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Implementing Sustainable Forest Management Using Six Concepts in an Adaptive Management Framework

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Certification and principles, criteria and indicators (PCI) describe desired ends for sustainable forest management (SFM) but do not address potential means to achieve those ends. As a result, forest owners and managers participating in certification and employing PCI as tools to achieving SFM may be doing so inefficiently: achieving results by trial-and-error rather than by targeted management practices; dispersing resources away from priority objectives; and passively monitoring outcomes rather than actively establishing quantitative goals. In this literature review, we propose six concepts to guide SFM implementation. These concepts include: Best Management Practices (BMPs)/Reduced Impact Logging (RIL), biodiversity conservation, forest protection, multi-scale planning, participatory forestry, and sustained forest production. We place these concepts within an iterative decision-making framework of planning, implementation, and assessment, and provide brief definitions of and practices delimited by each concept. A case study describing SFM in the neo-tropics illustrates a potential application of our six concepts. Overall our paper offers an approach that will help forest owners and managers implement the ambiguous SFM concept.

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INTRODUCTION

Sustainable forest management (SFM) has developed many different meanings but fundamentally involves perpetuating ecological, economic, and/or social forest assets (Aplet *et al.*, 1993; Goodland, 1995; Floyd, 2002). The types of assets or capital that could be perpetuated include provision of ecological goods and service production such as carbon storage and biodiversity (Franklin and Kohm, 1997), and sustained production of commercial commodities such as timber (Helms, 1998). To reconcile current with future demands, FAO (1993, p. 3) has described sustainable forest management as "securing an improved livelihood for present generations, while maintaining the potential of the forest heritage for future generations."

Over the past quarter century, two parallel developments in SFM have occurred. These developments are an expansion in the meaning of sustainable forestry—from sustained yield to sustaining ecological, economic, and/or social capital—and a development of evaluative programs—including principles, criteria and indicators (PCI) and certification principles (Rametsteiner & Simula, 2003). The PCI and certification programs suffer from two deficiencies. First, PCI evaluative systems, by describing desired ends but not means, may create trial-by-error inefficiencies due to implementation gaps. Second, certification programs, despite rapid recent growth, provide limited applicability to approximately 7% of global productive forest land (approximately 25% of global roundwood production), 60% of which lies in North America and 30% of which lies in Europe (United Nations Economic Commission for Europe/FAO, 2006). In addition to issues of management capacity and transaction costs, certification has limited utility to entities in many parts of the world that do not need to secure a social license to operate for forest management (such as Canadian crown land lease requirements) or do not need external endorsement for timber trade (such as European demand for certified wood products) (Overdevest & Rickenbach, 2006). Assessment and its associated metrics are critical for monitoring rather than practicing SFM.

To address these deficiencies, we propose six concepts that delimit SFM implementation practices. Our concepts, ordered alphabetically, include:

BMPs/RIL (1-Retention of nontarget live trees; 2-Minimization of soil compaction within road/trail area; 3-Protection of water quality via adequate buffers);

Biodiversity conservation (1-Emulation of natural disturbance frequency, intensity, and magnitude; 2-Development of structural complexity including CWD retention; 3-Retention of live trees as biological legacies);

Forest protection (1-Mixed forest composition; 2-Low density stands; 3-Browsing and invasive species control; 4-Variable forest structure)

Multi-scale planning (1-Land use planning across forest management units; 2-Land use planning across landscapes)

Participatory forestry (1-Participation of relevant stakeholders in planning, implementing & monitoring; 2- Empowering governance)

Sustained forest production (1-Optimum ecological yield: extension of rotation/entry period; 2-Optimum economic yield: contraction of rotation/entry period).

The following literature review bridges the implementation gap between goal setting and evaluative monitoring, and provides options for SFM outside of formal certification programs. In the first section of the review, we describe our decision-making framework in terms of planning, implementation, and assessment. Next, we offer proposed definitions and simplified practices for each of our six concepts based on a brief literature review. Finally, we offer a brief case study of a neo-tropical forest company as a hypothetical illustration of how our decision-making framework and management concepts might be utilized.

Iterative Decision-Making Framework

A major challenge to sustainable forestry is the inherent difficulty in accurately forecasting which capital stocks need to be sustained for the future. Uncertainty comes from many sources, including changes in human population levels and densities, ecological understanding and conditions, economic demands and technology, and social institutions and values. One response to this dilemma is to employ adaptive management in SFM decision-making (Norton, 2005). Adaptive management involves four decision-making stages of planning, implementation, evaluation, and modification (plan, do, check, and act (PDCA) Walters & Holling, 1990). Successful implementation of adaptive management requires institutionalization of the adaptive management process so that it is used routinely and systematically. In addition, emphasis should be placed on closing the loop of adaptive management via periodic monitoring and revision (Bormann et al., 2007).

Capital Objectives (First Column)

The first column in Table 1 lists the forest capital stocks that could be sustained for future human well-being, including ecological, economic, and social capital from Aplet et al. (1993), which could also be divided into natural, built/financial, and human/social capital from Vemuri & Costanza (2006).

Ecological capital according to De Groot et al. (2002) consists of four major components: (1) regulatory functions; (2) habitat composition and structure; (3) production functions (foundation of economic capital); and (4) information provision (foundation of social capital). Economic capital, the most quantifiable capital type, includes net present value of: (1) cash and cash equivalents from forest activities; (2) built/manufactured goods, such as buildings, roads, and machinery; and (3) natural resources with current market value including stocks of goods such as land and timber, and funds of services such as carbon storage and wildlife provision. Social capital according to Baker & Kusel (2003) consists of three major components that may be influenced by forests: (1) human development in terms of education, health, and innovation; (2) cultural beliefs, historic interests, and social norms; and (3) political relationships in terms of family members, friends, and professional networks.

The weighting of ecological, economic, and social capital against trade-offs depends both on the priorities of landowners and managers, and also on capital substitutability or fungibility. The weak sustainability perspective (Solow, 1974) holds that increased economic and/or social capital can entirely substitute for loss of ecological capital. This perspective is exemplified by Hartwick's rule which holds that nonrenewable ecological capital may

TABLE 1 Iterative Decision-Making Framework for Sustainable Forest Management

Planning Capital objectives	*Implementation* Management concepts	*Assessment* Principles, criteria & indicators
Maintain goals within changing conditions	Adaptive management	Management planning & monitoring
(1) Nondeclining or restored ecological capital (habitat, protection, regulation & information functions)	(1) BMPs/RIL (2) Biodiversity conservation (3) Forest protection (4) Multi-scale planning	(1) Protective functions/soil & water resources (2) Biological diversity (3) Ecological health (4) Forest land area (5) Maintenance of high conservation value areas
(2) Nondeclining or maximized economic capital (net present market value of cash, built resources, and natural resources)	(6) Sustained forest production	(6) Productive functions & carbon storage
(3) Nondeclining or maximized social capital (human, cultural, and political)	(5) Participatory forestry	(7) Socio-economic benefits (8) Legal-political institutions

be depleted, but the economic (Ricardian) rents from depletion—earnings above resource extraction, conversion, and distribution costs—must be re-invested in economic or social capital, rather than being consumed, to maintain non-declining consumption and production over time (Hartwick, 1977). An intermediate perspective, the safe minimum standard (Ciriacy-Wantrup, 1952, Crowards, 1998), only allows depletion of nonrenewable ecological capital when the costs of preservation are socially immoderate or intolerable—defined by Berrens et al. (1998) as reducing historic economic growth by more than one-half of one standard deviation. Finally, the strong sustainability perspective introduced by Daly (1990) holds that ecological capital provides the foundation for development of social capital, and social capital provides the structure for development of economic capital, and therefore all ecological capital must be preserved. Daly proposed three rules for strong sustainability: (1) renewable resource harvests equaling rate of regeneration; (2) nonrenewable resource depletion equaling rate of substitute creation; and (3) waste emission not exceeding natural assimilation capacity. Technological innovation and economic discounting diminish the imperative of strong sustainability, while other factors increase the imperative. These factors include: (1) population growth, which creates increased scale of human disturbances and demands on natural resource stocks (Toman and Ashton, 1996); (2) economic institutional deficiencies, including costs of production external to market transactions and government intervention subsidies; and (3) information uncertainty, which creates option loss by consuming resources immediately (Graham-Tomasi, 1995), particularly considering prospects for improved information in the future (Arrow & Fisher, 1974). Forest owners and managers who subscribe to strong sustainability will need to conserve ecological capital as the foundation upon which economic and social capital are developed.

Management Concepts (Second Column)

Our six management concepts form the second column in Table 1. We organized this column so that landowners and managers who choose to prioritize ecological, economic, or social capital objectives can then select from among a reduced subset of management concepts to allocate resources more efficiently. The concepts may be applied at various spatial scales: for example, BMP/RIL may be applied at tree scale; forest protection and sustained forest production at stand scales; and biodiversity conservation, multi-scale planning and participatory forestry at forest management unit and watershed scales. We organized our concepts in Table 1 by those most critical for maintaining a particular capital type: ecological, economic, or social.

Many SFM concepts are discussed in the literature, but are often described individually rather than in a holistic fashion as we attempt in this

TABLE 2 Individual SFM Implementation Concepts from Literature

Terms	Definition & source	Our analogous concept
Community-based ecosystem management (CBEM)	Local community involvement in ecological protection and restoration activities, based upon conviction that human communities and natural ecosystems are interdependent (Gray et al., 2001).	Participatory forestry
Ecosystem approach (EA)	The ecosystem approach is a strategy for the integrated management of land, water and living resources that promotes conservation and sustainable use in an equitable way (CBD 1995 Malawi Principles).	Multi-scale planning
Low/positive impact forestry	Reduction of soil compaction, reduction of residual tree damage, reduction of road sizes and densities, minimization of water quality degradation, and consolidation of harvest treatments to minimize wildlife impacts (Lansky, 2003, McEvoy, 2004).	BMPs/RIL
Natural disturbance based forestry (formerly termed ecological forestry)	Emulation of natural disturbances via management in terms of intensity, return interval, and spatial pattern (Seymour and Hunter, 1999).	Biodiversity conservation
Variable retention forestry (formerly termed new forestry)	Retention of old growth structure of large live trees, logs, and snags within harvested stands (Lindenmayer and Franklin, 2002).	Biodiversity conservation

literature review. A subset of these concepts are listed in Table 2. We incorporated community-based ecosystem management in participatory forestry; the ecosystem approach in multi-scale planning; low/positive impact forestry in BMPs/RIL; natural disturbance based forestry in biodiversity conservation; and variable retention forestry in biodiversity conservation.

Assessment Categories (Third Column)

The third column in Table 1 involves categories of assessment involving certification on forest management unit scale and PCI on a broader scale. The four most widespread principles, criteria and indicator programs globally (in alphabetical order) are the Helsinki (Pan-European) Process via Ministerial Confeerence on Protection of Forests in Europe (MCPFE), International Tropical Timber Organization (ITTO) Initiative, Montreal Process, and Tarapoto Proposal. The four largest certification programs globally are the Canadian Standards Association (CSA), Forest Stewardship Council (FSC), Program for the Endorsement of Forest Certification Schemes (PEFC), and Sustainable Forest Initiative (SFI) (Rametsteiner and Simula, 2003). We summarized the content of these programs by using eight PCI categories from McDonald & Lane (2004) and Holvoet & Muys (2004) and organize these categories to correspond with our six management concepts. One assessment category "management planning and monitoring" is separated in the top row because it corresponds best with our over-arching concept of adaptive management.

MANAGEMENT CONCEPTS

Best Management Practices (BMPs)/Reduced Impact Logging (RIL)

Definition

BMPs/RIL are the most spatially limited of the concepts because they focus on the operations aspect of forest management. BMPs for logging operations in the United States originated from the 1972 Clean Water Act mandate for states to develop performance standards to control non-point source pollution. BMPs involve a number of recommended practices to prevent sediment discharge, including: site preparation procedures (e.g. road and trail planning and minimization); erosion control guidelines for haul roads and skid trails (e.g. dip and water bar placement relative to road slope); stream crossing procedures (e.g. road crossing angle and bridge structure); corridor retention guidelines near major water bodies (e.g. minimum corridor size requirements relative to stream-side slope); and site closure procedures (e.g. erosion control, road closure, and slash dispersal recommendations). RIL adds recommended practices for protecting standing live trees, such as inventory mapping, directional felling, and vine cutting where applicable.

BMPs/RIL have both ecological and economic impacts. Complying with BMPs generally reduces gross harvest revenue by 1–5%, due largely to restrictions on streamside wood removal (Cubbage, 2004). RIL can boost net present values by up to 20% by protecting future growing stock, diminishing wood waste, and increasing operational efficiency (Holmes et al., 2002). However RIL is cost prohibitive in stands with high densities of commercially valuable trees where even-aged silvicultural treatments are often preferred (Van der hout, 2000). RIL also involves up-front barrier of high up-front training costs (Putz et al., 2000).

Practices – (1) Retention of nontarget live trees

RIL practices damage or kill half as many nontarget trees as conventional logging, primarily due to inventory, directional felling, and vine cutting. In Brazilian Amazon forests, for example, conventional logging damaged or killed 124 trees/ha, while RIL damaged or killed less than 60 trees/ha (Pereira et al., 2002). In addition to maintaining biodiversity, protecting live trees has commercial value in preventing dispersal limitation otherwise common with heavy, animal dispersed seeds (McEuen & Curran, 2004).

Practices – (2) Minimization of soil compaction within road/trail area

Compaction from machinery may prevent tree root anchoring, hydration, and oxidation (Siegel-Issem et al., 2005). Soil compaction (particularly at 20–30 cm depth) is generally harmful if bulk density rises more than 15% (Lacey & Ryan, 2000). High sand texture (Gomez et al., 2002) and/or soil dryness (McNabb et al., 2001) generally offset the impacts of compaction. The displacement of topsoil due to logging operations has confounding effects: litter loss reduces nitrogen and phosphorus levels thus inhibiting seedling and sapling growth (Tan & Chang, 2007), while removal of competing vegetation may also stimulate seedling and sapling growth (Fleming et al., 2006).

Practices – (3) Protection of water quality via adequate buffers

A review of nearly all U.S. state BMPs revealed that riparian buffer requirements are most commonly 15 m on each bank with 50–75% canopy cover retention, but may exceed 20 m (Blinn & Kilgore, 2001). Buffers at least 11 meters wide (on slopes <10%) maintain habitat for macroinvertebrates (Vowell, 2001) and moderate mean water temperature fluctuations to 0.5–0.7° C per day compared to 1.5–3.6° C per day without buffers (Wilkerson et al., 2006). However, aquatic coarse woody debris recruitment and maintenance of terrestrial bird and mammal habitat may require larger buffers of 30–50 m in the temperate zone (Lee et al., 2004). Riparian buffers also retain eight times more sediment than clearcut harvest areas on an area-adjusted basis, and more total sediment volume than road water bars (Wallbrink & Croke, 2002). However, rainfall quantity (Hartanto et al., 2003) and road sizes and locations (Sidle et al., 2006) outweigh either harvest intensity or BMPs/RIL practices in determining sediment discharge into water bodies.

Biodiversity Conservation

Definition

Biodiversity conservation involves retaining tree composition and/or structure to maintain or restore organism diversity from individual tree to stand to watershed to regional to global spatial scales. Forest owners and managers must be explicit in their diversity objectives in terms of endemic or red-listed species as concentrations of these species groups are incongruent (Ceballos & Ehrlich, 2006). Forest biodiversity conservation requires both coarse filter mechanisms, such as protected areas, as well as fine filter strategies for monitoring and ensuring the viability of populations of organisms not adequately protected by coarse filter approaches (Schwartz, 1999). Wildlife management in terms of maintaining game species is a subset of this concept.

Practices – (1) Emulation of natural disturbance frequency, intensity, and magnitude

Disturbance has been defined as "any relatively discrete [non-autogenic] event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment" (Pickett & White, 1985, p. 7). Disturbances are typically characterized by their frequency (periodicity), intensity (energy release), magnitude (spatial extent), and timing (phenology). Disturbance based forestry involves emulating these characteristics of natural disturbance regimes. However, finding appropriate historical reference periods for disturbance emulation can be difficult. For instance, much of the available information on pre-European forest condition coincides with cooler climatic conditions at the end of the Little Ice Age (Landres et al., 1999). In addition, the timing of natural disturbances can be difficult or costly to emulate, such as fires during dry weather. Nonetheless, natural disturbances often need to be considered because of the major role they play in determining forest composition, structure, and function.

Low intensity harvests (<25% canopy cover reduction) have greatest applicability to the hardwood forests of eastern North America where such harvests emulate the magnitude (less than 0.1 ha gaps) and frequency (50–200 year return intervals) of historic natural disturbance regimes (Seymour et al., 2002). Such harvests maintain late successional bird species diversity, but diminish early successional diversity (Faccio, 2003). Such harvests have minor impacts on vascular species richness after 25 years (Reich et al., 2001) excluding mycroheterotrophic species such as orchids, nonvascular mosses and lichens (Humphrey et al., 2002). Harvests of much greater intensity would be appropriate to emulate crown fire regimes to which pyrophytic trees have adapted in boreal biomes, and also hurricane and fire gap disturbances to which long-lived tree colonists such as mahogany have adapted in tropical biomes (Hall et al., 2003). In addition, harvesting intensity involves trade-offs in terms of intensity, frequency, and magnitude to supply a given wood volume. More intensive but concentrated harvests can maintain shade-tolerant perennial plants in the temperate biome (Decocq et al., 2004) and reduce secondary disturbance effects, including hunting and wildfire.

Practices – (2) Development of structural complexity including coarse woody debris retention

Natural disturbances characteristically leave large accumulations of standing and downed coarse woody debris (CWD) (Franklin & MacMahon, 2000). Though logging also leaves coarse woody debris, the typical logging slash of undecayed small diameter residual tops and branches differs substantially from the large standing snags and downed logs deposited after natural disturbances. Whole tree harvesting can remove coarse woody debris from a forest altogether. Clearcuts in temperate and boreal zones particularly lack moderately decayed standing snags greater than 30 cm diameter that provide habitat for cavity nesting birds (Pedlar et al., 2002). In addition, large downed logs are often lacking, which otherwise boost microsite moisture conditions and inhibit competing vascular plants, accelerating tree population recovery from disturbance, even in tropical biomes where decomposition rates are high (Beard et al., 2005). Another tool for developing mature forest structure, in addition to manipulating CWD volumes, involves employing variable density marking and rotated sigmoid rather than inverse J diameter distributions (Keeton, 2006).

Practices – (3) Retention of live trees as biological legacies

Biological legacies have been defined as “the organisms, organic material, and organically-generated patterns that persist through a disturbance and are incorporated into the recovering ecosystem” (Franklin & MacMahon, 2000, p.1183). Even intense natural disturbances seldom result in complete tree mortality. For example, after forest fires, unburned areas or “fire skips” frequently lie within 50–200 m of severely burned areas in pine forests (Kashian et al., 2005), and, though pine forests require frequent fires (<100 years) to maintain their dominance, few such fires were historically stand-replacing (Kuuluvainen, 2002). Retention of mature trees to emulate this variability can increase song bird populations (Norton & Hannon, 1997), increase shade- and moisture-dependent vascular plant populations, and provide microsites and mycorrhizae inoculum (Lazaruk et al., 2005) for natural regeneration. The Montane Alternative Silvicultural System (MASS) compared dispersed retention (via irregular shelterwood) against aggregated retention (via patch cuts) in temperate coniferous forests. Economically, dispersed retention was most viable as diminished regeneration growing space was offset by a 30–40% increase in basal area growth of retained trees (Mitchell, 2001). Ecologically, aggregated retention of leave patches greater than 1 ha in hydric to mesic areas most resembled unlogged old-growth composition in terms of forest-dwelling birds (Tittler et al. 2001) and non-vascular plants (Rheault et al., 2003).

Forest Protection

Definition

Forest protection involves instituting management practices that maintain acceptable rates of plant mortality and morbidity/die-back. The acceptability threshold for tree mortality in particular will differ depending on managers' objectives and forest type. In plantations, manager objectives dominate within resource constraints, while in natural forests these objectives will necessarily be determined by historic range of variability of natural disturbances, such as fires (Aplet & Keeton, 1999).

The silvicultural practices to modulate tree mortality described below include all of those that define the field of silviculture—"control of forest establishment, composition, structure, and growth" (Smith et al., 1996, p. 3). Non-silvicultural treatments may also be necessary including chemical applications of fertilizers and pesticides, and mechanical treatments such as log yard irrigation.

The various disturbances that incite mortality can be classified in terms of visible internal tree damage from low to high: predisposing, inciting, or contributing factors (Manion, 1996). These etiological factors were first proposed to act hierarchically, but the factors interact in multiple ways. For example, the predisposing factor of high stand density in a natural forest (Bragg et al., 2003), along with the contributing factor of fungal bark disease (Rhoads et al., 2002), increase likelihood of the inciting factor of bole breakage from ice.

Despite management practices listed below, forest health vulnerability is partially determined by site conditions. For example, *Acer saccharum* growth rates are largely associated with soil calcium levels (Schaberg et al., 2006). Similarly, damage from large, high-intensity disturbances (LIDs characterized by a return interval > 50 years across 50–100,000 km^2 (Foster et al., 1998)), including fires, floods, and hurricanes, is largely correlated with atypical weather events and geophysical characteristics of elevation, aspect, and edge proximity (Kulakowski & Veblen, 2002).

Practices – (1) Mixed forest composition

Mixed tree species provide resistance against disturbances primarily through two mechanisms. The first mechanism is structural diversity, such as a mix of deciduous and conifers trees in the Northeast providing resistance against both wind and ice damage (Rhoads et al., 2002). This mechanism emerges from tree species differing in resistance (susceptibility to attack and mortality) and resilience (ability to recover pre-disturbance characteristics) to the same etiological factor. For example, palm (*Arecaceae* spp.)-dominated forests have high wind resistance because of their flexible stems, while tabonuco (*Dacroydes excelsa*)-dominated forests have high wind resilience because their litter, with high isoterpenes and low polyphenols, decomposes relatively quickly (Beard et al., 2005).

The second mechanism is host dilution, such as angiosperm volatiles disrupting scolytid olfactory cues from monoterpenes and thus increasing Norway spruce (*Picea abies*) resistance to bark beetle infestation (Zhang, 2003). Another example of host dilution is angiosperm roots interrupting gymnosperm root grafting and thus discouraging spread of *Heterobasidion annosum* and *Armillaria* fungal root diseases in western pine and cedar (Rizzo & Slaughter, 2001).

In addition to providing structural diversity and host dilution, mixed species forests (such as two or more species in plantations) improve stand-level wood production under certain conditions. Complementary mixtures of species with at least two different light tolerances, and additive mixtures of at least one nitrogen-fixing species in nitrogen-poor soils, often result in increased stand-level diameter growth compared to monoculture plantations because of delayed density-dependent thinning (Kelty, 2006; Piotto, 2008).

Practices – (2) Low density stands

Many tropical and subtropical plantations of eucalyptus (*Eucalyptus globulus*), gmelina (*Gmelina arborea*), radiata pine (*Pinus radiata*), and teak (*Tectona grandis*) have low levels of mortality, not only because of their relocation outside of the native pest range, but also because of their vigor due to periodic thinnings (Gadgil & Bain, 1999). Increased tree vigor most often improves tree resistance to insect infestations. For example, oak with the highest live crown ratios were five times less likely to suffer severe defoliation and mortality from gypsy moth (*Lymantria dispar*) than those with the lowest live crown ratios (Gottschalk et al., 1998). Similarly, tree losses to secondary beetles (e.g. mountain pine beetle (*Dendroctonus ponderosae*), engraver beetles (*Ips* spp., *Scolytus* spp.)) can often be reduced by thinning which not only boosts tree pitch-out defenses due to increased vigor, but also increases microclimatic drought and increases flight distance between infected and neighboring trees (Baier et al., 2002). During the switch from endemic to eruptive population phases, beetle densities increase, beetle physiology changes, and beetle behavior changes by expanding host range to healthy trees, but even during these eruptions, beetles most favor dead and dying trees over vigorous ones (Wallin & Raffa, 2004).

Practices – (3) Browsing and invasive species control

During forest establishment in particular, browsing animals and exotic plant species may need to be controlled. Browsing animals attracted to regeneration flushes can shift tree species composition from species with less to more recalcitrant foliage and thereby reduce long-term soil fertility (Cote et al., 2004). Furthermore, invasive exotic tree species can establish after a stand-replacing disturbance and persist even after stocking and vertical stratification have recovered (Brearley et al., 2004). Together browsing and exotic species invasions can generate positive feedbacks that retard forest regeneration—in one such case, hemlock wooly adelgid (*Adelges tsugae*) created light openings that spurred hardwood regeneration, high deer populations browsed the palatable hardwood saplings, and the vacated growing space became occupied by invasive understory species including intermediate fern (*Dryopteris intermedia*) and Japanese barberry (*Berberis thunbergii*) (Eschtruth et al., 2006).

Practices – (4) Variable forest structure

Forest structure may need to be either diversified or simplified depending on the disturbance of concern. In terms of biotic disturbances, retained overstory trees provide canopy shade necessary to prevent invasion of pine weevil (*Pissodes strobi*) into white pine (*Pinus strobus*) leaders, and mahogany shoot borer (*Hypsipyla grandella*) into mahogany (*Swietenia* spp.) and cedar (*Cedrela* spp.) leaders (Mahroof et al., 2000). On the other hand, overstory trees infected with dwarf mistletoe (*Arceuthobium* spp.) and Douglas-fir tussock moth (*Orgyia pseudotsugata*) can release infestations into the lower canopy.

In terms of abiotic disturbances, build up of fine and coarse fuel loads directly affect fire behavior and tree mortality (Odion et al., 2004). Harvesting can ameliorate this impact via felling of ladder fuels (Stephens, 1998) but only if such harvesting also involves treating woody slash, which otherwise persists for up to 30 years in xeric conifer forests (Stephens & Moghaddas, 2005).

Multi-Scale Planning

Definition

Another approach to sustainable forest management involves landscape-level zonation (Seymour & Hunter, 1999). This approach has been termed "specialized forestry" and "triad forestry" and involves allocation of protected reserves, intensively managed forest plantations, and extensively managed mixed-use natural forests in various proportions and locations across the landscape.

Specialized forestry is supported by the economic law of absolute advantage, which holds that forest owners will gain economically if they specialize management for each forest property on a spatial basis toward the products each is best able to produce (Vincent & Binkley, 1993). The economic benefits are apparent in tree growth rates of 5–20 m^3/ha/yr in plantations compared to 1–3 m^3/ha/yr in natural forests (Sedjo & Botkin, 1997). The ecological benefits are suggested by protected areas, considered one of the strongest methods of reducing biodiversity loss (Noss & Cooperrider, 1994). Natural managed forests provide a critical addition to these two components both by supplying large, high-value sawlogs, and also by supporting beta-landscape scale biodiversity, which cannot be maintained in the small number of existing protected areas alone (Soule & Sanjayan, 1998).

Practices – (1) Land use planning across forest management units including HCV identification

Land use planning can be implemented at alpha forest management unit scales of 1–100 ha. To maintain biodiversity, for example, organism abundance can be compared against natural and planted forest types and age classes using a small-scale spatially explicit (SSA) model to determine cutting intensity and reserve establishment (Higdon et al., 2005). Similarly, linear programming can be used to maximize discounted net economic returns from timber harvests, within constraints for establishing reserves for water quality buffers, deer wintering habitat, and steep slopes (Montigny & MacLean, 2006). Six categories of high conservation value (HCV) forests can also be identified within a forest management unit for special attention: biodiverse, representative, threatened, providing ecosystem services, providing economic products, and providing socio-cultural identity (Jennings et al., 2003).

Practices – (2) Land use planning across landscapes including opportunity cost zoning & forest cover maintenance

Land use planning can also be implemented to integrate various project scale activities across watersheds, landscapes and countries' political boundaries. Spatial targeting forest management to areas where potential benefits exceed opportunity cost and management costs along with consideration of risk of reversal, can result in increased efficiency of management objective attainment per dollar expended (Wunscher et al., 2008). Zoning specific areas for specific management practices based on opportunity cost analyses via remote sensing may also avert leakage in terms of diverting management practices to unintended locations (Stickler et al., 2009). Finally, although maintenance of forest cover is a crude metric, human well-being and forest cover are related in complex ways.

A loss of up to 50% of forest cover in Brazilian Amazon can improve human development index (HDI) in terms of per capita income, literacy, and life expectancy inexplicable by immigration alone, but such indices drop to original levels with increasing loss of forest cover, perhaps due to resource depletion (Rodrigues et al., 2009).

PARTICIPATORY FORESTRY

Definition

Participatory or community-based forestry involves formal vestment of responsibility for forest management activities with unrelated people, living in close proximity to the forest, for their own socio-economic benefit (Glasmeier & Farrigan, 2005). With roots in compliance of worker health and safety legal standards, participatory forestry has expanded to involvement of indigenous and local community members in forest management planning, implementation, and/or assessment, also termed by the Center for International Forestry Research (CIFOR) as 3R approach of "rights, responsibilities, and returns." A review of 69 case studies on community forestry found the following four variables most effective predictors of success in terms of achieving community-defined objectives (Pagdee et al., 2006): (1) clear and well-defined property rights; (2) effective community institutions and developed community capacity; (3) motivating incentives which align with community interests; and (4) stocked and productive lands.

Practices – (1) Participation of relevant stakeholders in planning, implementing, & monitoring

Co-management between forest ownership entities and relevant stakeholders can mitigate transaction costs arranging, bargaining, monitoring and/or enforcing exchanges. "When (local forest owners) have a role in making local rules, or at least consider the rules to be legitimate," state Ostrom & Nagendra (2006: p. 19224), "they are frequently willing to engage themselves in monitoring and sanctioning of uses considered illegal (on private or public property)." Gaining community participation in rule-making as well as monitoring requires at a minimum (Sheppard & Meitner, 2005): (1) choosing a small but representative sample of neighboring community participants; (2) improving capacity or functioning of participants through education and training so that participants can meaningfully contribute to decision-making; and (3) offering participants a meaningful and clear role in outcomes.

The examples of most active local participation in forest management involve group ownership of forest resources where participants have most to gain, such as *ejido* system of Mexico as documented by Bray et al. (2005). At least half of Mexico's approximately 60 million hectares of temperate and tropical forest is held in legal communal ownership by over 30,000 *ejidos*. Economically, the *ejidos* provide full-time, permanent employment for one-quarter to over three-quarters of residents, and a portion of annual profit is typically invested at community discretion in building clinics, meeting houses, and schools. Ecologically, annual rates of forest loss on *ejidos* are

0.6–1%, compared to 1–4% for managed non-*ejido* rural areas, and 0–0.5% for protected areas in Mexico. These low deforestation rates may be due to enforced cultural and social pressures that maintain commercial forest land for the future (Dalle et al., 2006). The smallest *ejidos* in terms of population sizes with longest history of management are most effective at reducing deforestation and fires (Alix-Garcia, 2007). However, this ecological advantage of participatory forestry in terms of local ownership and control over all stages of forest management must be tempered by the fact that other characteristics confounding variables—such as forest type and condition, elevation and slope, distance to settlements and transportation corridors, and human population growth rates—also strongly influence deforestation rates.

Practices – (2) Empowering governance

Legal and political institutions play a major role in community participation in forest management. Facilitation and endorsement by government regimes, allows effective implementation of clear and firm rules on resource use under group ownership (Ostrom et al., 1999). In frontier areas government legitimacy of land tenure and community land use rules can reduce forest cover loss. For example, miskito indigenous people defend forest frontier against mestizo colonist agricultural encroachment in one side of a park (Bosawas, Nicaragua) more effectively than other side of a park (Rio Plantano, Honduras) due to: (1) external support from The Nature Conservancy (TNC) and U.S. AID along with local NGO Centro Humboldt support for negotiation, information gathering, monitoring, and enforcement; and also (2) the government of Nicaragua formally recognizing both indigenous land rights and their local governing institutions (Hayes, 2008). Both horizontal and vertical institutional linkages increase effectiveness of natural resource management (Berkes, 2007).

Sustained Forest Production

Definition

Sustained forest production is based on sustained timber yield, or removing a quantity of timber based on growth rates that can be maintained in perpetuity, with given entry frequencies, over a given spatial area. Timber is removed at rates of culminating mean annual increment (MAI) per rotation for one and two cohort silvicultural systems. Biological tree growth is maximized at the intersection of diminishing periodic annual increment (PAI) and culminating MAI (Smith et al., 1996).

Timber is removed at rates of average net vegetative growth per entry for three or more cohort silvicultural treatments and non-timber forest product harvests. Under uneven-aged silvicultural treatments, sustained timber yield for anticipated entry cycles can be established by determining biological tree growth rates minus mortality (for particular species and size classes). Removal can occur in aggregated spatial patterns through area regulation or in dispersed spatial patterns through volume regulation. Volume regulation is more complicated than area regulation but necessary in forests with irregular spatial distributions of commercial trees. Post-harvest monitoring is critical under either regulation system to ensure that species-specific rates of recruitment and regeneration, and commercial quality, meet targets (Smith et al., 1996).

Whether rotation and entry periods are extended or contracted relative to culminating MAI will depend both on managers' objectives and on site-specific management contexts, such as whether nutrient reductions significantly reduce tree growth. An emerging variation of sustainable production is maintaining maximum biomass on site to maximize carbon credit returns, which will generally involve deferral of biomass removal into future and extension of rotation and entry periods relative to baseline prior to project inception.

Practices – (1) Optimum ecological yield: extension of rotation/entry period

Intensive harvesting may diminish soil nutrients and thus long-term productivity in terms of ability of forest to maintain its growth rate. Southeastern temperate mixed forests are relatively resilient in terms of available soil carbon, nitrogen and phosphorus (C-N-P), as these all recover at rates proportional to the forests' age after clearcutting (Palmer et al., 2005). However, many cations including calcium, magnesium, potassium, and sulfur, recover at half the rate of C-N-P, which could delay the recovery time to restore original nutrient levels to one and a half times the age of the forest at harvesting (Elliott et al., 2002). Whole tree harvesting of removing tops and limbs from the stand is an aggravating factor that can more severely reduce soil nutrients and expand rotation length (Belleau et al., 2006). In addition, younger soils in tropical regions generally indicate nitrogen limitation and older soils phosphorus limitation (Tanner et al., 1998; Paoli & Curran, 2007) so even recovery of these nutrients to pre-harvest levels may be low relative to plant growth requirements.

Practices – (2) Optimum economic yield: contraction of entry/rotation period

A limitation of sustained timber yield is its static focus on volume growth at one point in time, rather than a dynamic focus on timber yield over multiple rotation or entry cycles with a discount rate. In 1849, Faustmann developed an equation to calculate the economically efficient timber rotation over time on even-aged stands (also called willingness to pay for land (WPL) or land expectation value (LEV)). This Faustmann equation has also been adapted to uneven-aged stands (Adams & Ek, 1974). The equation calculates net present value (NPV) of all future timber revenues minus all future management costs at a particular discount rate. Discounting future benefits and costs is necessary to account for inflation and risk (Price, 1993). Because of the nature of forestry with its short-term costs and long-term benefits, the discount rate strongly influences the type and amount of forest that will be sustained into the future. For example, a change from 6% to 4% in real (inflation-adjusted) discount rates in Sri Lanka changed the most profitable silvicultural treatment from exploitive diameter-limit to regenerative shelterwood, though neither proved as profitable as tea cultivation (Ashton et al., 2001). Risk in developing countries and time frames less than 20 years can shift standard discount rates from less than 5 to 10% to more than 10 to 15% per year (Newell & Pizer, 2004). High discount rates that exceed the rate of timber in-growth convert the economically efficient decision from treating timber as an annuity into treating it as a lump sum. In addition, the theory of diminishing marginal returns calls for shortening rotation/entry periods to optimize level of effort where marginal revenue equals marginal cost. However, a number of circumstances may extend the economically efficient rotation, including: yield as opposed to *ad valorem* property taxes; loss of productive capacity over time through soil nutrient losses (Erickson et al., 1999); high regeneration costs (Binkley, 1987); and inclusion of non-timber amenity values, assuming such values increase with forest age (Hartman, 1976).

CASE STUDY

Background

We chose one case study, Masonite Costa Rica (hereafter referred to as Masonite C.R.), to illustrate how our decision-making framework and management concepts (Table 1) might be utilized. Although our case study is purely hypothetical because our framework has not been actually implemented, the study provides a concrete example of abstract concepts. The company was chosen because it has been widely promoted as a pioneering example of SFM in the region, having been FSC certified for over 15 years—might our framework expedite fulfillment of certification standards, and illustrate inefficiencies in even exemplary management practices?

Masonite C.R. was founded as Portico in 1982 by a group of investors with their purchase of Puertas y Ventanas de Costa Rica. The company grew through vertical integration in the 1980s by purchasing forest land and saw mills, and subsequently expanded into the U.S. market through a niche of selling solid royal mahogany doors to both contractors and home improvement centers. In the mid-1990s, the global door manufacturer Masonite acquired the Costa Rica company. Nearly all of Masonite C.R.'s wood comes from 7,000 ha involving more than two dozen parcels owned in fee simple by its subsidiary Tecnoforest Del Norte. These broadleaf forests (wet to moist tropical forest types *sensu* Holdridge (1971)) lie in the lowland Atlantic region of northeastern Costa Rica. Mean annual rainfall is approximately 400 cm in this region, elevation is 15–50 m, and soils are inceptisols and ultisols with a pH near 4.0 (Lieberman and Lieberman, 1987). Characteristics of trees >10 cm dbh in the nearby La Selva research station include 80–110 species/ha with a mean height of 30–40 m and mean age of 60–80 years. The forest density is typically 400–530 stems/ha with a basal area of 25–30 m^2/ha, allocated 36% to *gavilan* (*Pentaclethra macroloba* Mimosaceae), 5% to *caobilla* (*Carapa guianensis* Meliaceae), and 3% to *palma* (*Welfia georgii* Palmae), with the remaining 56% of basal area filled by a diversity of tree species, each constituting less than 1% of the total (Lieberman & Lieberman, 1987).

Selection of Capital Objectives

Masonite C.R.'s primary objective is non-declining economic capital, which it plans to achieve by maintaining its solid door sales in the U.S. and by expanding its molded panel door sales in Central America. The 100,000 doors produced annually by Masonite C.R. contribute approximately 1% to the $2 billion annual revenues of the parent company. Masonite C.R. additionally receives government payments of approximately $22/ha/yr in return for suspending logging over a 15-year contract period on a maximum of 1500 ha as a public payment for bundled environmental services of biodiversity, carbon storage, scenic beauty, and water flow regulation and quality. Masonite C.R. is not subject to property taxes, but must pay income taxes, and must acquire government permits to harvest and transport wood.

Implementation of Management Concepts

Masonite C.R. most utilizes the concepts of BMPs/RIL and sustained production to achieve its economic capital objectives, and utilizes to a lesser extent biodiversity conservation, forest protection, and participatory forestry to meet legal and FSC certification obligations. Masonite C.R. only invokes multi-scale planning on a forest management unit scale.

In terms of BMPs/RIL multi-scale planning, Masonite C.R. has made Geographical Information System (GIS) maps based on inventory information which identify property boundaries, designate road and trail locations, identify water bodies (including full retention 10 m riparian buffers required by law on perennial streams with less than 25% slopes), and identify all trees over 60 cm dbh by number. The tree numbers, corresponding to a species list, include red numbers on reserve trees and blue numbers on target trees with shaded parabolas diagramed on the map to show desired felling directions to minimize live tree damage.

In terms of BMPs/RIL, the target trees are marked at dbh and vines are cut during on-the-ground inventory. Bole-only skidding is done with Caterpillar D5 or D6 bulldozers using 200 m cable winches. Skid trails are limited to 5% of total treatment area, while haul roads and landings are limited to 3%.

Sustained production is practiced by Masonite C.R. by removing 60% of commercial stems greater than 60 cm dbh, of which approximately 60% is gavilan, 30% is caobilla, and 10% is a mix of *Vochysia guatemalensis* and *Virola* spp. The silvicultural target is to reduce the total volume of commercial species by half, removing 25–30 m^3/ha during the first entry and 15–20 m^3/ha during subsequent 15-year entries (based on a growth rate of 0.5–1 cm dbh/yr). The volumes are regulated by diameter class to maintain an inverse J curve, where half the volume comes from 60–95 cm dbh classes, and half from 95–150 cm dbh classes to remove a total of 10,000 m^3 annually from 400 ha. Although polycyclic, diameter-limit cutting systems are common in the neotropics, such systems may cause: (1) failure of recruitment due to stratified even-aged stands (Ashton & Peters, 1999) or (2) failure of regeneration due to inadequate light and competition from understory vegetation. Due to paucity of information on regeneration requirements of *C. guianensis* and *P. macroloba* in the literature, we can only postulate on regeneration success based on other managed tropical forests. On the positive side in terms of creation of available growing space, average annual timber removal in the Masonite C.R. forests is four times volumes in Bolivia where regeneration of commercial species has been inadequate (Howard et al., 1996). On the negative side in terms of available growing space, gaps of 50 m^2 (0.005 ha) common in the Costa Rican forests are only one-quarter to one-hundredth the size recommended to ensure sufficient regeneration of true mahogany (*Swietenia macrophylla*) (Webb, 1999). Future monitoring must assess whether the Masonite C.R. forests can support sustained production of commercial grade species via both regeneration and recruitment. Furthermore, uneven-aged silviculture focused on galivan and caobilla may lead to uniformity in tree species and age classes over time (Okuda et al., 2003).

Assessment via Certification and Criteria Categories

FSC certification was pursued primarily to provide a social license to operate, as formalized third-party assessment helps ensure continued access to both timber harvesting in Costa Rica and to consumer markets in the United States. Direct costs of certification in terms of annual audits, are equivalent to \$1/ha/yr. Indirect costs of certification are estimated at \$15/ha/yr, primarily involving data collection and documentation. These indirect costs include, for example, verifying legal chain of custody with bar codes that must be affixed sequentially to stumps, raw timber, and finished wood products. Under FSC certification, contract foresters also conduct periodic supervisory audits that include worker safety practices, rare tree species population counts, standing tree mortality inventories, and riparian buffer width confirmation.

Iterative Review and Revision

The adaptive management mechanism employed by Masonite C.R. involves written reports required after each harvest. Details on tree harvests and road systems from the reports, in particular, inform subsequent management decision-making—such as why trees marked for cutting were retained, or why a section of road needed to be re-located. The iterative decision-making process may be successful in terms of sustained yield and BMPs/RIL: nearly one-third of the forest property is undergoing second entry harvests with commercial yields exceeding the 15 m^3/ha target, and the initial establishment of roads and trails has reduced second entry per-volume harvest costs by approximately one fifth. Future harvests will provide more definitive evidence on whether regeneration is sufficient to meet commercial yield targets, and whether initial roads and trails continue to function as planned.

Many elements of Masonite C.R.'s management, such as its monitoring program for road conditions and sustained yield, were developed over 15 years of trial-and-error modification through external audit findings rather than through deliberate internal planning. Our framework, in contrast, could have assisted Masonite C.R. in strategically aligning itself at inception with practices that target external certification standards and its own economic objectives.

Furthermore, our framework would have flagged weaknesses in four management concepts: implementing biodiversity conservation with structural and compositional diversity in silvicultural practices rather than only guards which deter illegal tree harvesting and hunting of agoutis (*Dasyprocta punctata*), peccary (*Tayassu pecari*), and tapir (*Tapirus bairdii*); implementing protection forestry with targeted culling rather than only passive assessment of mortality rates for commercial timber species; implementing multi-scale planning in terms of coordinated landscape management rather than only forest management unit scale mapping and incidental location near national park buffer zones; and implementing participatory forestry in terms of stakeholder meetings on management and benefit-sharing to meet local community needs rather than only local employment and housing.

Conclusion

Overall, our concepts provide discrete practices for managers to begin to implement the ambiguous concept of SFM. Our iterative framework of selecting capital objectives, implementing practices via management concepts, and assessing outcomes via criteria and PCI categories provides a strategic decision-making process for managers in various forest biomes—regardless of their participation with forest certification—to accomplish explicit objectives for non-declining forest capital. Conversations regarding which forest management practices are genuinely sustainable will be perpetual, due to variances in baseline references and time period, along with spatial variation in substitutability of ecologic capital with economic and social capital. Our framework, however, may help organize these considerations in terms of discrete management practices.

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