn and latex), the effect of labor on the emergy evaluation did not depend on land area, but did depend on chemical inputs. As the labor necessary to produce such products required smaller land areas in these strategies, a greater proportion of emergy flows came in the form of labor. In contrast, sago and breadfruit required much less labor as well as no chemical inputs to maintain agricultural production.

Fraction Renewable Index Supports Lowering Intensity

In production contexts, greater deviations from natural processes require greater amounts of external energy sources to sustain productivity (Altieri 1995; Pimentel and Pimentel 1996). In Sarawak, all strategies relied on natural processes and utilized large proportions of renewable energy (0.77-0.98; Table 3). This analysis shows that when labor-intensive (and chemical input reliant) strategies become more prevalent, the Fraction Renewable Index decreases in managed forest areas. This allows the Fraction Renewable to serve as a proxy for comparing efficiency and sustainability in different management strategies. As demand increased for high-value products such as peppercorn, an increase in hand tool, power tool, fuel, fertilizer, herbicide, pesticide, and labor inputs also occurred, further decreasing the fraction of renewable energy. However, the Fraction Renewable Index often increases according to changes in labor and resource allotment as proportions of lightly-managed strategies increase within managed areas. The inverse is true for non-renewable input requirements, potentially increasing sustainability as this index increases (Table 3).

Historically, the Iban have not had resources such as agrochemicals, commercially-produced seeds, or heavy machinery at their disposal. Iban in Rumah Siba rely on kitchen gardens, agroforestry, and gathering to produce dietary fruits and vegetables. Extensive hunting, fishing, trapping, and animal husbandry supply some 95% of animal products in their diets. Iban land management strategies developed with little dependence on outside resources, largely sustained with renewable energies during its development. As Iban informants in Rumah Siba recognize the decreased fertility of continuously-cropped lands, rice and peppercorn interplanted with trees gradually give way to lightly-managed fallows studded with woody species. Combining fallows with active replanting allows for soil nutrient and organic matter regeneration, stems some erosion, and also allows for limited production to supplement local food security.

In contrast, interviews and emergy analysis results indicate that land managers who do not plan for succession will invest more purchased resources to maintain production, often at great environmental expense. For Iban in Rumah Siba, purchased resources increasingly include chemical fertilizers, biocides, and power tools. Interviews indicated these resources allowed cash crop land managers to take advantage of the thriving peppercorn export market. Mechanized systems containing purchased resources including machinery, chemicals, and fossil fuels influence such markets (Rydberg and Jansen 2002). Utilization of purchased resources from these markets, such as subsidized chemical inputs or readily available rice imports, results in a further decrease of emergy sustainability. Renewable energy capture of fallow areas cannot address these decreases.

Fallow areas are necessary for soil regeneration and continued production in most subsistence contexts, but the the presented emergy evaluation did not include fallows when calculating the resource requirements for important production species. While Rumah Siba land managers acknowledged the importance of fallows, no study participants practiced fallow management to restore soil beyond background rates. Further, they were also unable to estimate areas currently in fallow, similar to utilized portions of regrowth and climax forests. This is important because choosing to account for resources reaching production areas underestimates the true emergy requirements needed for production. As rice, manioc, peppercorn, latex, sago, and breadfruit are the only agricultural products examined in this evaluation, this study underestimates the true value Rumah Siba Iban land managers derive, or could potentially derive, from their land management strategies. Thus, a detailed evaluation of all harvested products in conjunction with those omitted from this evaluation would give a more accurate representation of land management yield and transformities.

Emergy Yield Ratio Favors Alternative Crops

The Emergy Yield Ratio is pertinent when analyzing commodity production systems where purchased resources concentrate natural energy for production. Renewable inputs of sun, rain, and wind are dispersed energy sources of lower quality, often requiring higher quality purchased energy sources to concentrate this renewable energy into desired products. Converting renewable and purchased energies to the common basis of solar emjoules allows for comparison. EYR quantifies effectiveness of this concentration process by calculating the amount of renewable emergy invested per investment of non-renewable emergy (Rayome 2010). Strategies with higher fractions of renewable emergy produce greater returns per invested non-renewable energy. Higher reliance on more traditional Iban management strategies produced greater returns than those relying on newer practices. For example, the EYR of 35.12 for sago agroforestry indicates over 35.12 solar emjoules of renewable emergy per each solar emjoule of purchased resources invested (Table 3). This contrasts with an EYR of only 1.1 for mechanized fruit production in Italy (Ulgiati and Brown 1998). Netting (1993) found a similar decrease in energy ratios from 11:1 for strategies dependent on human labor, to 4:1 for animal labor, to less than 2:1 for those based on machines and agrochemicals.

Transforming Strategy Inputs to Final Products

Transformity results indicate that breadfruit had the greatest amount of output relative to emergy input. Strategies emphasizing local rice production have lower transformities and greater yields per area than peppercorn. In contrast, higher labor and resource inputs associated with peppercorn may offset by fallows on managed lands, and species therein contribute to production and ecosystem recovery. This demonstrates the importance of all products coming from a given management strategy when calculating how effective inputs are over the strategy area. Increasing labor in production areas would translate to greater yields from combined rice, manioc, and latex strategies.

In strategies producing one of the four popular species or two alternatives, breadfruit had a lower transformity relative to others, underscoring the need to consider all products and services provided by combined strategies. For example, both rice and peppercorn-based combined production strategies also include a number of high-value perennial and agroforested products in addition to ecosystem services such as biodiversity. This reflects indigenous farmers' need to minimize risk and insure subsistence yields, regardless of pest outbreaks or climate variability (Lyman et al. 1996), by trading potential high crop yields for stability associated with polycultural management (Liebman 1995). Investing in high-yield monocultures with limited fallow can produce greater yields, but often at greater environmental and social cost, even in agroforested strategies. Historical examples show the potential of such strategies to yield negligible production during extreme events, even more problematic when monocultures shift from staple species to niche cash crops. Iban land managers attempt to circumvent this by interplanting rice and peppercorns with tree polycultures, thus taking productive advantage of fallow periods.

Peppercorn Has Greatest Environmental Impact

ELR values for combined multi-crop strategies in Rumah Siba and surrounds ranged from 0.11 to 0.28. This is close to the near-zero values for unmanaged wilderness settings such as those found in rural Borneo. These values indicated a similar level of cumulative environmental impact at the combined strategy level, but the impact of individual strategies varied more. Single-crop strategy ELR values ranged from 0.02 to 0.30, reflecting the effects of labor and purchased emergy inputs relative to managed areas. The greater ELR for peppercorn compared to rice reflects the greater environmental cost of using more purchased resources. This is also true of the greater environmental benefit from devoting a greater proportion of managed land area to fallows or other lower-intensity strategies.

Almost all purchased resources have negative environmental costs associated with their production, use, and environmental assimilation (Rayome 2010). In Rumah Siba and the parks studied, some portions of land manager lifestyles are non-renewable. Humans have many requirements to survive, and these requirements create an environmental load. In circumstances where fewer supporting human activities originate within a strategy, human-based environmental loads are greater. In addition, purchased employee labor completes almost all parks management, further increasing human-based environmental stress on parks. For example, while the ELR of breadfruit was the lowest of all strategies (0.02; Table 3), this particular strategy is meant to complement other strategies with differing ELR values. Breadfruit is a staple crop meant to supplement or entirely replace starch from rice, but does form a complete nutrition foodstuff itself. While appropriate for starch production, incorporating breadfruit may not be an appropriate without also accounting for volunteer and purchased labor as well as increased environmental loading of companion management strategies.

Low ELR values in conjunction with high renewable inputs indicate Iban and Sarawak Forestry strategies utilize surrounding environs without resource depletion. The ELR for current multi-crop strategies relying on peppercorn was 0.13 greater than those relying on rice, indicating similar degrees of environmental stress among systems and warranting examination of individual strategy ELR values. In this case, the ELR of peppercorn (0.30; Table 3) was 0.21 greater than rice (0.09; Table 3), due in part to variations in non-renewable and purchased inputs relative to overall management strategy areas. Indices quantifying production-based environmental stress are necessary for selecting production methods that include productivity-sustaining resource protections (Pimentel and Pimentel 1996).

Our results corroborate findings from studies of other similar land management systems (Rayome 2010; Trujillo 1998). A reduction of agricultural land in fallow will accelerate soil erosion and deforestation, therefore placing a greater strain on the environment (Lal 1995; Dreschel et al. 2001; Thomaz et al. 2014). The Iban are descendants of populations indigenous to the region, and traditionally practice forms of land management similar to those of their ancestors (Sutlive 1978). However, Iban land management strategies are in transition, orienting toward cash crops and export markets. Intensifying management strategies through additional non-renewable or purchased inputs increases environmental stress and potential for degradation. For example, erosion and fertilizer application contribute to soil fertility alterations that may have unintended peripheral consequences (de Neergaard et al. 2008; Tanaka et al. 2009). Similar human population pressures affect the humid tropics globally, increasing the relevance of examining management decisions that lead to negative environmental consequences (Bhagwat et al. 2008; Corlett & Primack 2008; Whitmore 1997).

ESI Favors Breadfruit Agroforestry

Calculated ESI values (Table 3) indicate that breadfruit had the greatest level of sustainability of any management strategy, combined or individual. ESI operates under the assumption that the purpose of sustainability is to obtain the highest yield relative to environmental stress (Ulgiati and Brown 1998). The high yield ratio and low environmental loading produced an ESI value of 1143.42 for sago agroforestry, while the lower yield ratio and higher environmental loading of manioc produced an ESI value of 30.90. For comparison, rice in China showed an ESI value of 1.83 (Lu et al. 2010). In the examined strategies, land area relative to labor and purchased emergy inputs were the most important considerations for high ESI values. The strategy with the least amount of land in production relative to labor utilized had higher ESI value, while those with the most land in more intense production had lower ESI value. Therefore, as was found in other soil and plant community studies of land management strategies, maintaining adequate land in fallow is essential to management sustainability. This can and should include actively-managed production fallows intended to support the overall nutrient recovery of managed ecosystems as well as the societies dependent upon them (Lal 1995; Dreschel et al. 2001; Rayome 2010).

When accounting for purchased emergy values as portions of overall use in combined strategies, fallow and mature forest are apparent drivers of sustainability. A fallow-to-production threshold exists that land managers in Rumah Siba must exceed in order to continue production-based strategies and avoid excessive forest removal or overuse. This lesson is stark because failure to manage for a proper fallow periods has led to the decline of other civilizations, particularly when stressed with growing populations and climatic variability (Frahm & Feinberg 2013; Buckley et al. 2010; Rayome 2010). While not assessed as a part of the current emergy analysis, communal forest management appears to provide the necessary fallow areas required. Fully test this assertion requires more precise data beyond proxies provided from nearby national parks.

Concluding Remarks

Anthropogenic climate change and market fluctuations are forcing subsistence populations to reexamine and alter management techniques. Subsistence methods employed in Rumah Siba and agroforestry-based alternatives presented by this work may prove advantageous under these circumstances, particularly in high-sensitivity ecoregions of the humid tropics such as rainforests. Strategies showing higher sustainability levels are of particular interest, as they require fewer environmental resources for production. Specifically, starch-based agroforestry is a viable management addition to Rumah Siba and similar subsistence strategies. Even in combined strategies where subsistence production is relatively sustainable, breadfruit or sago-based alternatives can supplement starch production as well as starch purchases made with cash crop profits, thus decreasing necessary cash crop areas and resulting environmental impacts. In the case of upland rice, the total land area required for human subsistence would decrease. In addition, less land area would be required for manioc-based animal feed, decreasing the ecological consequences of husbandry as well. Further, alternative strategies would also provide opportunities for other benefits such as animal habitat and forest regrowth, further increasing advantages over higher-impact strategies. More complete understanding of Rumah Siba and other indigenous management strategies, including rationale behind crop choices, land use planning, and the ratio of necessary forests and fallows to production stages, will aid in developing and applying multiuse alternatives to address present environmental problems locally and in similar tropical areas.

Chapter Six: Thesis Conclusions

Meeting Goals and Objectives

The purpose of this research was to understand effects of land management strategies in tropical rainforests. Novel characteristics are now ubiquitous in some tropical forests, an alarming fact for biodiversity conservation interests as well as populations subsisting therein. The accumulating effects of management focused on immediate needs that may ignore long-term consequences has overwhelmed local forest resilience thresholds and spurred transitions toward novel ecosystem states. Because these states may be difficult to reverse through traditional restoration practices, past management strategies may no longer be appropriate in heavily-impacted locations. Instead, accepting the potential of novelty for developing new management protocols may be required if we are to maintain forest functions and characteristics. Determining where novel traits are increasing, where these traits cannot be reversed without great difficulty, and how such traits can be managed for human benefits is essential. In tropical forests experiencing multi-faceted impacts from expanding populations, new species introductions, and intensifying management practices, means for addressing novelty can be pragmatic for reforestation and restoring essential functions as well as ease pressure on vital conserved areas.

The research in this thesis focused on lowland dipterocarp forests of Borneo, and strategies for their management as practiced in western Sarawak, Malaysia. Descriptions included current practices such as production and management outcomes. The work assessed physical measures of management effectiveness as well as local views and official stances on management practices in biodiverse, high-sensitivity rainforest ecosystems. Land manager views contrasted greatly, with management groups holding somewhat antagonistic views despite having similar biodiversity and related management goals. Further, comparing different land management strategies on the common basis of emergy allowed developing a baseline for recommending management alterations. By including perceptions of management sustainability as well as assessing strategy sustainability through emergy analysis, illustrating a more complete management picture. Such a picture, when interpreted through the lens of novelty and novel forest restoration strategies, places current management and its effects on one end of the novelty continuum. Applying novel multiuse management that incorporates restoration into agriculture recognizes humans affect where ecosystems lie on the novelty continuum. In this regard, manuscript chapters on novelty in tropical forests, management in the case study rainforest ecosystem, and management sustainability as determined by emergy analysis form the body of this thesis.

Rainforest Impacts and Novelty

Human impacts in tropical forests often result both in difficulty maintaining production and restoring impacted land. Increasingly, impacts accumulate in ways that encourage novel courses of ecosystem development. Ecosystems tending toward novel characteristics are in some ways correcting an organizational imbalance with what remains in the wake of human impact. Attempting to increase functional efficiency from a new and unprecedented mixture of survivors and colonizers supports the need for alternative management protocols for areas that may not be suited for more commonplace restoration techniques. This thesis presented the notion that including mixed-use production and restoration landscapes may be an appropriate way to address novelty and its effects. Use of agro-successional techniques developed with ecoregional management, landscape fluidity, and applied historical ecology inform such mixed-use management, with agroforestry being the structural guide. Recognizing that fully restoring historical forests may not be possible, management emphasis may be better directed toward functionality, rebuilding natural capital, and restoring ecosystem services lost due to human activity. As human populations continue to increase pressure on remaining forest lands, this shift in emphasis may assist in providing services preferred by local peoples, recover services essential to maintaining forest resilience, and potentially circumvent additional forest losses. In circumstances where traditional restoration may prove unsuccessful, novel management can instead serve as a pragmatic compromise.

Management of Rainforests in Borneo

Governments and indigenous peoples often approach natural resource management in different and sometimes conflicting ways. This thesis analyzed and compared strategies employed by Sarawak Government forestry officials in Kubah and Gunung Gading National Parks and those of Iban farmers in Rumah Siba Perdu. Areas under study were of the lowland dipterocarp rainforest ecosystem type managed for different outcomes. Priorities underlying management goals often lead to conflict, due in part to increasing human population pressures, expanding markets, and local impacts of climate change. Interview results indicated forestry official bias against farmer management strategies, specifically noting that prioritizing short-term profits negatively affected production stability and ecosystem integrity. However, farmers in Rumah Siba Perdu expressed concern regarding overuse of public lands, excessive resource extraction, and a general need for conservation in managed areas. Because current farming poses an impact, alternative cropping strategies that are both more productive and more ecologically-appropriate may be one means to dispel negative consequences. Multiuse agroforestry-based ecosystems are one such means for coping with increasing human populations as well as future economic and environmental conditions in areas unsuitable for traditional restoration.

Emergy Analysis for Sustainability

This thesis also posited that emergy analysis is an effective measure of sustainability in determining how to apply multiuse agroforestry ecosystems. Using emergy, it was determined that altering management strategies to incorporate more subsistence-based multiuse agroforestry could benefit local populations and ecosystems. Fraction Renewable Index, Environmental Yield Ratio (EYR), Environmental Loading Ratio (ELR) supported including agroforestry, and Emergy Sustainability Index (ESI) values generated from emergy analysis. Previous work has confirmed this assumption in similarly-applied ecosystem management strategies (Rayome 2010). Fraction Renewable Index variations were due to increases in labor-intensive strategies, especially those driven by chemical inputs such as peppercorns. Variability in EYR values is due to effectiveness of concentrating renewable energy inputs by purchased, non-renewable inputs into desired subsistence or cash crop products. This includes sun, wind, and rain energy inputs in management strategies concentrated by labor, tool, and chemical inputs into commodity products removed from managed areas. ELR variations were due to the greater environmental costs of utilizing more purchased resources, particularly tool and chemical inputs, relative to renewable resources in peppercorn, latex, and conservation forestry-based strategies. This is also true of the greater environmental benefit from devoting a higher proportion of agricultural area to managed fallows or to agroforestry strategies. Variability in ESI values is due to the combined variability of both EYR and ELR values for a given management strategy, as ESI is defined as the ratio of EYR to ELR values.

Interpreting Results

Findings in Sarawak display the complexity in analyzing perceptions and sustainability of rainforest management strategies, including those producing multiple crop species. Interviews determined the importance of certain species as well as their yields based on the described management strategies, but interview data and personal observation indicated underestimation of harvest and subsequent effects. Emergy analysis supported the importance of fallows and alternative strategies in Rumah Siba strategies as well as the influence of purchased inputs on sustainability. In general, subsistence strategies showed a high degree of sustainability related to land area and management intensity, particularly those proposed for agroforested species. Sustainability as related to land are and management intensity was also highly affected by management therein, with strategies requiring more purchases resulting in lower overall sustainability. These results suggest that land management strategies including greater amounts of lightly-managed fallow and agroforestry areas have higher sustainability than those without. Further, Iban subsistence land management strategies in Rumah Siba as well as breadfruit and sago-based agroforestry alternatives have promise for restoring ecological functions and increasing productive capacity. When applied, such strategies may also contribute to biodiversity conservation by stemming the expansion of human activities into less-impacted areas.

Final Project Comments

This research project illustrates the need for examining land management strategies at combined and individual species levels. In Rumah Siba, current subsistence management appeared more sustainable than any of the current cash cropping strategies examined. However, current strategies of any type showed less sustainability than conservation management or either proposed subsistence agroforestry technique. Agroforestry strategies developed as alternatives to subsistence or cash crop management in Rumah Siba have potential for use as portions of more appropriate long-term forest management strategies. Emergy sustainability confirmed this assertion due to a decreased reliance on labor and chemical inputs for both breadfruit and sago agroforestry when compared with other strategies. In contrast, multi-crop strategies require greater amounts of land for both cultivation and fallows, but also promote biotic diversity and resource security in times of change. For example, in peppercorn-based strategies, polyculture plantings intermixed with encouraged regrowth provide a patchwork mosaic of hosts for potential pests, discouraging specialists and potentially having decreased pest burdens when compared with monoculture plots (Gurr et al. 2003; Altieri and Nicholls 2004). This has an additional effect of reducing labor and biocide inputs associated with pest control and removal. In contrast, upland rice presents a high potential for crop failure due to high emphasis on monoculture production. Heavy reliance on labor and biocides may prove inadequate for combating specialist pests, while such investments further decrease resource security in the event of crop failure.

Economically, much of Borneo and Southeast Asia are in developing status. Historically, the Iban in Rumah Siba farmed for subsistence, with the majority of their efforts directed to providing for their families. Any additional efforts on their part provide funds to increase quality of life. Further, these efforts must be productive and sustainable, as they live on potentially-contested lands in a fragile ecosystem. These lands are highly valued by the government of Malaysia and multinational corporations in part due to their natural resource wealth. Subsistence land management strategies provide a means for indigenous populations in Malaysia to maintain their customary land rights in light of these challenges (Bulan 2006), while also ensuring adequate resources to meet the majority of their subsistence needs. Anticipating management effects on their lands encourages applying subsistence strategies in ways that increase agricultural productivity, decrease production impact, or both. Exploring the potential of novelty to guide successional regrowth in ways that benefit human populations is one means to increase natural capital stores and subsequent ecosystem service production. Over time, such novel management may spare other regions from impact, further augmenting the value of novel forests as conservation buffers.

Future Directions

While this research focused on the island of Borneo, project design and conclusions are applicable to other tropical forest regions, especially those difficult to restore and subject to continuous human impacts. The next step in research on novel tropical forest management is to design and implement research projects that combine restoration and ecosystem service production. One such project, the Liko Nā Pilina hybrid ecosystems project, combines native and non-native species to facilitate ecosystem service recovery in degraded Hawaiian rainforests. Native tropical forests in Hawaii are declining, and restoration is extremely difficult. Hawaiian forests evolved in isolation from human activities, showing decreased resilience when faced with human impacts such as fragmentation or non-native species invasions. The research site is a military training site structurally-altered by aggressive invasives species. Invasion has altered species dominance therein, resulting ecosystem processes and functions produce few ecosystem services when compared with reference forests. Species identified as invasives have been removed and replaced with native species such as ōhi'a (*Metrosideros polymorpha*) and non-natives shown to have low invasion risk such as mango (*Mangifera indica*). The project design accounts for conditions necessary in establishing co-dominance of native and non-native species while decreasing future invasion risk and providing similar ecosystem services as native-dominated forests. Projects such as Liko Nā Pilina allow a dual-purpose of pro-active restoration to current and potential future conditions as well as exemplifying the strategic advantage of recognizing novelty in ecosystem management perspectives (SERDP 2014; Warman 2015).

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Appendix A: Interview Information

Recruitment Letter

Dear Borneo Resident:

I am a second year doctoral candidate in the Department of Environment and Resource Studies at the University of Waterloo, Canada conducting research under the supervision of Dr Stephen Murphy on the use of different land management strategies in tropical regions. As land management strategies often vary in desired outcomes, such may be a source of conflict in developing areas. This research will be conducted in two stages: a one-on-one open-ended survey and interview stage, and a later modeling and analysis stage to compare different land management types for inclusion in my doctoral thesis. As a resident of the ecologically-important region of Borneo, I would appreciate the opportunity to speak with you about your experience on this topic. I plan to conduct the first phase of this research between the hours of 8:00AM and 8:00PM during the time period of 15 March and 29 March 2013. Your involvement in this first survey and interview stage is entirely voluntary and there are no known or anticipated risks to participation. If you agree to participate, involvement should not take more than one hour. The questions are very general (for example, how many kilograms of rice did you produce this year)? However, you may decline answering any questions you do not wish to answer. All information you provide will be considered confidential and will be grouped with responses from other participants. With your consent, your responses may be audio recorded, with this information referenced at a later date. Further, you will not be identified by name in any thesis, report, or publication resulting from this study; with your permission, anonymous quotations may be used. The data collected will be kept for a period of three (3) years in my supervisor's office at the University of Waterloo.

If after receiving this invitation, you have any questions about this study or would like additional information to assist you in reaching a decision about participation, please contact project supervisor Dr Stephen Murphy, Chair, Department of Environment and Resource Studies, at 00+1-519-888-4567, Ext. 35616, or sd2murph@uwaterloo.ca. I would also like to assure you that this study has been reviewed and received ethics clearance through the Office of Research Ethics at the University of Waterloo. However, the final decision about participation is yours. Should you have comments or concerns resulting from your participation in this study, please contact Dr Maureen Nummelin, Director, Office of Research Ethics, at 00+1-519-888-4567, Ext. 36005 or maureen.nummelin@uwaterloo.ca.

Interview Questions

Survey/Interview Preamble:

Many populations practice land management strategies that may conflict in providing ecosystem services necessary for human survival. My research will attempt to understand land management in terms of biodiversity, carbon sequestration, food and livelihood production, and total energy use of a given management strategy as well as manager viewpoints on these measures. This project will be conducted in two stages: a one-on-one open-ended survey and interview stage, and a later modeling and analysis stage to compare different land management types for inclusion in my doctoral thesis. By providing your perceptions of management strategies and potential improvements in the first research stage, I am able to develop alternatives that may be more acceptable to multiple parties, potentially preserving the ecosystems and services upon which you depend. The second stage consists of visually modeling and analyzing management strategy measures to allow sustainability comparisons over time, providing a better understanding of what land management outcomes, perceptions, and alternatives mean for ecosystem services in Borneo and land management in general.

The following demographic questions are necessary for identification and comparison of survey and interview data. Please note participation is entirely voluntary and there are no known or anticipated risks to participation. If you agree to participate, involvement should not take more than one hour. The questions are very general (for example, how many kilograms of rice did you produce this year)? However, you may decline answering any questions you do not wish to answer. All information you provide will be considered confidential and will be grouped with responses from other participants. With your consent, your responses may be audio recorded, with this information referenced at a later date. Further, you will not be identified by name in any thesis, report, or publication resulting from this study; with your permission, anonymous quotations may be used.

Informant identifier:
Informant age:
Place of birth:
Language group/ethnicity:
Profession:
How long have you lived in this area?
How long have you been managing land?
How long have you been managing your current land?
Where did you learn to manage land?
Describe your training and past experience in land management:

<u>List field types, quantities, and sizes of each (primary/surrounding forest = approximate total of areas used):</u>
Field crop(s):
Garden crops:
Managed forest:
Other:

<u>List by each managed area/field:</u>
During one year, what crops are planted or harvested in each field?
How many months do you or others work each of your fields?
How many harvests per year in each field?
Are harvests continuous or single events for each crop?
How long is each harvest event for each crop?
How many days of the week are worked in each field normally?
During harvest?

During other times?
How often do you visit each field?

Last year, how many family members or unpaid volunteers worked in each field normally?
How many hours per day for each normally?
Last year, how many family members or unpaid volunteers worked in each field during harvest?
How many hours per day for each during harvest?
Last year, how many paid laborers worked in each field normally?
How many hours per day for each normally?
Last year, how many paid laborers worked in each field during harvest?
How many hours per day for each during harvest?
What wages were paid to laborers normally?
Unit of payment (per bag/kg/etc.):
What wages were paid to laborers during harvest?
Unit of payment (per bag/kg/etc.):
How much was paid on average per day to each laborer (average per bag/kg/etc.)?
How far away is each field (estimated distance in both km and time walking)?
Is there a similar level of work in each field?
Which fields have the most work?
Which fields have the least work?

Fertilizing:

In the last three years, have you fertilized, applied uncomposted manure, or applied compost to any fields? If no, skip to biocides.
How often is this applied?

Do you use chemical fertilizer?
Brand/type of chemical fertilizer:
Amount per application:
Unit of the chemical fertilizer amount (litre, kg, etc.):
Price of fertilizer by unit:
How many people apply the chemical fertilizer?
How long does it take to apply chemical in each field per year?
How many times did you use chemical fertilizer in the last three years?
Do you use chemical fertilizer continuously, every year, every other year, or every third year?
If less than every third year, last time chemical fertilizer was used:
How many times did you use only chemical fertilizer from a specific source?
Type of chemical fertilizer used each time:
Do you use these chemical fertilizer types continuously, every year, every other year, or every third year?
If less than every third year, last time these chemical fertilizer types were used:

Do you use uncomposted mulch?
Source of above:
Amount per application (litre, kg, etc.):

How many people to the apply the mulch?
How long does it take to apply each mulch type in each field per year?
How many times did you use mulch in the last three years?
Source of each type made:
Do you use mulch continuously, every year, every other year, or every third year?
If less than every third year, last time mulch was used:
How many times did you use only mulch from a specific source?
Type of mulch used each time:
Do you use these mulch types continuously, every year, every other year, or every third year?
If less than every third year, last time these mulch types were used:
How many people worked to make the mulch?
How many times is mulch harvested/made?
How many times per year is mulch harvested/made?

Do you use uncomposted manure?
Source of above:
Amount per application (litre, kg, etc.):
How many people do the fertilizing?
How long does it take to apply each manure type in each field per year?
How many times did you use uncomposted manure in the last three years?
Source of each type made:
Do you use uncomposted manure continuously, every year, every other year, or every third year?
If less than every third year, last time uncomposted manure was used:
How many times did you use only uncomposted manure from a specific source?
Type of uncomposted manure used each time:
Do you use these uncomposted manure types continuously, every year, every other year, or every third year?
If less than every third year, last time these uncomposted manure types were used:
How many people worked to gather the uncomposted manure?
How many times is uncomposted manure gathered?
How many times per year is uncomposted manure gathered?

Do you use compost?
Compost source (crop/harvest waste, manure, etc.):
Amount per application (litre, kg, etc.):
How many times did you make compost in the last three years?
Source of each type made:
Do you make compost continuously, every year, every other year, or every third year?
If less than every third year, last time compost was made:
How many times did you make compost with only manure?
Type of manure used each time:
Do you use manure continuously, every year, every other year, or every third year?
If less than every third year, last time manure was used:
How many people worked to make the compost?
How many times is compost made in a year (last time it was made)?

How many people worked to make the manure compost?
How many times is manure compost made in a year (last time it was made)?

If you no longer fertilize, when was the last time you used any fertilizer source in any field?

Pest prevention:
Have you weeded or cleared any field in the last year? If no, skip to field labor.
How often do you weed or clear each field per year?
How often do you weed with hand tools in each field?
How often do you weed with herbicide in each field?
Brand/type of herbicide:
Amount per application:
Unit of the chemical herbicide amount (litre, kg, etc.):
Price of chemical herbicide by unit:

Have you planted any green manure in any field in the last year?
Did you weed the green manure?
How did you weed the green manure?
How many times has each field been weeded or cleared with hand tools in the last three years?
How many times has each field been weeded or cleared with herbicide in the last three years?
How many people weeded or cleared with hand tools?
During one year, how long total does it take to weed or clear each field with hand tools?
How many people weeded or cleared with herbicide?
During one year, how long total does it take to weed or clear each field with herbicide?
Is each field weeded or cleared with hand tools every year, every other year, or every three years?
If less than every third year, last time a field was weeded or cleared with hand tools:
Is each field weeded or cleared with herbicide every year, every other year, or every three years?
If less than every third year, last time a field was weeded or cleared with herbicide:

In the last year, was anything done to avoid diseases or pest attacks in any field?
What was done?
Where did you learn of these methods?
How often do you use pesticides/insecticides in each field?
Brand/type of pesticide/insecticide:
Amount per application:
Unit of the chemical pesticide/insecticide amount (litre, kg, etc.):
Price of chemical pesticide/insecticide by unit:
Who did the work to avoid the diseases or pest attacks?
How long is the remedy used per year to avoid disease or pest attack?

Field labor:
In the last two years, was any field type pruned or trimmed (including removal of suckers)?
How many times were these fields pruned or trimmed in the last five years?
Are these fields pruned or trimmed every year, every two years, or every three years?

If less than every third year, last time the field was pruned or trimmed:
Who prunes or trims the fields?
During one year, how long total does it take to prune or trim a field?
Is any field tree-shaded for the benefit of another plant?
In the last five years, were any of the shade trees pruned or trimmed?
Are the shade trees pruned or trimmed every year, every two years, or every three years?
If less than every third year, last time the shade trees were pruned or trimmed:
Who prunes or trims the shade trees in each field?
During one year, how long total does it take to prune or trim shade trees in each field?

Do you graft new branches or canes onto any tree to promote more fruiting?
What fields have grafted trees?
Do you graft branches or canes yearly, every other year, or every three years?
If less than every third year, last time any grafting occurred:
Who does the grafting?
During one year, how long does grafting take?

In the last five years, how many times have you changed plants/trees in favor of younger ones?
Do you change plants/trees every year, every other year, or every three years?
If less than every third year, last time any plants/trees were changed:
Who does the plant/tree changing?
During one year, how long does changing plants/trees take?
During one year, how much money is spent buying products for changing plants/trees?

Do you have a nursery area different than your fields for any plants?
Do you water this nursery?
When was the last time you watered this nursery?
How much water do you use when watering the nursery?
Do you have a garden area different than your fields for any plants?
Do you water this garden area?
When was the last time you watered this garden area?
How much water do you use when watering the garden area?
What plants do you start from saved seeds?
What plants do you start from purchased seeds?
What is the source of your purchased seeds?
What plants do you start from gathered seeds?
What is the source of your gathered seeds?
What plants do you start from cuttings or non-seed parts?
What is the source of cuttings or non-seeds parts?
Who does work in the nursery or garden area?
During one year, how long does work in the garden or nursery area take?
During one year, how much money is spent buying products for nurseries or gardens?
What is the average age of planted plants in any field (can refer to managed forests or other natural ecosystems types)?
Do you water any fields?

How often have you watered any fields in the last three years?
How much water do you use when watering fields?

Do you make raised beds in any of your fields?
Do you make raised beds every year, every two years, or every three years?
If less than every third year, last time raised beds were made:
Who makes the raised beds?
During one year, how long does making raised beds take?
During one year, how much money is spent buying products for raised beds?
Do you make living fences or shrubbery in any fields?
Do you make regular fences in any fields?
Do you cut boundaries for any fields?
Do you make fences or cut boundaries every year, every two years, or every three years?
If less than every third year, last time fences made or boundaries cut:
Who makes the fences or cuts the boundaries?
During one year, how long does making fences or cutting boundaries take?
During one year, how much money is spent buying products for fences or boundary cutting?
Who does this work?
How long will it take?

How much of each crop was removed from the fields last year (including all crops)?
Unit of measurement for each (kg/bag/plants):
How much of each crop was removed from the fields two years ago (including all crops)?
Unit of measurement for each (kg/bag/plants):
How much of each crop do you expect to remove from the fields this year (including all crops)?
Unit of measurement for each (kg/bag/plants):
Will this year be better, worse, or the same as last year or the year prior?
If different, by how much?
Where do you sell your management products?
How long does it take to get to each location?
How do you get to each location?
Price paid per unit for each crop:
How much of these crops are sold to cooperatives or associations?
Price paid per unit for each crop:
How much total do you expect to make from all farm product sales this year?
What was your management income this past year?
Were any prices less due to undesirable qualities such as damage or fermentation?
What was your management income the year before last?
Were any prices less due to undesirable qualities such as damage or fermentation?

What tools do you buy each year (machete, file/stone, shovels, harvest bags, tarps, etc.)?
How much does each tool cost?
Do any tools require maintenance? If so, how much? Cost?
How long does each tool last normally?

Open-ended Biodiversity Questions:
In your managed or utilized areas, what animals/birds/fish have you seen in the last week?
Last month?
Last three months?
Last six months?
Last year?
Do you feel there are more or less animals/birds/fish in your fields compared to the last three years?
What is your opinion of the animals/birds/fish in your managed areas?
Does this differ by managed area?
What is your opinion of the animals/birds/fish in other managed areas?
Does this differ by management type?
Have others expressed an opinion of the animals/birds/fish in your managed areas?
Have others expressed an opinion of the animals/birds/fish in other managed areas?

In your managed or utilized areas, what plant species have you seen in the last week?
Last month?
Last three months?
Last six months?
Last year?
Do you feel there are more or less plant species in your fields compared to the last three years?
What is your opinion of the plant species in your managed areas?
Does this differ by managed area?
What is your opinion of the plant species in other managed areas?
Does this differ by management type?
Have others expressed an opinion of the plant species in your managed areas?
Have others expressed an opinion of the plant species in other managed areas?

Open-ended Carbon Storage Questions:
How many trees do you have on your lands?
What kinds of trees are present?
How large are these trees?
How many trees are in forested areas you utilize?
What kinds of trees are present?
How large are the trees in forested areas you utilize?
Do you cut any trees?
What kind of trees do you cut?
How many trees do you cut?
How often do you cut trees?
How large are the cut trees?
Are there any other plants that make up a majority of any area you manage or utilize?
What kinds of plants are these? Can include field, cash crop, invasive, or other species.
How much area do these species utilize?
How long do any of your managed or utilized areas have these species present?
What is your opinion of the dominant species in your managed areas?

Does this differ by managed area?
What is your opinion of the dominant species in other managed areas?
Does this differ by management type?
Have others expressed an opinion of the dominant species in your managed areas?
Have others expressed an opinion of the dominant species in other managed areas?

Feedback Letter

Dear Study Participant:

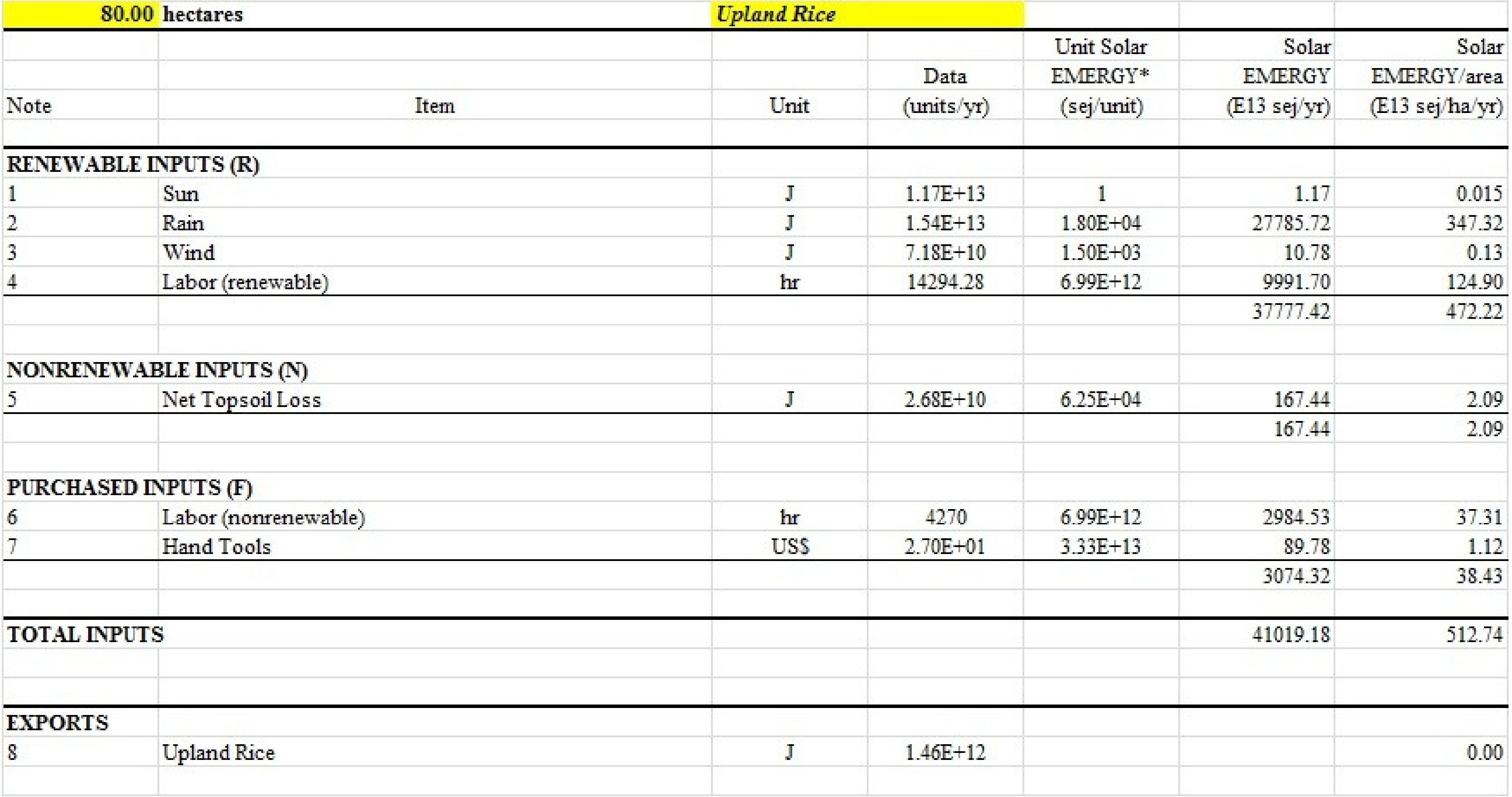
I greatly appreciate your willingness to assist in my doctoral research through participation in this study. The title of this project, "Modeling and evaluation of ecosystem service delivery strategies in Malaysian Borneo," reflects the idea that many populations practice land management strategies that may conflict in ecosystem services necessary for human survival. This research will attempt to understand land management in terms of such services as biodiversity, carbon sequestration, food and livelihood production, and total energy use of a given management strategy. This research will be conducted in two stages: a one-on-one survey and open-ended interview stage, and a later modeling and analysis stage to compare different land management types. By providing your perceptions of management strategies and potential improvements in the first research stage, I am able to develop alternatives that may be more acceptable to multiple parties, potentially preserving the ecosystems and services upon which you depend. The second stage consists of visually modeling and analyzing management strategies to allow comparison of sustainability over time, providing a better understanding of what land management outcomes, perceptions, and alternatives mean for ecosystem services in Borneo and land management in general.

All information you have provided will be considered confidential and grouped with responses from other participants. If you have consented to audio-recording, your responses may be referenced at a later date. Further, you will not be identified by name in any thesis, report, or publication resulting from this study; with your permission, anonymous quotations may be used. The data collected will be kept for a period of three (3) years in my supervisor's office at the University of Waterloo. Results and analysis are anticipated no less than two (2) years from the completion of the first research stage in July 2013. Should you have any questions or concerns about the results of this study, including how to receive a copy of the study findings, please contact me at the email address listed below. Alternately, you may wish to contact project supervisor Dr Stephen Murphy, Chair, Department of Environment and Resource Studies, at 00+1-519-888-4567, Ext. 35616, or sd2murph@uwaterloo.ca for additional information. Further, I would also like to remind you that this study has been reviewed and received ethics clearance through the Office of Research Ethics at the University of Waterloo. In the event you have any comments or concerns resulting from your participation in this study, please contact Dr Maureen Nummelin at 00+1-519-888-4567, Ext. 36005 or maureen.nummelin@uwaterloo.ca.

Thank you again for your participation.

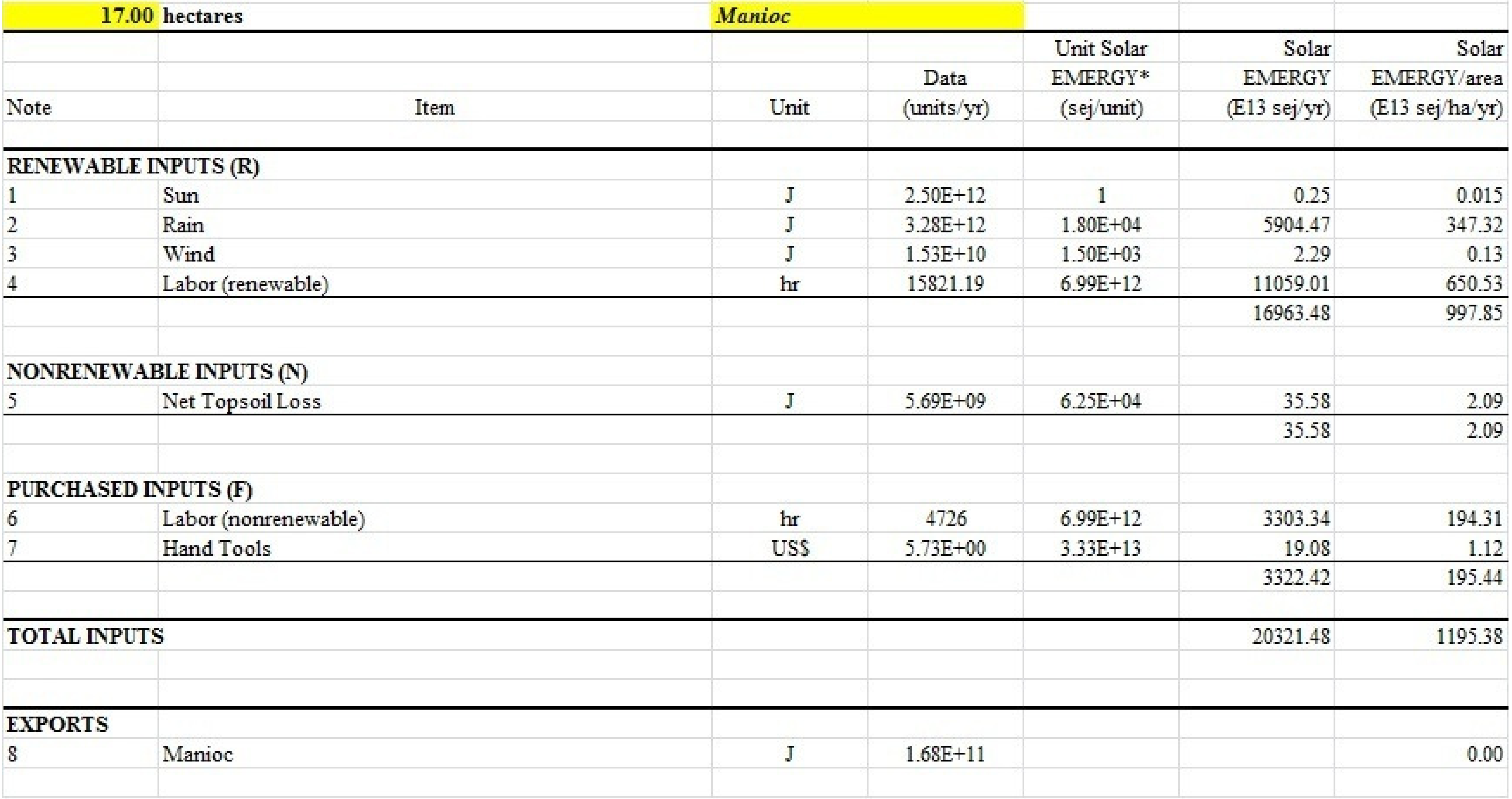
Appendix B: Supplementary Emergy Evaluation Tables

Table 4. Emergy Evaluation Upland Rice



80.00	hectares	*Upland Rice*				
Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY* (sej/unit)	Solar EMERGY (E13 sej/yr)	Solar EMERGY/area (E13 sej/ha/yr)
RENEWABLE INPUTS (R)						
1	Sun	J	1.17E+13	1	1.17	0.015
2	Rain	J	1.54E+13	1.80E+04	27785.72	347.32
3	Wind	J	7.18E+10	1.50E+03	10.78	0.13
4	Labor (renewable)	hr	14294.28	6.99E+12	9991.70	124.90
					37777.42	472.22
NONRENEWABLE INPUTS (N)						
5	Net Topsoil Loss	J	2.68E+10	6.25E+04	167.44	2.09
					167.44	2.09
PURCHASED INPUTS (F)						
6	Labor (nonrenewable)	hr	4270	6.99E+12	2984.53	37.31
7	Hand Tools	US$	2.70E+01	3.33E+13	89.78	1.12
					3074.32	38.43
TOTAL INPUTS					41019.18	512.74
EXPORTS						
8	Upland Rice	J	1.46E+12			0.00

Table 5. Emergy Evaluation Manioc

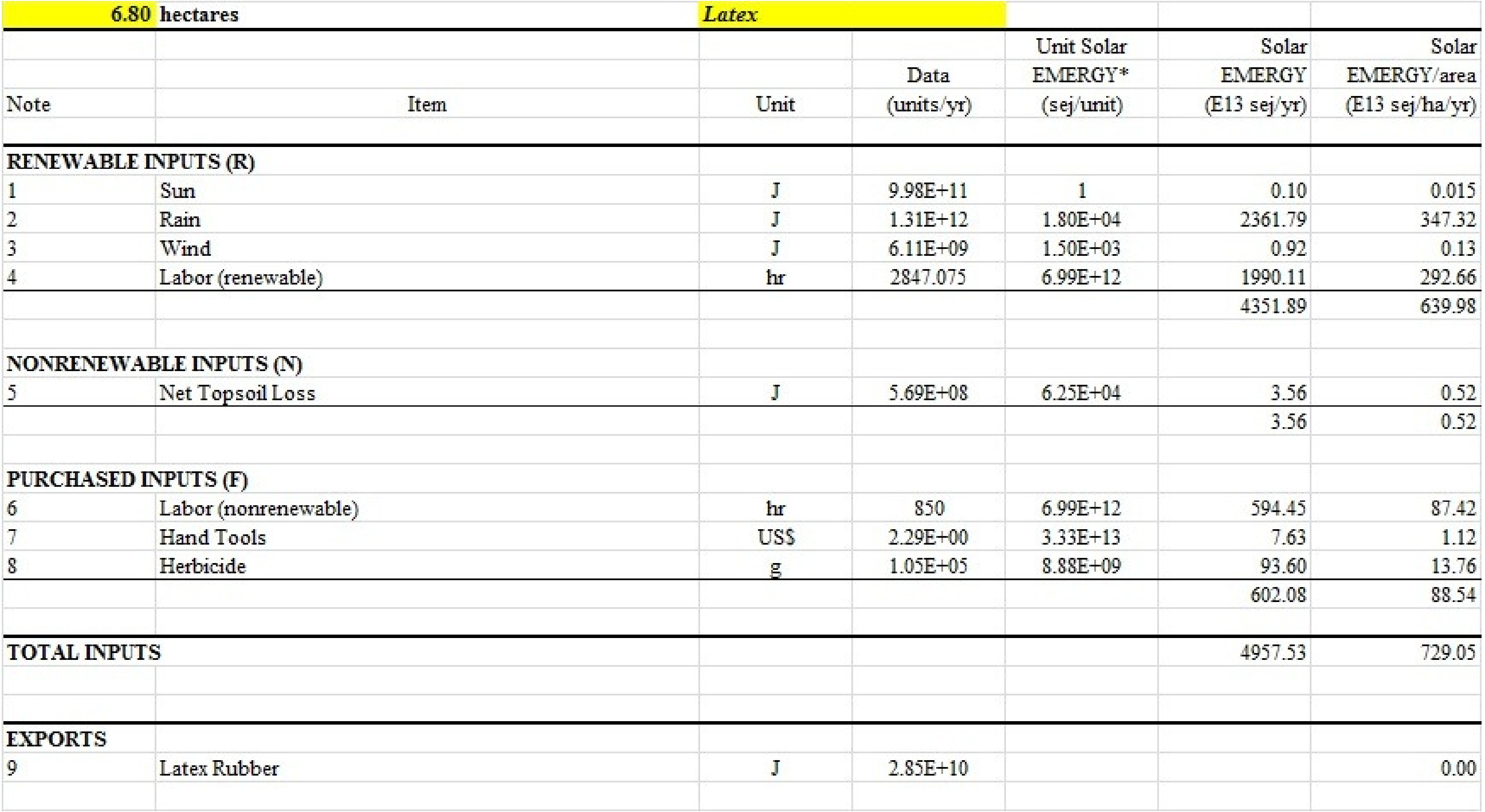


17.00	hectares	*Manioc*				
				Unit Solar	Solar	Solar
			Data	EMERGY*	EMERGY	EMERGY/area
Note	Item	Unit	(units/yr)	(sej/unit)	(E13 sej/yr)	(E13 sej/ha/yr)
RENEWABLE INPUTS (R)						
1	Sun	J	2.50E+12	1	0.25	0.015
2	Rain	J	3.28E+12	1.80E+04	5904.47	347.32
3	Wind	J	1.53E+10	1.50E+03	2.29	0.13
4	Labor (renewable)	hr	15821.19	6.99E+12	11059.01	650.53
					16963.48	997.85
NONRENEWABLE INPUTS (N)						
5	Net Topsoil Loss	J	5.69E+09	6.25E+04	35.58	2.09
					35.58	2.09
PURCHASED INPUTS (F)						
6	Labor (nonrenewable)	hr	4726	6.99E+12	3303.34	194.31
7	Hand Tools	US$	5.73E+00	3.33E+13	19.08	1.12
					3322.42	195.44
TOTAL INPUTS					20321.48	1195.38
EXPORTS						
8	Manioc	J	1.68E+11			0.00

Table 6. Emergy Evaluation Peppercorn

90.00	hectares	*Peppercorn*				
				Unit Solar	Solar	Solar
			Data	EMERGY*	EMERGY	EMERGY/area
Note	Item	Unit	(units/yr)	(sej/unit)	(E13 sej/yr)	(E13 sej/ha/yr)
RENEWABLE INPUTS (R)						
1	Sun	J	1.32E+13	1	1.321	0.015
2	Rain	J	1.74E+13	1.80E+04	31258.94	347.32
3	Wind	J	8.08E+10	1.50E+03	12.12	0.13
4	Labor (renewable)	hr	14864.85	6.99E+12	10390.53	115.45
					41649.47	462.77
NONRENEWABLE INPUTS (N)						
5	Net Topsoil Loss	J	3.01E+10	6.25E+04	188.37	2.09
					188.37	2.09
PURCHASED INPUTS (F)						
6	Labor (nonrenewable)	hr	4440	6.99E+12	3103.66	34.49
7	Hand Tools	US$	1.13E+03	3.33E+13	3774.00	41.93
7	Power Tools	US$	1.61E+03	3.33E+13	5344.65	59.39
8	Fuel	L	2.73E+02	6.60E+04	0.00	0.00
9	Fertilizer	g	4.50E+03	1.99E+09	0.90	0.01
10	Herbicide	g	1.35E+02	8.88E+09	0.12	0.00
11	Pesticide	g	2.70E+01	8.88E+09	0.02	0.00
					12223.36	135.82
TOTAL INPUTS					54061.19	600.68
EXPORTS						
11	Peppercorn	J	2.70E+07			0.00

Table 7. Emergy Evaluation Latex Rubber

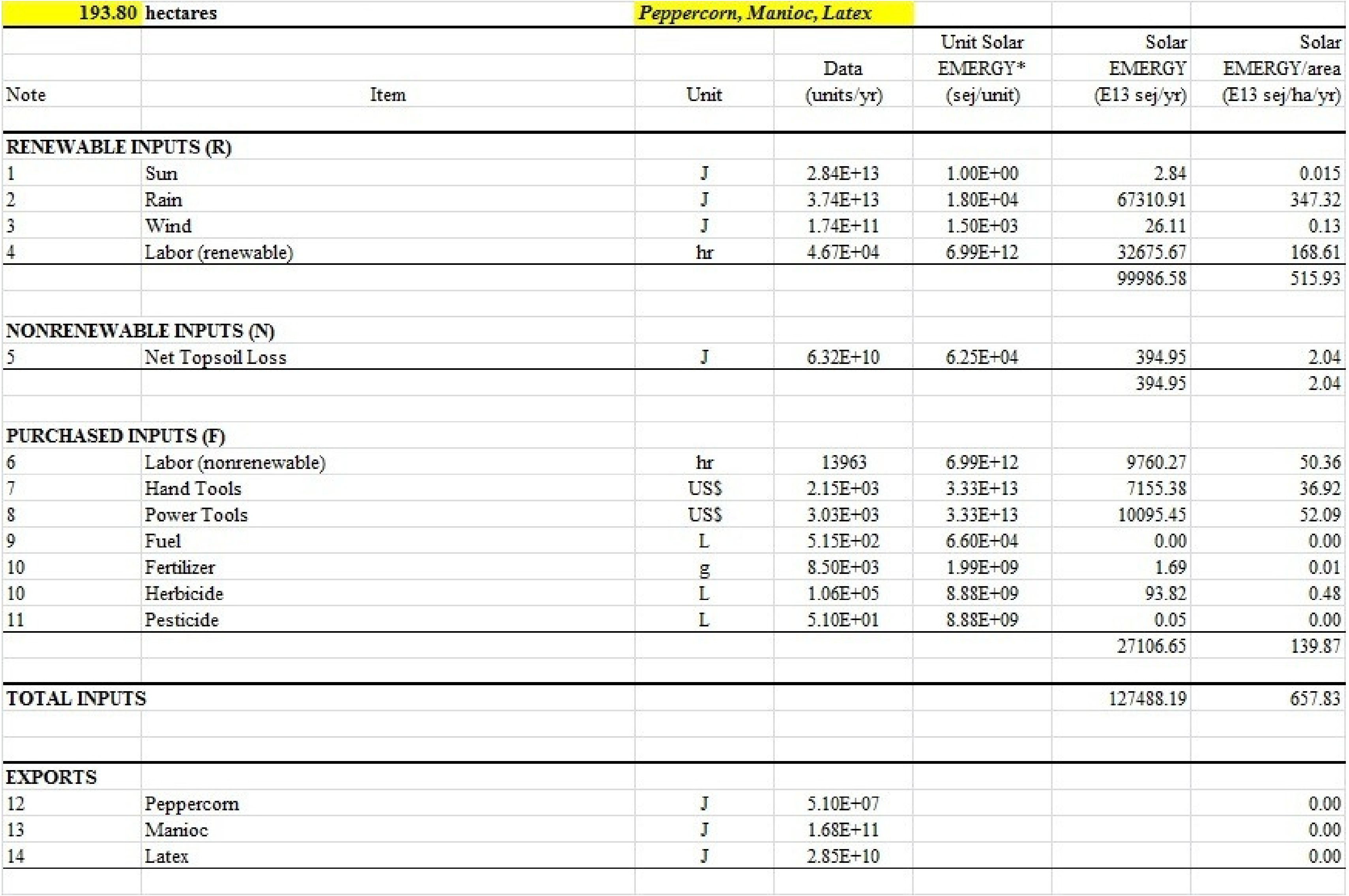


6.80	hectares	Latex				
Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY* (sej/unit)	Solar EMERGY (E13 sej/yr)	Solar EMERGY/area (E13 sej/ha/yr)
RENEWABLE INPUTS (R)						
1	Sun	J	9.98E+11	1	0.10	0.015
2	Rain	J	1.31E+12	1.80E+04	2361.79	347.32
3	Wind	J	6.11E+09	1.50E+03	0.92	0.13
4	Labor (renewable)	hr	2847.075	6.99E+12	1990.11	292.66
					4351.89	639.98
NONRENEWABLE INPUTS (N)						
5	Net Topsoil Loss	J	5.69E+08	6.25E+04	3.56	0.52
					3.56	0.52
PURCHASED INPUTS (F)						
6	Labor (nonrenewable)	hr	850	6.99E+12	594.45	87.42
7	Hand Tools	US$	2.29E+00	3.33E+13	7.63	1.12
8	Herbicide	g	1.05E+05	8.88E+09	93.60	13.76
					602.08	88.54
TOTAL INPUTS					4957.53	729.05
EXPORTS						
9	Latex Rubber	J	2.85E+10			0.00

Table 8. Emergy Evaluation Rice, Manioc, Latex

193.80	**hectares**	***Rice, Manioc, Latex***				
Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY* (sej/unit)	Solar EMERGY (E13 sej/yr)	Solar EMERGY/area (E13 sej/ha/yr)
RENEWABLE INPUTS (R)						
1	Sun	J	2.84E+13	1.00E+00	2.84	0.015
2	Rain	J	3.74E+13	1.80E+04	67310.91	347.32
3	Wind	J	1.74E+11	1.50E+03	26.11	0.13
4	Labor (renewable)	hr	4.90E+04	6.99E+12	34281.48	176.89
					101592.39	524.21
NONRENEWABLE INPUTS (N)						
5	Net Topsoil Loss	J	6.32E+10	6.25E+04	394.95	2.04
					394.95	2.04
PURCHASED INPUTS (F)						
6	Labor (nonrenewable)	hr	1.46E+04	6.99E+12	10239.92	52.84
7	Hand Tools	US$	6.53E+01	3.33E+13	217.50	1.12
8	Herbicides	g	1.05E+05	8.88E+09	93.60	0.48
					10551.02	54.44
TOTAL INPUTS					112538.36	580.69
EXPORTS						
9	Rice	J	3.09E+12			0.00
10	Manioc	J	1.68E+11			0.00
11	Latex	J	2.85E+10			0.00

Table 9. Emergy Evaluation Peppercorn, Manioc, Latex

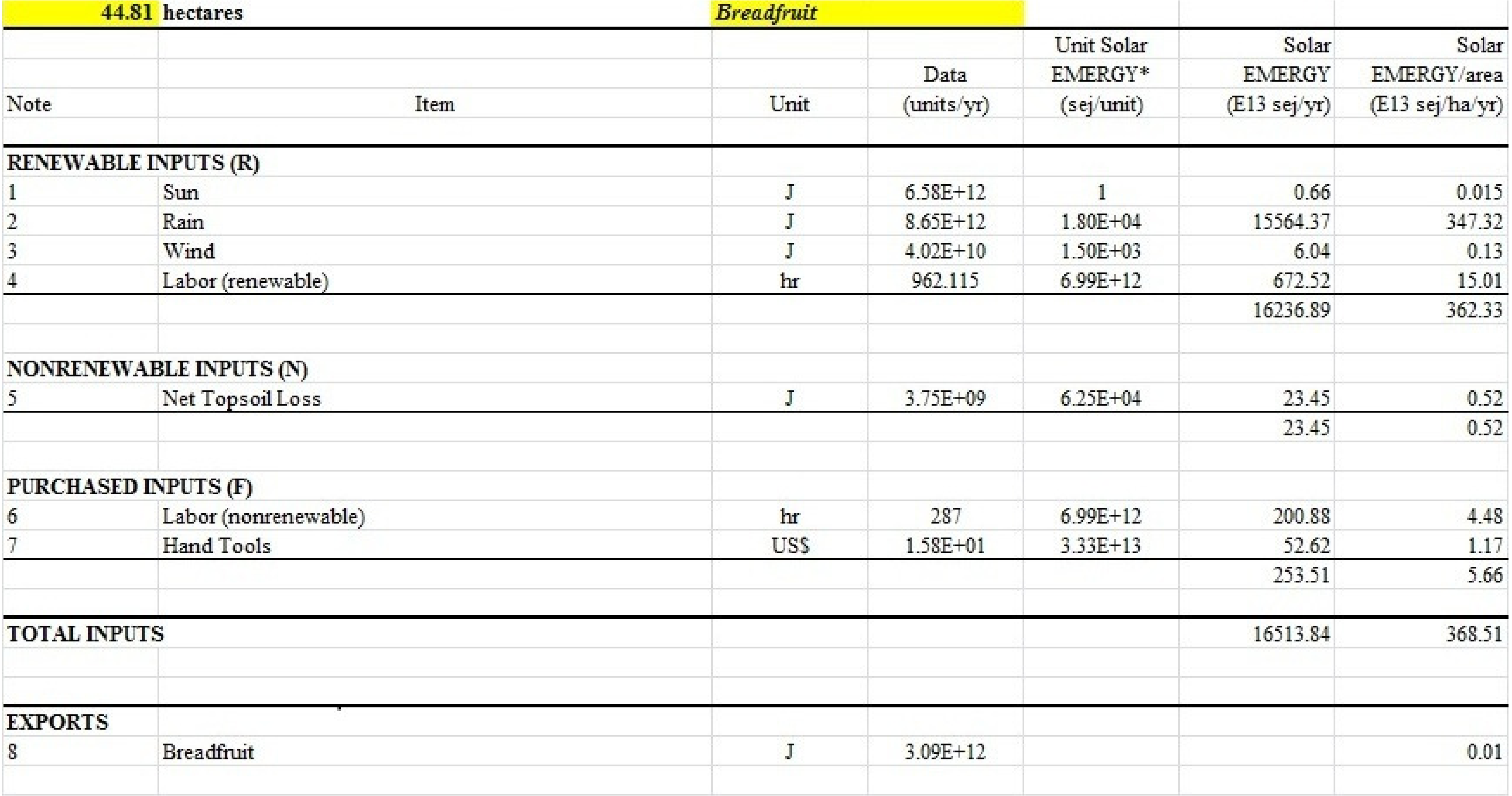


193.80	**hectares**	*Peppercorn, Manioc, Latex*				
Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY* (sej/unit)	Solar EMERGY (E13 sej/yr)	Solar EMERGY/area (E13 sej/ha/yr)
RENEWABLE INPUTS (R)						
1	Sun	J	2.84E+13	1.00E+00	2.84	0.015
2	Rain	J	3.74E+13	1.80E+04	67310.91	347.32
3	Wind	J	1.74E+11	1.50E+03	26.11	0.13
4	Labor (renewable)	hr	4.67E+04	6.99E+12	32675.67	168.61
					99986.58	515.93
NONRENEWABLE INPUTS (N)						
5	Net Topsoil Loss	J	6.32E+10	6.25E+04	394.95	2.04
					394.95	2.04
PURCHASED INPUTS (F)						
6	Labor (nonrenewable)	hr	13963	6.99E+12	9760.27	50.36
7	Hand Tools	US$	2.15E+03	3.33E+13	7155.38	36.92
8	Power Tools	US$	3.03E+03	3.33E+13	10095.45	52.09
9	Fuel	L	5.15E+02	6.60E+04	0.00	0.00
10	Fertilizer	g	8.50E+03	1.99E+09	1.69	0.01
10	Herbicide	L	1.06E+05	8.88E+09	93.82	0.48
11	Pesticide	L	5.10E+01	8.88E+09	0.05	0.00
					27106.65	139.87
TOTAL INPUTS					127488.19	657.83
EXPORTS						
12	Peppercorn	J	5.10E+07			0.00
13	Manioc	J	1.68E+11			0.00
14	Latex	J	2.85E+10			0.00

Table 10. Emergy Evaluation Sago Agroforestry

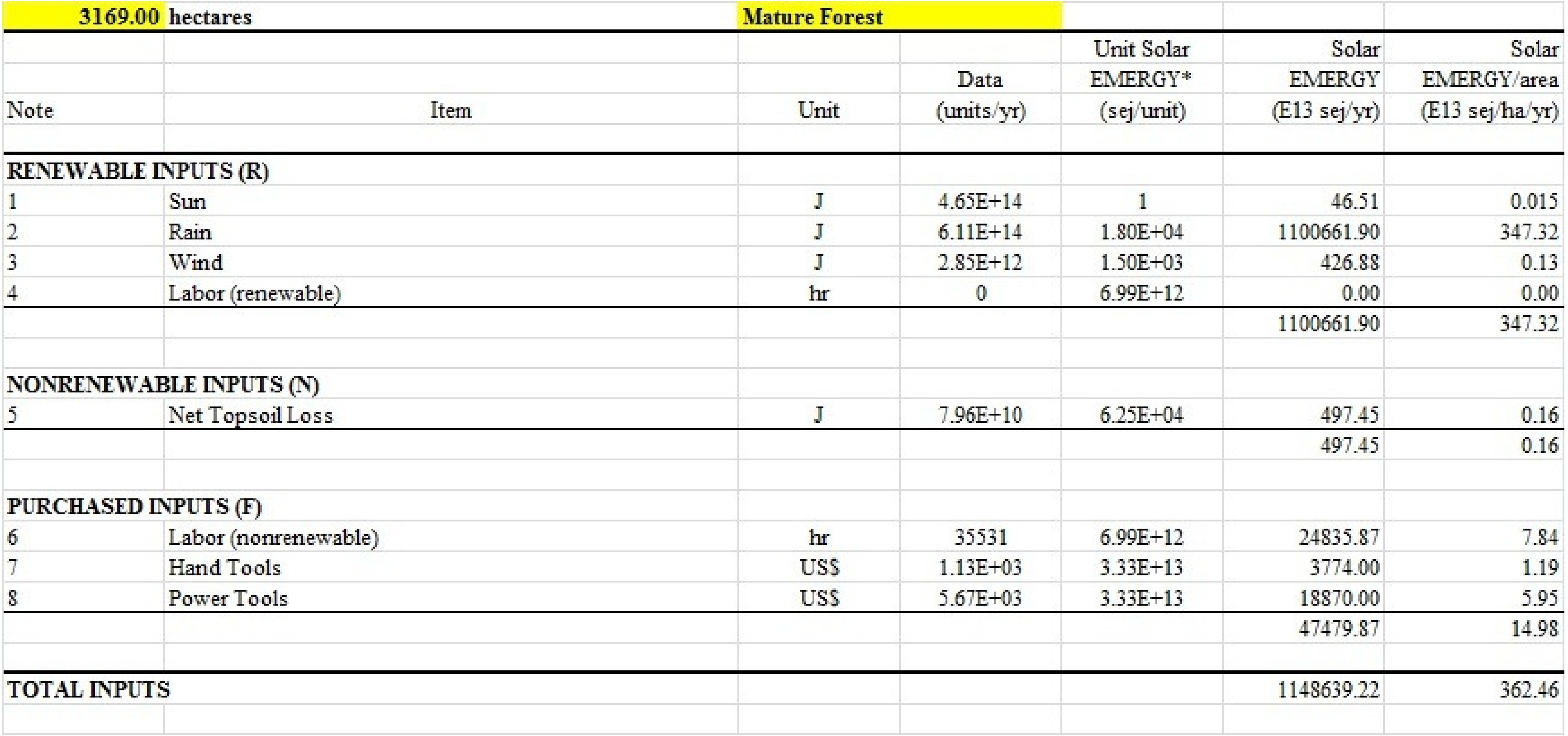
49.73	hectares	*Sago*				
Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY* (sej/unit)	Solar EMERGY (E13 sej/yr)	Solar EMERGY/area (E13 sej/ha/yr)
RENEWABLE INPUTS (R)						
1	Sun	J	7.30E+12	1	0.73	0.015
2	Rain	J	9.60E+12	1.80E+04	17272.78	347.32
3	Wind	J	4.47E+10	1.50E+03	6.70	0.13
4	Labor (renewable)	hr	2382.38	6.99E+12	1665.28	33.49
					18938.06	380.81
NONRENEWABLE INPUTS (N)						
5	Net Topsoil Loss	J	4.16E+09	6.25E+04	26.02	0.52
					26.02	0.52
PURCHASED INPUTS (F)						
6	Labor (nonrenewable)	hr	712	6.99E+12	497.42	10.00
7	Hand Tools	US$	1.75E+01	3.33E+13	58.31	1.17
					555.73	11.17
TOTAL INPUTS					19519.82	392.51
EXPORTS						
8	Sago	J	3.09E+12			0.01

Table 11. Emergy Evaluation Breadfruit Agroforestry



44.81	**hectares**	*Breadfruit*				
Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY* (sej/unit)	Solar EMERGY (E13 sej/yr)	Solar EMERGY/area (E13 sej/ha/yr)
RENEWABLE INPUTS (R)						
1	Sun	J	6.58E+12	1	0.66	0.015
2	Rain	J	8.65E+12	1.80E+04	15564.37	347.32
3	Wind	J	4.02E+10	1.50E+03	6.04	0.13
4	Labor (renewable)	hr	962.115	6.99E+12	672.52	15.01
					16236.89	362.33
NONRENEWABLE INPUTS (N)						
5	Net Topsoil Loss	J	3.75E+09	6.25E+04	23.45	0.52
					23.45	0.52
PURCHASED INPUTS (F)						
6	Labor (nonrenewable)	hr	287	6.99E+12	200.88	4.48
7	Hand Tools	US$	1.58E+01	3.33E+13	52.62	1.17
					253.51	5.66
TOTAL INPUTS					16513.84	368.51
EXPORTS						
8	Breadfruit	J	3.09E+12			0.01

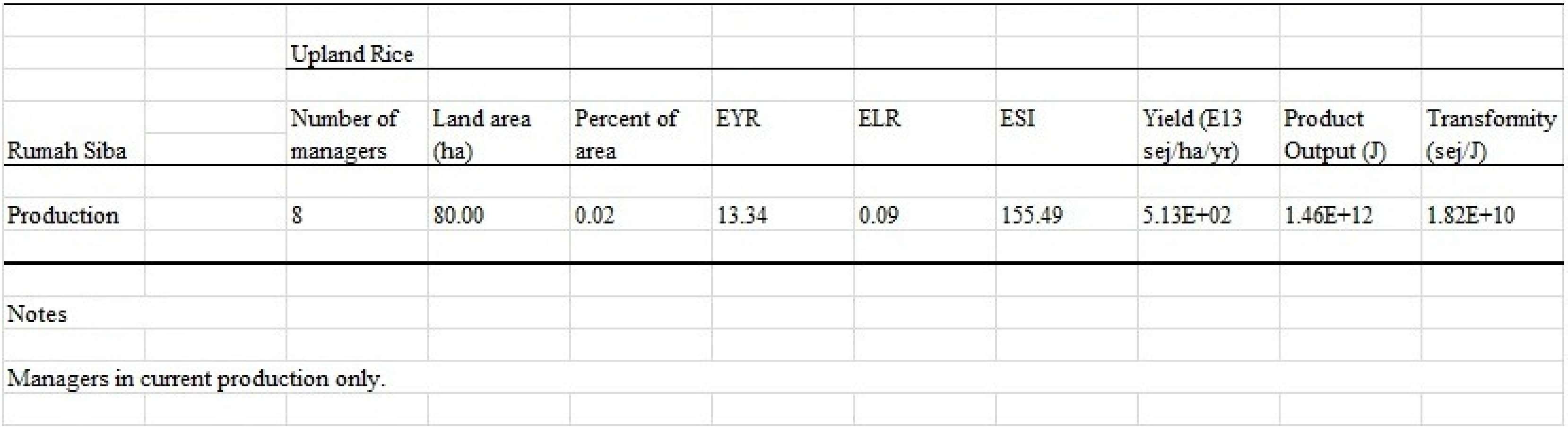
Table 12. Emergy Evaluation Mature Forest Management



3169.00	hectares	Mature Forest				
Note	Item	Unit	Data (units/yr)	Unit Solar EMERGY* (sej/unit)	Solar EMERGY (E13 sej/yr)	Solar EMERGY/area (E13 sej/ha/yr)
RENEWABLE INPUTS (R)						
1	Sun	J	4.65E+14	1	46.51	0.015
2	Rain	J	6.11E+14	1.80E+04	1100661.90	347.32
3	Wind	J	2.85E+12	1.50E+03	426.88	0.13
4	Labor (renewable)	hr	0	6.99E+12	0.00	0.00
					1100661.90	347.32
NONRENEWABLE INPUTS (N)						
5	Net Topsoil Loss	J	7.96E+10	6.25E+04	497.45	0.16
					497.45	0.16
PURCHASED INPUTS (F)						
6	Labor (nonrenewable)	hr	35531	6.99E+12	24835.87	7.84
7	Hand Tools	US$	1.13E+03	3.33E+13	3774.00	1.19
8	Power Tools	US$	5.67E+03	3.33E+13	18870.00	5.95
					47479.87	14.98
TOTAL INPUTS					1148639.22	362.46

Appendix C: Supplementary Emergy Indices Tables

Table 13. EYR, ELR, ESI, and transformity of upland rice in Iban management of Rumah Siba Perdu and surrounds, Sarawak, Malaysia.

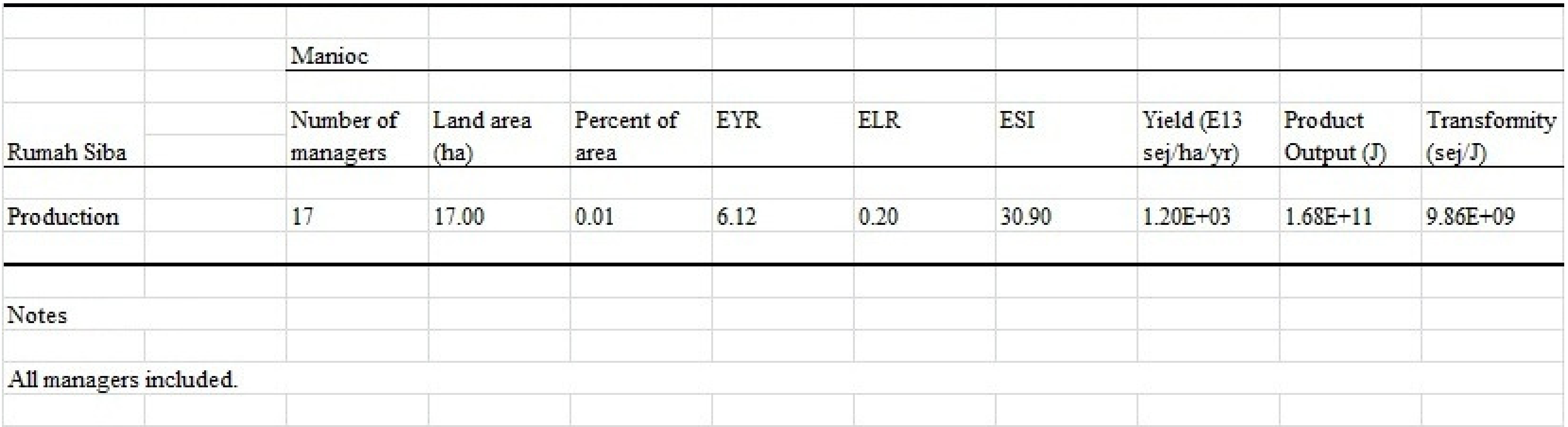


		Upland Rice								
Rumah Siba		Number of managers	Land area (ha)	Percent of area	EYR	ELR	ESI	Yield (E13 sej/ha/yr)	Product Output (J)	Transformity (sej/J)
Production		8	80.00	0.02	13.34	0.09	155.49	5.13E+02	1.46E+12	1.82E+10

Notes

Managers in current production only.

Table 14. EYR, ELR, ESI, and transformity of manioc in Iban management of Rumah Siba Perdu and surrounds, Sarawak, Malaysia.

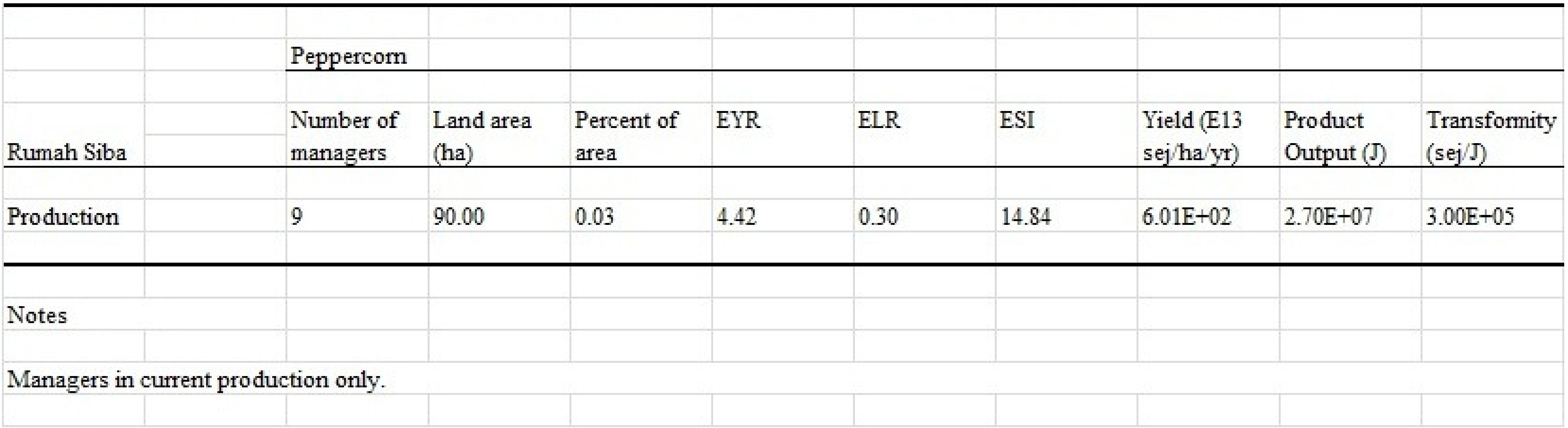


		Manioc								
Rumah Siba		Number of managers	Land area (ha)	Percent of area	EYR	ELR	ESI	Yield (E13 sej/ha/yr)	Product Output (J)	Transformity (sej/J)
Production		17	17.00	0.01	6.12	0.20	30.90	1.20E+03	1.68E+11	9.86E+09

Notes

All managers included.

Table 15. EYR, ELR, ESI, and transformity of peppercorn in Iban management of Rumah Siba Perdu and surrounds, Sarawak, Malaysia.

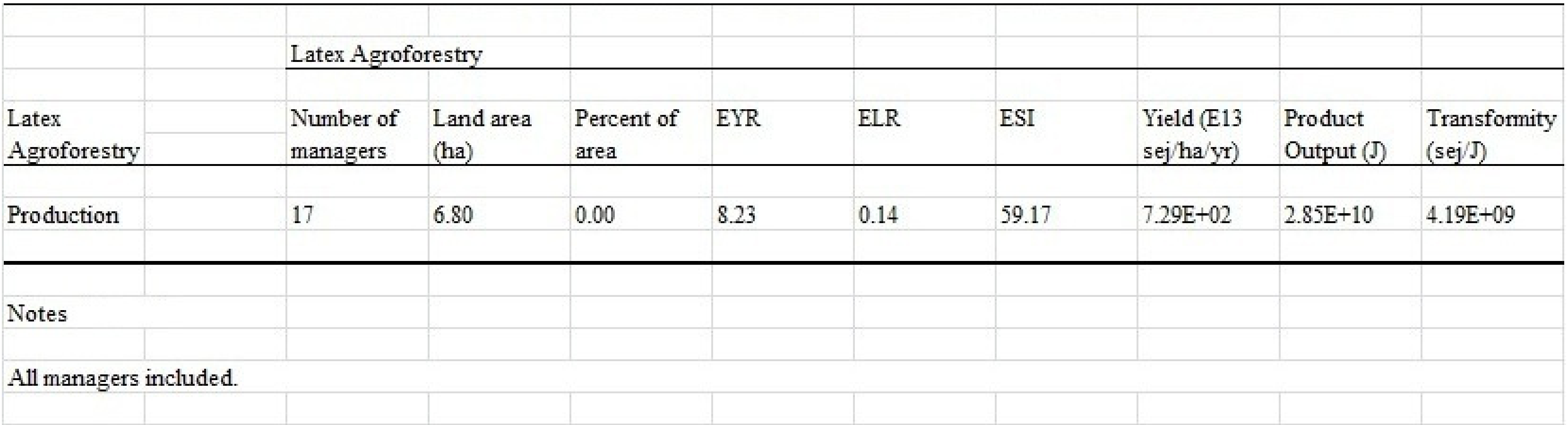


	Peppercorn								
Rumah Siba	Number of managers	Land area (ha)	Percent of area	EYR	ELR	ESI	Yield (E13 sej/ha/yr)	Product Output (J)	Transformity (sej/J)
Production	9	90.00	0.03	4.42	0.30	14.84	6.01E+02	2.70E+07	3.00E+05

Notes

Managers in current production only.

Table 16. EYR, ELR, ESI, and transformity of latex agroforestry in Iban management of Rumah Siba Perdu and surrounds, Sarawak, Malaysia.

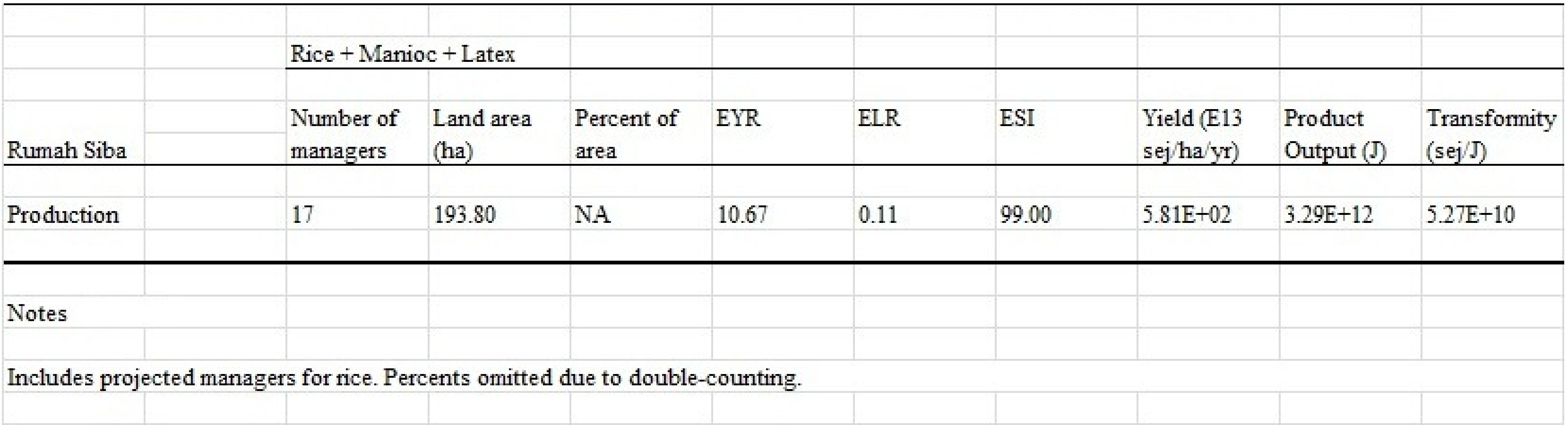


		Latex Agroforestry								
Latex Agroforestry		Number of managers	Land area (ha)	Percent of area	EYR	ELR	ESI	Yield (E13 sej/ha/yr)	Product Output (J)	Transformity (sej/J)
Production		17	6.80	0.00	8.23	0.14	59.17	7.29E+02	2.85E+10	4.19E+09

Notes

All managers included.

Table 17. EYR, ELR, ESI, and transformity of rice, manioc, and latex in Iban management of Rumah Siba Perdu and surrounds, Sarawak, Malaysia.

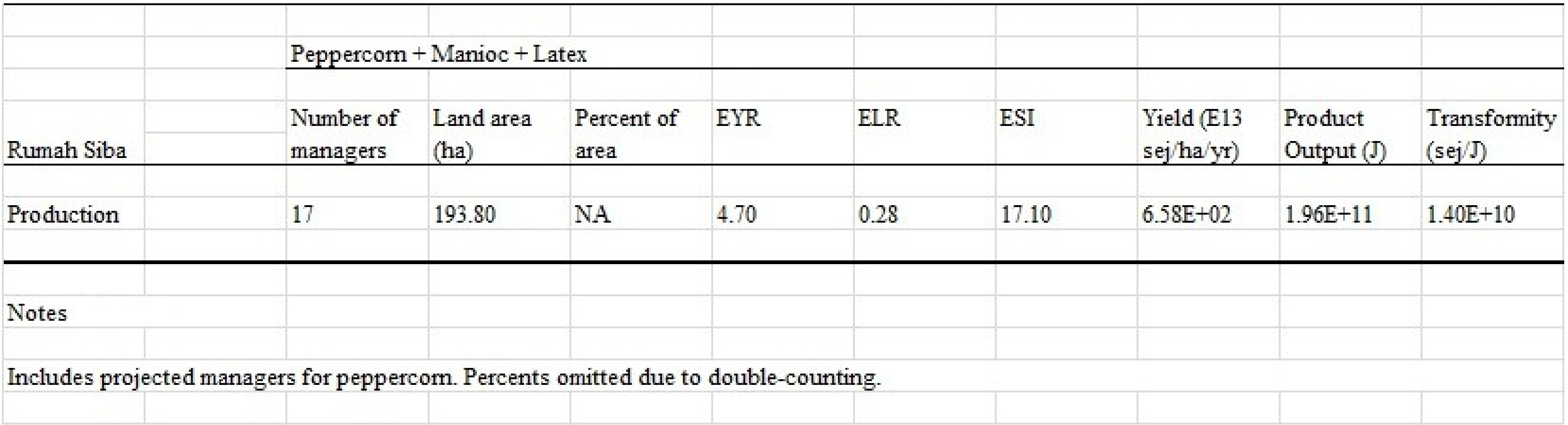


		Rice + Manioc + Latex								
Rumah Siba		Number of managers	Land area (ha)	Percent of area	EYR	ELR	ESI	Yield (E13 sej/ha/yr)	Product Output (J)	Transformity (sej/J)
Production		17	193.80	NA	10.67	0.11	99.00	5.81E+02	3.29E+12	5.27E+10

Notes

Includes projected managers for rice. Percents omitted due to double-counting.

Table 18. EYR, ELR, ESI, and transformity of peppercorn, manioc, and latex in Iban management of Rumah Siba Perdu and surrounds, Sarawak, Malaysia.

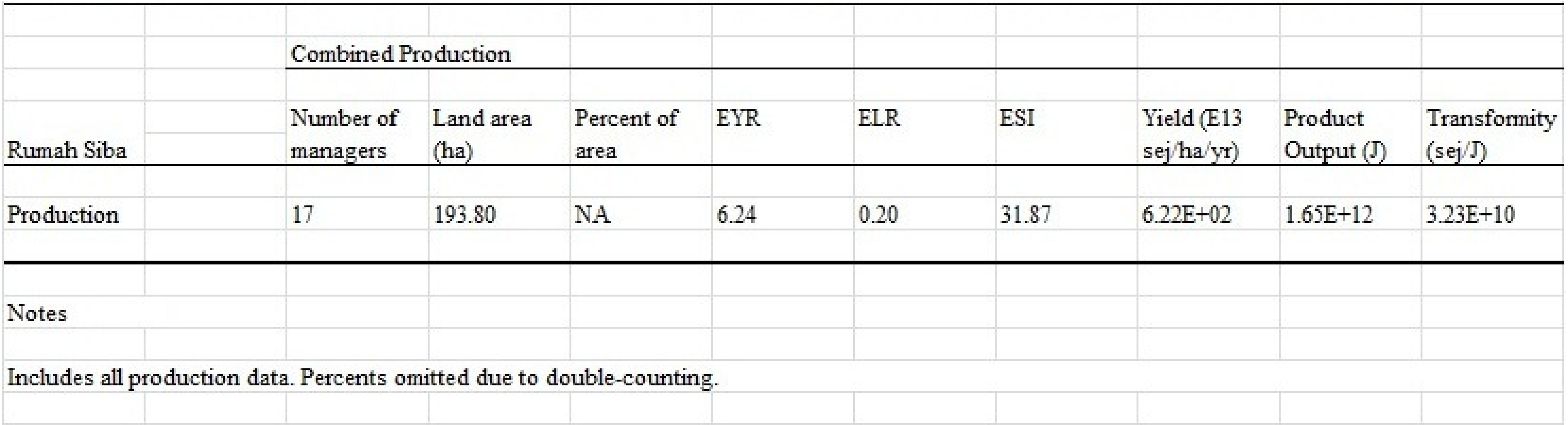


		Peppercorn + Manioc + Latex								
Rumah Siba		Number of managers	Land area (ha)	Percent of area	EYR	ELR	ESI	Yield (E13 sej/ha/yr)	Product Output (J)	Transformity (sej/J)
Production		17	193.80	NA	4.70	0.28	17.10	6.58E+02	1.96E+11	1.40E+10

Notes

Includes projected managers for peppercorn. Percents omitted due to double-counting.

Table 19. EYR, ELR, ESI, and transformity of combined production in Iban management of Rumah Siba Perdu and surrounds, Sarawak, Malaysia.

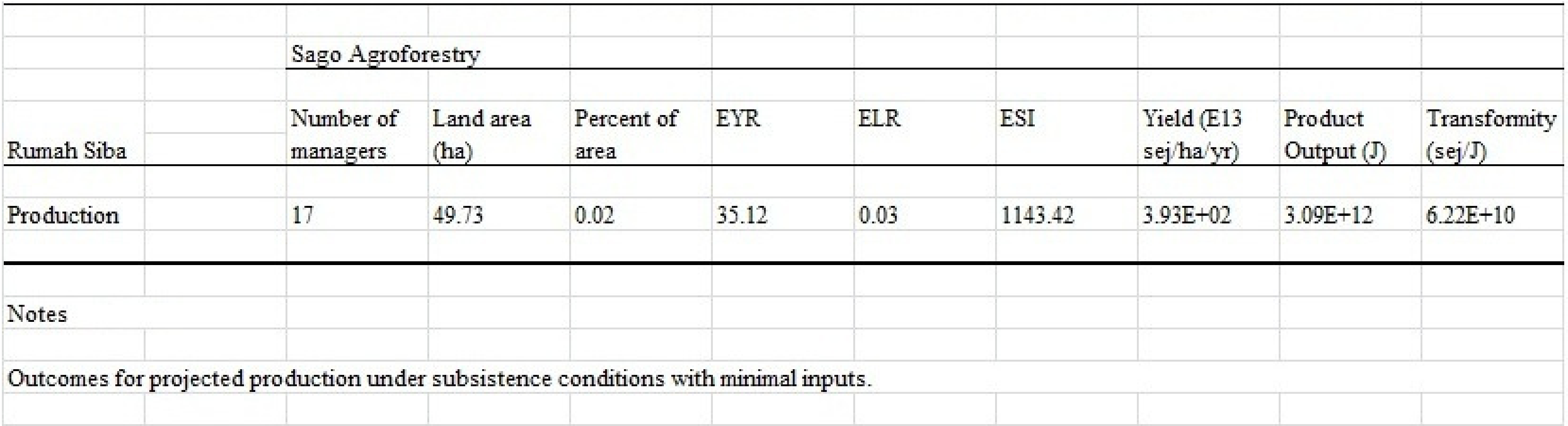


		Combined Production								
Rumah Siba		Number of managers	Land area (ha)	Percent of area	EYR	ELR	ESI	Yield (E13 sej/ha/yr)	Product Output (J)	Transformity (sej/J)
Production		17	193.80	NA	6.24	0.20	31.87	6.22E+02	1.65E+12	3.23E+10

Notes

Includes all production data. Percents omitted due to double-counting.

Table 20. EYR, ELR, ESI, and transformity of sago agroforestry in Iban management of Rumah Siba Perdu and surrounds, Sarawak, Malaysia.

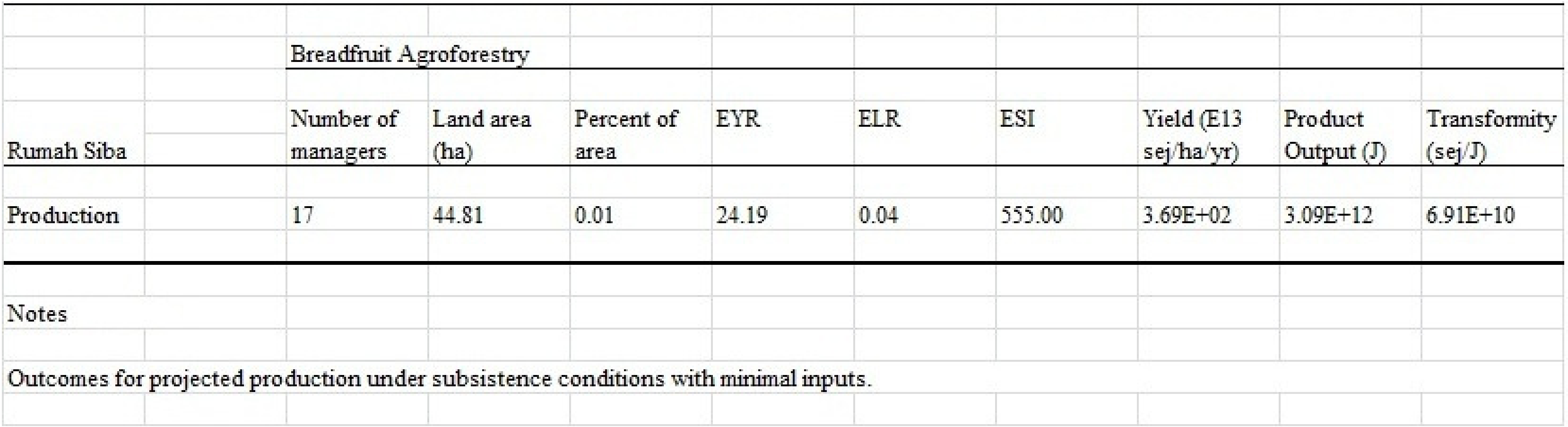


		Sago Agroforestry								
Rumah Siba		Number of managers	Land area (ha)	Percent of area	EYR	ELR	ESI	Yield (E13 sej/ha/yr)	Product Output (J)	Transformity (sej/J)
Production		17	49.73	0.02	35.12	0.03	1143.42	3.93E+02	3.09E+12	6.22E+10

Notes

Outcomes for projected production under subsistence conditions with minimal inputs.

Table 21. EYR, ELR, ESI, and transformity of breadfruit agroforestry in Iban management of Rumah Siba Perdu and surrounds, Sarawak, Malaysia.



		Breadfruit Agroforestry								
Rumah Siba		Number of managers	Land area (ha)	Percent of area	EYR	ELR	ESI	Yield (E13 sej/ha/yr)	Product Output (J)	Transformity (sej/J)
Production		17	44.81	0.01	24.19	0.04	555.00	3.69E+02	3.09E+12	6.91E+10

Notes

Outcomes for projected production under subsistence conditions with minimal inputs.

Table 22. EYR, ELR, ESI, and transformity of mature forest management, Sarawak, Malaysia.

	Mature Forest Management								
Both Parks	Number of managers	Land area (ha)	Percent of area	EYR	ELR	ESI	Yield (E13 sej/ha/yr)	Product Output (J)	Transformity (sej/J)
Management	NA	3169.00	0.94	24.19	0.04	555.00	3.62E+02	NA	NA

Notes

Number of managers reflects paid labor in parks only. Mature forest in Rumah Siba is managed comunally, while parks do not produce the outputs measured in this study.

Appendix D: Emergy Analysis Calculation and References

Upland Rice				
1	**Sun**			
	Annual energy =	(Avg. Total Annual Insolation J/yr)(Area)(1-albedo)		
	Insolation:	1.69E+07	J/m2/yr	(calculated using solar constant
				of 2 Langleys/sec and
		80.00	ha	integrating over changing
	Area:	8.00E+05	m2	surface area for one year,
	Albedo:	0.1325		latitude 1N, longitude 111W)
	Annual energy:	1.17E+13	J	
	Emergy per unit input =	1	sej/J	
2	**Rain**			
	Annual energy =	(cm/yr)(Area)(0.01m/cm)(1E6g/m3)(4.94J/g)(1 - runoff)		
	cm/yr:	420		
	Area:	80.00	ha	
	Area, m2:	8.00E+05		
	runoff coefficient:	7.00E-02		
	Annual energy:	1.54E+13	J	
	Emergy per unit input =	1.80E+04	sej/J	
3	**Wind**			
	Area:	80.00	ha	
	Area, m2:	8.00E+05		
	Density of Air: 1.3 kg m^{-3}			
	Wind Velocity - Average 10 m		2.2	m/s
	Geostrophic wind: 2.32 m s^{-1} (assume that observed winds are 0.6 of geostrophic wind)			
	Drag coefficient: 0.001			
	Multiply the above for basal			
	Transformity: 1.50 E3 sej J^{-1} (Odum 1996)			
		7.18E+10	J/year	
	Transformity:	1.50E+03	sej/J	(Odum 1996)

4	*Labor (renewable)*					
Family	18564	hr /yr				
% R	77	%	(Trujillo 1998)			
Total	14294.28	hr/yr	=family*%R			
Transformity:	6.99E+12	sej hr-1	(Trujillo 1998)			
5	**Net Topsoil Loss**					
	Erosion rate =	0.4	t/ha/yr	(Bruijnzeel 2004)		
	No-Till Upland Rice	80.00	ha			
	Soil loss	32.00000	t/yr			
	Soil loss	32000000	g/yr			
	g organic/ g soil =	0.04				
	Energy cont./g organic=	5.00	kcal/g organic	(Ulgiati et al. 1994)		
		4186	J/kcal			
	Annual energy:	2.68E+10	J			
	Emergy per unit input =	6.25E+04	sej/J	(Ulgiati et al. 1994)		
6	*Labor (purchased)*					
Family	18564	hr /yr				
Purchased	0	hr /yr				
%F	23	%	(Trujillo 1998)			
Total	4270	hr/yr	=Family*%F+Purchased			
Transformity:	6.99E+12	sej/hr	(Trujillo 1998)			
7	**Hand Tools**					
	Annual consumption	1.13E+03	US$			
	Percent use for area =	2.38%				
	Annual consumption for area =	2.70E+01				
	Emergy per unit input =	3.33E+13	sej/US$			

8	**Exports**					
	Oryza sativa (upland rice)					
	Mass (g)	9.65E+07				
		3.60E+00	kcal/g			
		4.19E+03	J/kcal			
		1.46E+12	J/yr			
		80.00	ha			
		1.82E+10	J/ha/yr			

Manioc						
1	**Sun**					
	Annual energy =	(Avg. Total Annual Insolation J/yr)(Area)(1-albedo)				
	Insolation:	1.69E+07	J/m2/yr	(calculated using solar constant		
				of 2 Langleys/sec and		
		17.00	ha	integrating over changing		
	Area:	1.70E+05	m2	surface area for one year,		
	Albedo:	0.1325		latitude 1N, longitude 111W)		
	Annual energy:	2.50E+12	J			
	Emergy per unit input =	1	sej/J			
2	**Rain**					
	Annual energy =	(cm/yr)(Area)(0.01 m/cm)(1E6g/m3)(4.94J/g)(1 - runoff)				
	cm/yr:	420				
	Area:	17.00	ha			
	Area, m2:	1.70E+05				
	runoff coefficient:	7.00E-02				
	Annual energy:	3.28E+12	J			
	Emergy per unit input =	1.80E+04	sej/J			
3	**Wind**					
	Area:	17.00	ha			
	Area, m2:	1.70E+05				
	Density of Air: 1.3 kg m^{-3}					
	Wind Velocity - Average 10 m		2.2	m/s		
	Geostrophic wind: 2.32 m s^{-1} (assume that observed winds are 0.6 of geostrophic wind)					
	Drag coefficient: 0.001					
	Multiply the above for basal					
	Transformity: 1.50 E3 sej J^{-1} (Odum 1996)					
		1.53E+10	J/year			
	Transformity:	1.50E+03	sej/J	(Odum 1996)		

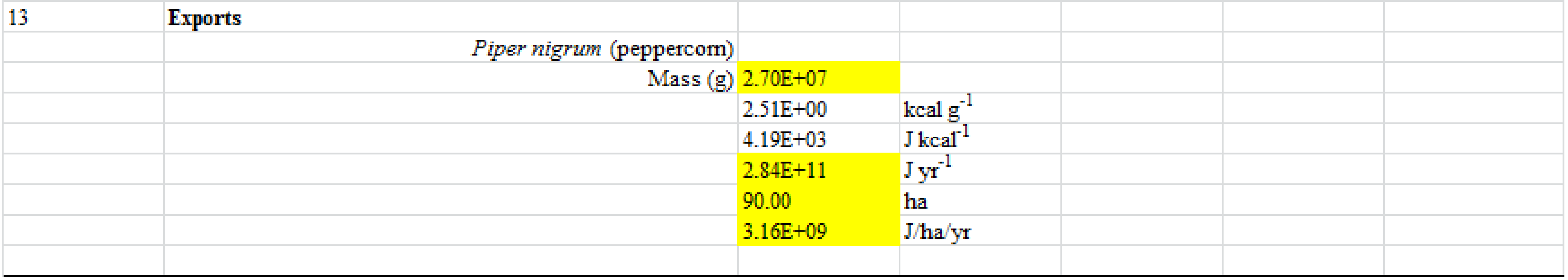
4	*Labor (renewable)*			
Family	20547	hr /yr		
% R	77	%	(Trujillo 1998)	
Total	15821.19	hr/yr	=family*%R	
Transformity:	6.99E+12	sej hr-1	(Trujillo 1998)	
5	**Net Topsoil Loss**			
	Erosion rate =	0.4	t/ha/yr	(Bruijnzeel 2004)
	Manioc	17.00	ha	
	Soil loss	6.80000	t/yr	
	Soil loss	6800000	g/yr	
	g organic/ g soil =	0.04		
	Energy cont./g organic=	5.00	kcal/g organic	(Ulgiati et al. 1994)
		4186	J/kcal	
	Annual energy:	5.69E+09	J	
	Emergy per unit input =	6.25E+04	sej/J	(Ulgiati et al. 1994)
6	*Labor (purchased)*			
Family	20547	hr /yr		
Purchased	0	hr /yr		
%F	23	%	(Trujillo 1998)	
Total	4726	hr/yr	=Family*%F+Purchased	
Transformity:	6.99E+12	sej/hr	(Trujillo 1998)	
7	**Hand Tools**			
	Annual consumption	1.13E+03		
	Percent use for area =	0.51%		
	Annual consumption for area =	5.73E+00		
	Emergy per unit input =	3.33E+13	sej/US$	

8	**Exports**					
	Manihot esculenta (manioc)					
	Mass (g)	2.50E+07	25 t ha yr			
		1.60E+00	kcal g^{-1}	0.32 raw to dry (FAO, 2006); 0.4 (USDA, 2014)		
		4.19E+03	J kcal^{-1}			
		1.68E+11	J yr^{-1}			
		17.00	ha			
		9.86E+09	J/ha/yr			

Peppercorn				
1	**Sun**			
	Annual energy =	(Avg. Total Annual Insolation J/yr)(Area)(1-albedo)		
	Insolation:	1.69E+07	J/m2/yr	(calculated using solar constant
				of 2 Langleys/sec and
		90.00	ha	integrating over changing
	Area:	9.00E+05	m2	surface area for one year,
	Albedo:	0.1325		latitude 1N, longitude 111W)
	Annual energy:	1.32E+13	J	
	Emergy per unit input =	1	sej/J	
2	**Rain**			
	Annual energy =	(cm/yr)(Area)(0.01 m/cm)(1E6g/m3)(4.94J/g)(1 - runoff)		
	cm/yr:	420		
	Area:	90.00	ha	
	Area, m2:	9.00E+05		
	runoff coefficient:	7.00E-02		
	Annual energy:	1.74E+13	J	
	Emergy per unit input =	1.80E+04	sej/J	
3	**Wind**			
	Area:	90.00	ha	
	Area, m2:	9.00E+05		
	Density of Air: 1.3 kg m^{-3}			
	Wind Velocity - Average 10 m		2.2	m/s
	Geostrophic wind: 2.32 m s^{-1} (assume that observed winds are 0.6 of geostrophic wind)			
	Drag coefficient: 0.001			
	Multiply the above for basal			
	Transformity: 1.50 E3 sej J^{-1} (Odum 1996)			
		8.08E+10	J/year	
	Transformity:	1.50E+03	sej/J	(Odum 1996)

4	*Labor (renewable)*					
Family	19305	hr /yr				
% R	77	%	(Trujillo 1998)			
Total	14864.85	hr/yr	=family*%R			
Transformity:	6.99E+12	sej hr-1	(Trujillo 1998)			
5	**Net Topsoil Loss**					
	Erosion rate =	0.4	t/ha/yr	(Bruijnzeel 2004)		
	Peppercorn	90.00	ha			
	Soil loss	36.00000	t/yr			
	Soil loss	36000000	g/yr			
	g organic/ g soil =	0.04				
	Energy cont./g organic=	5.00	kcal/g organic	(Ulgiati et al. 1994)		
		4186	J/kcal			
	Annual energy:	3.01E+10	J			
	Emergy per unit input =	6.25E+04	sej/J	(Ulgiati et al. 1994)		
6	*Labor (purchased)*					
Family	19305	hr /yr				
Purchased	0	hr /yr				
%F	23	%	(Trujillo 1998)			
Total	4440	hr/yr	=Family*%F+Purchased			
Transformity:	6.99E+12	sej/hr	(Trujillo 1998)			
7	**Hand Tools**					
	Annual consumption	1.13E+03	US$			
	Percent use for area =	2.68%				
	Annual consumption for area =	3.03E+01				
	Emergy per unit input =	3.33E+13	sej/US$			

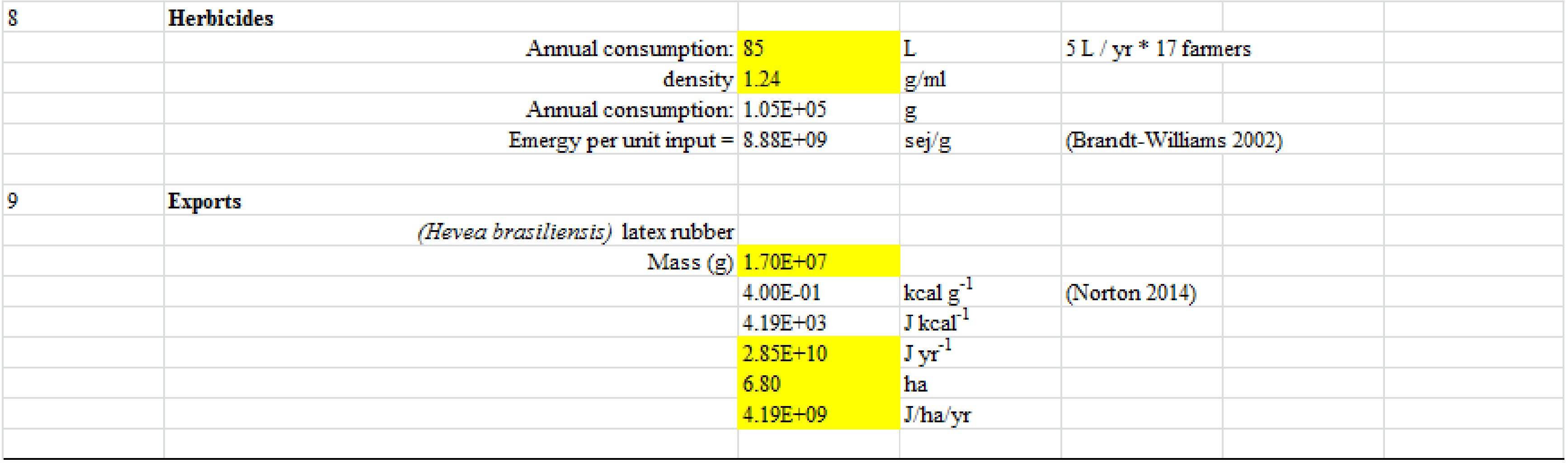
8	**Power Tools**			
	Annual consumption	1.61E+03	US$	35 RM / yr cutter cost over 10 yrs + 500 RM / yr mai
	Percent use for area =	100.00%	Grass cutter only	
	Annual consumption for area =	1.61E+03		
	Emergy per unit input =	3.33E+13	sej/US$	
9	**Fuel**			
	Annual consumption:	272.55	L	Includes gasoline and two-cycle engine oil (8 gal * 3
	density	3.30E+07	J/L	(Grubler et al. 2012; (44.75 GJ / t * 1E9 J / GJ) / 1356 L
	Annual consumption:	8.99E+09	J	
	Emergy per unit input =	6.60E+04	sej/J	(Odum 1996)
10	**Fertilizer**			
	Annual consumption:	4500	kg	25 kg / bag * 20 bags / yr * 9 farmers
	density	1000	kg/g	
	Annual consumption:	4.50E+06	g	
	Emergy per unit input =	1.99E+09	sej/g	(Brandt-Williams 2002)
11	**Herbicides**			
	Annual consumption:	135	L	15 L / yr * 9 farmers
	density	1.24	g/ml	
	Annual consumption:	1.67E+05	g	
	Emergy per unit input =	8.88E+09	sej/g	(Brandt-Williams 2002)
12	**Pesticides**			
	Annual consumption:	27	L	3 L /yr * 9 farmers
	density	1.24	g/ml	
	Annual consumption:	3.35E+04	g	
	Emergy per unit input =	8.88E+09	sej/g	(Brandt-Williams 2002)



13	**Exports**					
	Piper nigrum (peppercorn)					
	Mass (g)	2.70E+07				
		2.51E+00	kcal g^{-1}			
		4.19E+03	J kcal^{-1}			
		2.84E+11	J yr^{-1}			
		90.00	ha			
		3.16E+09	J/ha/yr			

Latex						
1	**Sun**					
	Annual energy =	(Avg. Total Annual Insolation J/yr)(Area)(1-albedo)				
	Insolation:	1.69E+07	J/m2/yr	(calculated using solar constant		
				of 2 Langleys/sec and		
		6.80	ha	integrating over changing		
	Area:	6.80E+04	m2	surface area for one year,		
	Albedo:	0.1325		latitude 1N, longitude 111W)		
	Annual energy:	9.98E+11	J			
	Emergy per unit input =	1	sej/J			
2	**Rain**					
	Annual energy =	(cm/yr)(Area)(0.01 m/cm)(1E6g/m3)(4.94J/g)(1 - runoff)				
	cm/yr:	420				
	Area:	6.80	ha			
	Area, m2:	6.80E+04				
	runoff coefficient:	7.00E-02				
	Annual energy:	1.31E+12	J			
	Emergy per unit input =	1.80E+04	sej/J			
3	**Wind**					
	Area:	6.80	ha			
	Area, m2:	6.80E+04				
	Density of Air: 1.3 kg m^{-3}					
	Wind Velocity - Average 10 m		2.2	m/s		
	Geostrophic wind: 2.32 m s^{-1} (assume that observed winds are 0.6 of geostrophic wind)					
	Drag coefficient: 0.001					
	Multiply the above for basal					
	Transformity: 1.50 E3 sej J^{-1} (Odum 1996)					
		6.11E+09	J/year			
	Transformity:	1.50E+03	sej/J	(Odum 1996)		

4	*Labor (renewable)*					
Family	3697.5	hr /yr				
% R	77	%	(Trujillo 1998)			
Total	2847.075	hr/yr	=family*%R			
Transformity:	6.99E+12	sej hr-1	(Trujillo 1998)			
5	**Net Topsoil Loss**					
	Erosion rate =	0.1	t/ha/yr	(Bruijnzeel 2004)		
	Latex Rubber	6.80	ha			
	Soil loss	0.68000	t/yr			
	Soil loss	680000	g/yr			
	g organic/ g soil =	0.04				
	Energy cont./g organic=	5.00	kcal/g organic	(Ulgiati et al. 1994)		
		4186	J/kcal			
	Annual energy:	5.69E+08	J			
	Emergy per unit input =	6.25E+04	sej/J	(Ulgiati et al. 1994)		
6	*Labor (purchased)*					
Family	3697.5	hr /yr				
Purchased	0	hr /yr				
%F	23	%	(Trujillo 1998)			
Total	850	hr/yr	=Family*%F+Purchased			
Transformity:	6.99E+12	sej/hr	(Trujillo 1998)			
7	**Hand Tools**					
	Annual consumption	1.13E+03				
	Percent use for area =	0.20%				
	Annual consumption for area =	2.29E+00				
	Emergy per unit input =	3.33E+13	sej/US$			



8	**Herbicides**					
	Annual consumption:	85	L	5 L / yr * 17 farmers		
	density	1.24	g/ml			
	Annual consumption:	1.05E+05	g			
	Emergy per unit input =	8.88E+09	sej/g	(Brandt-Williams 2002)		
9	**Exports**					
	(Hevea brasiliensis) latex rubber					
	Mass (g)	1.70E+07				
		4.00E-01	kcal g^{-1}	(Norton 2014)		
		4.19E+03	J $kcal^{-1}$			
		2.85E+10	J yr^{-1}			
		6.80	ha			
		4.19E+09	J/ha/yr			

Sago						
1	**Sun**					
	Annual energy =	(Avg. Total Annual Insolation J/yr)(Area)(1-albedo)				
	Insolation:	1.69E+07	J/m2/yr	(calculated using solar constant		
				of 2 Langleys/sec and		
		49.73	ha	integrating over changing		
	Area:	4.97E+05	m2	surface area for one year,		
	Albedo:	0.1325		latitude 1N, longitude 111W)		
	Annual energy:	7.30E+12	J			
	Emergy per unit input =	1	sej/J			
2	**Rain**					
	Annual energy =	(cm/yr)(Area)(0.01 m/cm)(1E6g/m3)(4.94J/g)(1 - runoff)				
	cm/yr:	420				
	Area:	49.73	ha			
	Area, m2:	4.97E+05				
	runoff coefficient:	7.00E-02				
	Annual energy:	9.60E+12	J			
	Emergy per unit input =	1.80E+04	sej/J			
3	**Wind**					
	Area:	49.73	ha			
	Area, m2:	4.97E+05				
	Density of Air: 1.3 kg m^{-3}					
	Wind Velocity - Average 10 m			2.2	m/s	
	Geostrophic wind: 2.32 m s^{-1} (assume that observed winds are 0.6 of geostrophic wind)					
	Drag coefficient: 0.001					
	Multiply the above for basal					
	Transformity: 1.50 E3 sej J^{-1} (Odum 1996)					
		4.47E+10	J/year			
	Transformity:	1.50E+03	sej/J	(Odum 1996)		

4	*Labor (renewable)*					
Family	3094	hr /yr			160 hrs for 365 kg of edible starch /	
% R	77	%	(Trujillo 1998)		4.38E-01	hrs / 1 kg processe
Total	2382.38	hr/yr	=family*%R		3.27E+05	hrs / village labor
Transformity:	6.99E+12	sej hr-1	(Trujillo 1998)		10 days * 7 hrs for harvested trunk	
5	**Net Topsoil Loss**					
	Erosion rate =	0.1	t/ha/yr	Bruijnzeel 2004		
	Agroforested Sago	49.73	ha			
	Soil loss	4.97314	t/yr			
	Soil loss	4973139	g/yr			
	g organic/ g soil =	0.04				
	Energy cont./g organic=	5.00	kcal/g organic	Ulgiati et al. 1994		
		4186	J/kcal			
	Annual energy:	4.16E+09	J			
	Emergy per unit input =	6.25E+04	sej/J	Ulgiati et al. 1994		
6	*Labor (purchased)*					
Family	3094	hr /yr				
Purchased	0	hr /yr				
%F	23	%	(Trujillo 1998)			
Total	712	hr/yr	=Family*%F+Purchased			
Transformity:	6.99E+12	sej/hr	(Trujillo 1998)			
7	**Hand Tools**					
	Annual consumption	1.13E+03				
	Percent use for area =	1.55%				
	Annual consumption for area =	1.75E+01				
	Emergy per unit input =	3.33E+13	sej/US$			

8	**Exports**					
	Metroxylon sagu (sago)					
	Mass (g)	7.46E+08	15 t per ha inc 8 yr no harvest and 20 yr life cycle (Flach 1997)			
		9.90E-01	kcal g^{-1}			
		4.19E+03	J kcal^{-1}			
		3.09E+12	J yr^{-1}			
		49.73	ha			
		6.22E+10	J/ha/yr			

Breadfruit						
1	**Sun**					
	Annual energy =	(Avg. Total Annual Insolation J/yr)(Area)(1-albedo)				
	Insolation:	1.69E+07	J/m2/yr	(calculated using solar constant		
				of 2 Langleys/sec and		
		44.81	ha	integrating over changing		
	Area:	4.48E+05	m2	surface area for one year,		
	Albedo:	0.1325		latitude 1N, longitude 111W)		
	Annual energy:	6.58E+12	J			
	Emergy per unit input =	1	sej/J			
2	**Rain**					
	Annual energy =	(cm/yr)(Area)(0.01 m/cm)(1E6g/m3)(4.94J/g)(1 - runoff)				
	cm/yr:	420				
	Area:	44.81	ha			
	Area, m2:	4.48E+05				
	runoff coefficient:	7.00E-02				
	Annual energy:	8.65E+12	J			
	Emergy per unit input =	1.80E+04	sej/J			
3	**Wind**					
	Area:	44.81	ha			
	Area, m2:	4.48E+05				
	Density of Air: 1.3 kg m^{-3}					
	Wind Velocity - Average 10 m		2.2	m/s		
	Geostrophic wind: 2.32 m s^{-1} (assume that observed winds are 0.6 of geostrophic wind)					
	Drag coefficient: 0.001					
	Multiply the above for basal					
	Transformity: 1.50 E3 sej J^{-1} (Odum 1996)					
		4.02E+10	J/year			
	Transformity:	1.50E+03	sej/J	(Odum 1996)		

4	*Labor (renewable)*					
Family	1249.5	hr /yr	(Janick & Paull, 2008)			
% R	77	%	(Trujillo 1998)			
Total	962.115	hr/yr	=family*%R			
Transformity:	6.99E+12	sej hr-1	(Trujillo 1998)			
5	**Net Topsoil Loss**					
	Erosion rate =	0.1	t/ha/yr	Bruijnzeel 2004		
	Agroforested Breadfruit	44.81	ha			
	Soil loss	4.48126	t/yr			
	Soil loss	4481257	g/yr			
	g organic/ g soil =	0.04				
	Energy cont./g organic=	5.00	kcal/g organic	Ulgiati et al. 1994		
		4186	J/kcal			
	Annual energy:	3.75E+09	J			
	Emergy per unit input =	6.25E+04	sej/J	Ulgiati et al. 1994		
6	*Labor (purchased)*					
Family	1249.5	hr /yr				
Purchased	0	hr /yr				
%F	23	%	(Trujillo 1998)			
Total	287	hr/yr	=Family*%F+Purchased			
Transformity:	6.99E+12	sej/hr	(Trujillo 1998)			
7	**Hand Tools**					
	Annual consumption	1.13E+03				
	Percent use for area =	1.39%				
	Annual consumption for area =	1.58E+01				
	Emergy per unit input =	3.33E+13	sej/US$			

8	**Exports**					
	Artocarpus altilis (breadfruit)					
	Mass (g)	7.17E+08	(BI, 2014)			
		1.03E+00	kcal g^{-1}			
		4.19E+03	J kcal^{-1}			
		3.09E+12	J yr^{-1}			
		44.81	ha			
		6.91E+10	J/ha/yr			

Mature Forest						
1	**Sun**					
	Annual energy =	(Avg. Total Annual Insolation J/yr)(Area)(1-albedo)				
	Insolation:	1.69E+07	J/m2/yr	(calculated using solar constant		
				of 2 Langleys/sec and		
		3169.00	ha	integrating over changing		
	Area:	3.17E+07	m2	surface area for one year,		
	Albedo:	0.1325		latitude 1N, longitude 111W)		
	Annual energy:	4.65E+14	J			
	Emergy per unit input =	1	sej/J			
2	**Rain**					
	Annual energy =	(cm/yr)(Area)(0.01 m/cm)(1E6g/m3)(4.94J/g)(1 - runoff)				
	cm/yr:	420				
	Area:	3169.00	ha			
	Area, m2:	3.17E+07				
	runoff coefficient:	7.00E-02				
	Annual energy:	6.11E+14	J			
	Emergy per unit input =	1.80E+04	sej/J			
3	**Wind**					
	Area:	3169.00	ha			
	Area, m2:	3.17E+07				
	Density of Air: 1.3 kg m^{-3}					
	Wind Velocity - Average 10 m			2.2	m/s	
	Geostrophic wind: 2.32 m s^{-1} (assume that observed winds are 0.6 of geostrophic wind)					
	Drag coefficient: 0.001					
	Multiply the above for basal					
	Transformity: 1.50 E3 sej J^{-1} (Odum 1996)					
		2.85E+12	J/year			
	Transformity:	1.50E+03	sej/J	(Odum 1996)		

4	*Labor (renewable)*					
Family	0	hr /yr				
% R	77	%	(Trujillo 1998)			
Total	0	hr/yr	=family*%R			
Transformity:	6.99E+12	sej hr-1	(Trujillo 1998)			
5	**Net Topsoil Loss**					
	Erosion rate =	0.03	t/ha/yr	Pimentel et al. 1987		
	Mature Forest	3169.00	ha			
	Soil loss	95.07000	t/yr			
	Soil loss	95070000	g/yr			
	g organic/ g soil =	0.04				
	Energy cont./g organic=	5.00	kcal/g organic	Ulgiati et al. 1994		
		4186	J/kcal			
	Annual energy:	7.96E+10	J			
	Emergy per unit input =	6.25E+04	sej/J	Ulgiati et al. 1994		
6	*Labor (purchased)*					
Family	0	hr /yr				
Purchased	35530.57	hr /yr	Forest data = parks average * farmer households			
%F	23	%	(Trujillo 1998)			
Total	35530.57	hr/yr	=Family*%F+Purchased			
Transformity:	6.99E+12	sej/hr	(Trujillo 1998)			
7	**Hand Tools**					
	Annual consumption	1.13E+03	US$	Data for Rumah Siba		
	Percent use for area =	94.24%				
	Annual consumption for area =	1.07E+03				
	Emergy per unit input =	3.33E+13	sej/US$			

8	**Power Tools**					
	Annual consumption	5.67E+03	US$	1000 MYR / 3 = US$		
	Percent use for area =	100.00%				
	Annual consumption for area =	5.67E+03				
	Emergy per unit input =	3.33E+13	sej/US$			