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By
M. K. Mahendrappa, C. M. Simpson, and C. T. Smith

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ASSESSING THE EFFECTS OF SILVICULTURAL PRACTICES ON SUSTAINED PRODUCTIVITY: A PROCEEDINGS OF THE IEA/BE WORKSHOP '93

May 16-22, Fredericton, N.B., Canada

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Abstract

During May 16-22, 1993, collaborators of various groups of Tasks VIII and IX associated with the International Energy Agency/Bio-Energy (IEA/BE) project met for the first time to participate in a workshop to discuss different aspects of wood harvesting, biomass production, and related environmental issues of concern. The general theme of the IEA/BE Workshop '93 was to assess the effects of silvicultural practices on sustained productivity. Invited speakers representing different activity groups addressed numerous environmental constraints facing the researchers in their efforts to determine the factors affecting sustained productivity of forest lands and the production constraints facing the foresters who are concerned with maximizing profits. Included in this publication are the papers prepared by the invited speakers, very slightly edited, mainly to ensure uniformity of presentation. The document should be useful to researchers and to some extent to forest managers as a reminder of the complexity of the problems and the need to address them. The ideas and opinions expressed in the papers are distinctly those of the authors and not of the publishers or editors.

Also included in the publication are the abstracts of the posters presented during the IEA/BE Workshop '93 and the list of participants.

Résumé

Du 16 au 22 mai 1993, des collaborateurs provenant de divers groupes chargés des Tâches VIII et IX, dans le cadre du projet de l'Agence internationale de l'énergie et de la bioénergie (AIE/BE), se sont réunis pour la première fois afin de discuter en atelier des divers aspects de la coupe du bois, de la production de la biomasse et des questions écologiques connexes qui suscitent une certaine inquiétude. L'atelier de 1993 de l'AIE/BE avait pour but d'évaluer les effets des techniques de sylviculture sur la productivité durable. Les conférenciers invités, représentant différents secteurs d'activité, ont traité des nombreuses contraintes d'ordre écologique que subissent les chercheurs dans leurs efforts pour déterminer les facteurs qui nuisent à la productivité durable des sols forestiers ainsi que des contraintes en matière de production que subissent les forestiers cherchant à optimiser les profits. La présente publication contient les textes des conférenciers invités, avec quelques légères modifications apportées principalement par souci d'uniformité. Cette publication devrait être utile aux chercheurs et, dans une certaine mesure, aux forestiers, en guise de rappel de la complexité des problèmes et du besoin de les résoudre. Les idées et les opinions exprimées dans ces textes sont expressément celles des auteurs et non celles des éditeurs ou des rédacteurs.

La présente publication contient également les résumés des communications affichées qui ont été présentées au cours de l'atelier de 1993 de l'AIE/BE ainsi que la liste des participants.

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WHOLE-TREE HARVESTING: ECOLOGICAL CONSEQUENCES AND COMPENSATORY MEASURES EXAMPLES FROM SWEDEN

Hélène Lundkvist
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Legislation and recommendations regarding whole-tree harvesting in Sweden are discussed in the context of the impacts whole-tree harvesting has on the ecosystem. Measures to counteract soil acidification from biomass harvesting and leaching due to acid deposition are discussed in some detail.

Present Status in Sweden

The annual energy consumption in Sweden amounts to about 450 TWh. Residues from conventional forestry contribute 60 TWh, as do hydropower and nuclear power, respectively. The potential for forest energy production within the coming decades has been estimated to be twice what is presently generated.

The incentive to increase the use of bioenergy came with the oil crisis in the mid-1970s. After that, the political decision to replace all nuclear power in Sweden by other energy sources by the year 2010 has necessitated research on the potential benefits, as well as the potential negative consequences, of bioenergy. Furthermore, a tax on carbon dioxide emission and government bills to increase recycling of energy and matter in society are steps that have strengthened the position for bioenergy. For a long time, the larger forest owners showed very limited or no interest in exploiting forest biomass for energy production. Rather, the issue was put forward by groups working for conservation of resources, including the use of renewable energy. With such a perspective, wood ash is considered a resource that should not be deposited in waste dumps but be recycled to forest sites. The amount of wood ash that could be recovered and recycled is appr. 150 000 tonnes per year. Intensive harvesting of forest biomass as well as application of wood ash will have an impact on the ecosystem. It will potentially affect productivity as well as other ecosystem characteristics.

Restrictions

Whole-tree harvesting practices, like other forestry practices, are legally regulated by the Swedish Forestry Act, which includes restrictions aimed at providing for sustainable forestry as well as for nature conservation and other public interests.

Apart from pure legislation there are also recommendations on different aspects of forest management provided by The National Board of Forestry. Such a set of recommendations (SKSFS 1986:1) for whole-tree harvesting was released by the Board in 1986 and is now being revised. These recommendations are derived from a site classification system based on soil type and vegetation type descriptions (Hägglund and Lundmark, 1981; Lundmark 1988). Thus, different site types within four climatologically different regions in Sweden have been assigned a recommended maximum biomass utilization during a forest rotation. Some examples, according to the recommendations, are: on fine textured soils in *Vaccinium myrtillus*/herbaceous vegetation types approximately 50% of the felling residues may be harvested in areas subject to early summer drought while on this site type in other areas, all felling residues may be harvested. On the other hand, in most cases, it is recommended that coarse soils, independent of vegetation type, be excluded from any harvesting of felling residues.

However, in a recent survey for The National Board of Forestry and a number of other state boards involved in energy production Rosén (1991) concluded that site adaptation of harvest of felling residues, with a few exceptions is not necessary, while it is important to adjust the compensatory measures according to the specific requirements at each site.

Impact of WTH on the Ecosystem

Soil organic matter and C balance

Obviously, removal of felling residues will affect the flow of organic material to the soil. Concerns about soil organic matter content and its effect on soil moisture conditions was also of major importance when the recommendations and restrictions presented above were formulated. However, in empirical investigations of field experiments we have not been able to demonstrate any significant difference in soil organic matter in the humus layer between conventionally harvested and whole-tree harvested (once or up to three times) treatments (Bengtsson, Olsson & Lundkvist, unpubl.). Model simulations of a Norway spruce forest over 300 years also show small differences, less than 10%, in the carbon pool after whole-tree harvest compared to stem-only harvest (Bengtsson & Wikström, in press).

In the long term a biofuel system, where biomass harvest and production are balanced, will have no net effect on CO_2 emissions. The effects on the net emission of CO_2 from biofuels as compared to that from oil was estimated by Eriksson & Hallsby (1992). They found that for the production of 50 TWh energy per year the net emission from oil would be 80 TgC yr^{-1}, thus 1200 TgC after 300 years, while for bioenergy (in their example, 80% made up from felling residues) it would show an initial increase but stabilize after 300 years on an accumulated emission of 52 TgC.

Nutrient, especially N, availability

For a long time, the major concern with regard to effects of whole-tree harvesting was the removal of nitrogen from sites that were known to be N-limited. With increasing deposition of nitrogen the picture is reversed and whole-tree harvesting has even been considered beneficial for environmental conservation and seen as one way to limit the nitrogen load in areas where the risk for nitrogen leaching is considerable. In southwest Sweden, where the yearly deposition of nitrogen is more than 25 kg ha^{-1}, the nitrogen leaching for an 80-year forest rotation has been estimated to be 120-192 kg ha^{-1} and the nitrogen removal at harvest of felling residues 250 kg ha^{-1} (reviewed by Lundborg (1993).

Soil acidity

The roots of a growing stand release protons in exchange for base cations that are taken up by the trees and consequently the natural process as forest growth proceeds is increased soil acidification. This process is reversed when felling residues or dead trees decompose and base cations are recycled to the soil.

The loss of base cations, whether by harvesting or by leaching from the site, will be accompanied by an increase in soil acidity. Nilsson *et al.*(1982) estimated the hydrogen ion production that theoretically would follow after different intensities of harvest at thinnings and final felling of a fertilized and an unfertilized stand of black spruce. They found that the hydrogen ion production ranged from 0.1 kg ha^{-1} yr^{-1} for an unfertilized stand subjected to stem harvest at final felling, but without previous thinnings, to 1.8 kg ha^{-1} yr^{-1} for maximum biomass use, *i.e.*, whole-tree harvesting at thinnings and final felling, in a fertilized stand. The latter value is of the same order of magnitude as the acidification caused by deposition in highly afflicted areas in Central Europe. These theoretical predictions have been confirmed by field observations. In field experiments with slash removal, Staaf and Olsson (1991) found that soil acidity had increased in plots where slash had been removed and that removal of all slash caused higher acidity than removal of slash excluding needles. Base cation budgets for two representative forest regions in Sweden (Rosén,1989) indicate that some areas in Sweden already suffer from a Ca deficit and that the pools of exchangeable base cations in some forest regions in Sweden will be depleted within one forest generation. Rosén (1988) compared the soil acidifying effects of a number of fuels and concluded that fuels derived from forest products contribute two to ten times more hydrogen ions per unit of energy derived than do oil or coal (53 mmol per MJ compared to 5-27 mmol per MJ). The actual contribution to acidification of fossil fuels may be difficult to compare to that of biofuels since the former produces strong acids with highly mobile anions that will cause acidification of deeper soil horizons and water, while the biofuel-induced acidification to a great extent is due to weak organic acids that primarily affect the upper soil horizon (Rosén. op cit.).

In conclusion, removal of slash is likely to have a significant effect on soil acidity.

Tree growth and ground vegetation

Removal of felling residues has been shown to affect tree growth (cf. overviews in Lundkvist, 1988; Rosén, 1991). Recent results from investigations by Leijon (pers. comm.) from a large series of field experiments from different parts of Sweden show a consistently larger volume increment for treatments where slash has been left on site. It has been estimated that a forest rotation, from planting to harvest, would be delayed 3-10 years by the removal of felling residues.

Studies on the effects of felling residues on ground vegetation are few. Bråkenhielm (pers. comm.) followed vegetation development through yearly measurements after clearfelling of a site with conventional or whole-tree harvesting methods, respectively. He found that slash harvest had a pronounced and long-lasting effect on the flora; heather and lingonberry declined in coverage as well as in frequency while mosses and lichens increased. Olsson (pers. comm.) in investigations 8 and 15 years after clearfelling of a number of sites accordingly found that slash removal had favored mosses, lichens, and narrow-leaved grasses at the expense of bilberry and herbs.

Soil organisms

Effects of harvesting of felling residues on the abundance of important elements of the soil organism community are well documented as reviewed by Lundkvist (1988) and Shaw *et al.* (1990). A number of soil fauna groups are known to be affected by harvesting as well as by increased intensity in harvesting. The most dramatic effect of slash harvesting on soil fauna abundance has been reported for enchytraeids (Lundkvist, 1983) that feed on litter and, therefore, play an important role in the regulation of organic matter decomposition. Also other groups like nematodes and rotifers are affected by harvesting of felling residues (Sohlenius, 1981).

Compensatory Measures

Forest revitalization including liming and wood ash recycling

Measures to counteract soil acidification from biomass harvesting and leaching due to acid deposition include liming and/or recycling of wood ash. In the long term, the only option is to reduce the acidifying emissions. In the short term, however, measures like liming and wood ash recycling have to be taken to improve the critically acute situation of forests and forest soils.

Liming

Liming as a forestry practice is considered for large-scale operations in Sweden as well as in other northwestern European countries. The Swedish Forestry Board has recommended liming for 650 000 ha where mineral soil pH has decreased below pH 4.4. Liming is applied to restore soil alkalinity and build up the buffering capacity to make the soil less susceptible to future acid deposition.

Liming has been practised for a long time in Europe. The first known extensive liming of forests was done in Germany in 1860 (Messmer, 1959). In areas where sulfur dioxide and heavy metal emissions had caused serious forest damage, "Rauchschäden", liming and fertilisation were measures to improve reforestation (König, 1924). From an inventory of old Swedish liming experiments Hallbäcken and Popovic (1985) concluded that for a long time the effect of liming was restricted to the humus layer and the upper 10-20 cm of the mineral soil. The deeper soil layers were affected only in the oldest (68 years) experiment. Liming has been found to affect tree growth by 10% (Andersson *et al.* 1988). On good sites, an initial tree growth decrease after some years was followed by a growth increase while on poor sites the growth decrease after liming may be long lasting. The explanation suggested for the different kinds of growth response involves liming effects on nitrogen availability (Andersson *et al.*, 1988).

Wood ash recycling

Recycling of wood ash from "forest product" fuels to forest soils in general, *i.e.*, also to mineral soils, is potentially valuable for different reasons: most nutrients, except nitrogen, will be recycled to the forest site in a form that will neutralize some of the acidification caused by the growing stand or by deposition. Furthermore, it would solve the waste management problems associated with ash deposits. Application of wood ash has been practised for a long time on peat soils where it has been shown to have a positive effect on tree growth (Silfverberg and Huikari, 1985). Long-term positive effects, in terms of increased tree growth on peat soils as well as increased soil pH 50 years after treatment, were reported by Bramryd and Fransman (1985).

Potential risks connected with wood ash application include pH and/or salt shocks to soil organisms and ground vegetation, heavy metal accumulation in the forest ecosystem and increased nitrification and nitrate leaching.

In experiments and practice where the ash has been applied in its soft untreated powder form, it has been found to cause considerable increases initially (1-2 units) in soil pH and possibly also an osmotic shock due to its high content of highly soluble salts (Bramryd, 1985). The heavy metal content of the wood ash can potentially cause problems; high doses, 30 tonnes per ha, of wood ash in soft form were shown to increase cadmium uptake in the crop (Bramryd, op cit.). However, Silfverberg and Issakainen (1991) reported that after treatment with 10 tonnes per ha of wood ash the cadmium level in forest berries (*Vaccinium myrtillus, V. vitis-idaea, V. uliginosum and Rubus chamaemorus*) did not exceed maximum levels recommended for human intake.

Most, or all, of the negative consequences of application of untreated ash may however, potentially be avoided if the ash is applied in a granulated form. A dose of 3.2 tonnes per ha of such granulated wood ash was applied in recently established field experiments in Sweden. It increased base saturation and pH slightly in the litter and the upper humus layer but there were no drastic changes in soil chemistry in the early phase after wood ash treatment. The abundance of enchytraeids, which are known to be sensitive to changes in pH and ionic strength in the soil solution, were not negatively affected by the granulated wood ash, but the cadmium content in the worm tissue at some sites did increase (Lundkvist, 1991). No short-term effects could be detected on the field and bottom layer vegetation, which was studied in one of the Swedish field experiments where granulated wood ash was applied after nitrogen fertilization (O. Kellner, pers. comm.).

In an amelioration context, granulated wood ash is likely to act as a slow-release fertilizer for most elements. In the Swedish experiments, potassium and calcium increased in the soil solution directly after ash application (H. Eriksson, pers. comm., H. Lundkvist and J. Bergholm, unpubl.) while phosphorus, for example, appears to be released at a slow rate (Clarholm, 1994). There was no effect of wood ash on nitrogen availability or nitrogen leaching in the field experiment (J. Bergholm and H. Lundkvist, unpubl.) while lab experiments showed increased nitrogen mineralization potential after wood ash application (A. Rudebeck and H. Lundkvist, unpubl.). The granulated wood ash did not affect the nutrient concentrations of the needles in the spruce stand in the first 2 years after treatment (H. Lundkvist and U. Rosengren-Brinck, unpubl.). Thus, the effects on soil chemistry and tree nutrient status of moderate doses of wood ash are likely to be minor.

Wood ash amendment to the soil, via changes in soil chemistry and litter quality could potentially lead to changes in the soil organism community and thereby alter the soil profile. For example, changes of mor profiles into more moderlike ones are likely to occur if burrowing earthworms increase or become established as has been shown to be the case at some of the Swedish sites, where only 2 years after ash application, the population of the soil surface-dwelling earthworm *Dendrobaena octaedra* had increased significantly (H. Lundkvist, unpubl.).

Mixed species forestry

The tree species composition of the stand will affect litter quality and the decomposer community, as well as abiotic ecosystem factors like soil physics and chemistry. The effects of plant species in general, not only tree species, on nutrient cycling was recently reviewed by Hobbie (1992). A mixed species forest will have greater diversity not only of tree species but also of other flora and fauna above and below ground. Therefore, from a nature conservancy point of view, it is more desirable than a monoculture. It has also been shown that species mixtures, where none is nitrogen fixing, in a stand could increase production and allow for greater harvests than in comparable single species stands. Recently developed growth and yield models for Norway spruce stands developed under birch shelter in Swedish experiments demonstrated both an increased total production and a higher production of Norway spruce in birch-sheltered stands as compared to pure Norway spruce stands (Tham, 1988; Burkhart and Tham, 1992). Positive effects on stand production of interactions between species have been shown also for other species combinations like Norway spruce/Scots pine, Scots pine/oak (*Quercus petraea*), Sitka spruce/lodgepole pine and Sitka spruce/Japanese larch (Chapman *et al.*, 1988; Brown, 1992; Morgan *et al.*, 1992).

The effects of mixing nitrogen-fixing trees into stands with non-nitrogen fixing trees was reviewed by Binkley (1992). He concluded that, in general, nitrogen cycling was increased by the presence of nitrogen-fixing trees. However, the effects on productivity varied, although in most cases the growth of the non-fixing species increased.

Compared to pure stands of Norway spruce, mixed stands of Norway spruce and birch have been shown to improve soil conditions as regards base saturation and pH in the litter and humus layers in 30-year-old stands in Sweden (P-O Brandtberg, J. Bengtsson and H. Lundkvist, pers. comm.). In the long term, mixing conifers with deciduous trees may lead to the establishment of earthworms in podzols which in turn will affect soil conditions and increase the turnover of organic matter and plant nutrients. Such changes were demonstrated in British investigations of heathlands that had been planted with birch and where earthworms became established and increased their population size (Satchell, 1980 a and b).

Conclusions

The ecological effects of whole-tree harvesting on the forest system are well documented and in some (but not all) cases consistent with the effects that are expected from theoretical considerations. Some (but not all) of the documented effects can be counteracted by application of compensatory measures, such as wood ash recycling. Based on available knowledge, bioenergy systems that include site specific compensatory measures are likely to be sustainable.

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HARVESTING METHODS AND AVAILABLE QUANTITIES IN LIGHT OF ECOLOGICAL CONSTRAINTS

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Abstract

Increased use of forest biomass for fuel means increased loss of soil nutrients, which is of major ecological concern and has led to recommendations about harvesting constraints. This paper discusses how ecological constraints affect available volumes of wood fuel and harvesting methods, and details how to reduce nutrient losses by adjusting methods and techniques. If it is necessary to compensate for nutrient losses, ash recycling is an ecologically sound model. However, the main cause of the nutrient imbalance is air pollution and acid rain resulting from the use of fossil fuels, causing nutrient leaching and damage to streams and lakes. Therefore, environmental effects of increased use of wood fuels must be viewed in a broader perspective and in relation to traditional energy sources.

Key Words: acid rain, ash recycling, biofuel, environment, nutrient compensation, wood fuel.

Introduction

There are many good reasons for increased use of wood for energy production. Some of the stronger arguments for wood fuels are that they are renewable, environmentally preferable, and indigenous, they promote regional economy, and they will play a key role in sustainable development. With a proper ecological-economical evaluation, wood fuels might also be or become a cheaper energy resource than fossil fuels (Lunnan and Moen, 1991).

However, more intensive use of the forests also implies increased removal of nutrients and a heavier load on the ecosystem. Therefore, studies of ecological effects have been included dating from the start of the IEA bioenergy program and as well the national Swedish program, in which I have participated for more than 15 years.

In my view, one of the main goals for ecological research within IEA is to provide advice and recommendations for harvesting of wood fuels and to assist in the creation of energy supply systems that are not ecologically *unacceptable.* It may sound provocative and I do not expect to get unanimous approval from the ecologists, but I want to stress that it may be more important to avoid irreversible catastrophes than to search for the desired optimal solution. The reason is that our present energy systems are far from perfect and a small improvement is better than no improvement at all.

A substantial complication is that many forest ecosystems are already so heavily environmentally loaded from air pollution that even moderately increased use may have negative effects. Consequently, wood fuel use may be severely restricted by ecological constraints. However, all types of wood fuels are not affected. Large volumes come from low quality stemwood or by-products etc., which can be used without increased nutrient removal. In addition, there are technical or methodological means to reduce the ecological effects or to compensate for the loss of nutrients.

Another important factor when evaluating ecological[1] or environmental consequences is the perspective or system boundaries. The result of environmental evaluations quite often depends on the chosen system boundaries. The environmental effects of wood fuels do not end until combustion and waste disposal and it is nec-

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[1] I use the word "environmental" when referring to the environment in general, while the word "ecological" usually refers to only one

essary to broaden the evaluation to include more than just the forest soil or the forest ecosystem.

As an "environmentally concerned technician" I give you my view, based on Swedish conditions, of ecological problems and how they may affect harvesting and use of wood fuels.

The Ecological Problem

We are already experiencing an ecological problem in parts of southern Sweden, without any whole-tree harvesting. The problem is air pollution and high deposition of sulphur (S), nitrogen (N), and acid rain (Hettelingh *et al.*, 1991). Acid rain causes a release of nutrients (base cations) that are essential for forest growth, and which may leach out from the forest ecosystem into streams, ground water and other ecosystems. If soil acidity becomes too low, below pH 4, growth can be negatively affected. Ordinarily, nitrogen is the growth limiting nutrient; some deposition will increase growth but, as a result, will also increase the uptake of other nutrients. In any case, nitrogen deposition is well above the critical load and more than can be assimilated by the vegetation and the soil; this situation is often described as "nitrogen saturation". Nitrogen leaching has been most evident in agricultural areas but increased leaching has also been observed from forests, especially after clearcutting (Rosén, 1982).

As long as there is a vital forest cover, most nitrogen deposition can be accumulated, but the problem becomes acute after clearcutting. For the first few years, there is not enough vegetation to assimilate the deposition and, additionally, large amounts of nutrients are released from the logging residues and leaching becomes considerably higher than what is normal after clearcutting. The leaching and increased supply of nutrients to streams have been of such magnitude that not only the streams but also parts of the sea have been seriously damaged. Therefore, deposition and nutrient losses have wider implications, beyond the effects on the forest soil and growth.

The basic problem is deposits of acid rain, sulfur, and nitrogen well above critical loads, which causes leaching and nutrient losses. Increased growth also contributes to an imbalance among available nutrients. This ecological problem is the result of the use of fossil fuels and actually has nothing to do with harvesting of wood fuels. But, wood fuel harvesting will increase the loss of nutrients even further, and can be "the straw that breaks the camel's back." Under normal conditions, without excessive air pollution, the ecological effects of increased biomass harvesting are generally believed to be moderate, except on poor soils. This holds true for for middle and northern Sweden.

One way to reduce nitrogen leaching and loss of nutrients is to harvest the logging residues for energy production and then return the nutrients when there is a growing forest stand that can assimilate them (Wikström, 1992). The nutrients could either be returned in the form of wood ash or fertilizer. Nitrogen is released as a gas at combustion but all other nutrients remain in the ash. This is good because it is undesirable to add more nitrogen to the concerned areas. This method is a possible way of "cleaning" nitrogen-saturated areas, preventing harmful nutrient leaching to streams, and maintaining storage of essential nutrients.

Present Ecological Constraints

Sweden's present ecological "constraints" date back to 1986 when the National Board of Forestry issued *recommendations* for the removal of biomass, in addition to stemwood (Skogsstyrelsen, 1986). The objective was to provide guidelines for how much and where biomass could be harvested without significant effect on the future production. The recommendations have three levels for removal of biomass; nothing, about 50% or most of the biomass, depending on felling form (thinning or final felling), geographical area, and forest/soil type. In essence, the areas where biomass harvesting should be avoided include: areas of nutrient poor soils; dry areas with coarse soils; and areas affected by acid rain. Furthermore, the recommendations state that biomass harvesting should only take place once during a rotation and there are no constraints in first thinnings.

Adjustments to these recommendations are being discussed. One of the main objections is that the air pollution, and its implications in southern Sweden, is more severe than was originally recognized and the constraints should be more strict. Another is that, with regard to compensating for nutrient loss, in general only areas with little organic material need to be protected, and the constraints could be more liberal than at present.

Different Types of Constraints

Ecological constraints on biomass removal can, in principle, be of different types and affect harvesting differently. At least four general types can be distinguished:

No removal on certain (poor) forest-soil types. This constraint has negligible practical significance as long as only poor soils are included. Those areas are of little interest because volumes are low and harvesting costs are consequently higher.

Limitations on the degree of removal. This is the only type of constraint that has direct technical implications, *i.e.*, the technique has to be adopted or developed. It is possible to limit removal of biomass (excluding the stem) to 50-75% but given the lower degree of recovery it is not economically attractive. Even now, 50% removal is at the lower end of the scale. It means that active measures must be taken to leave material, which reduces volume significantly and increases costs. (I very much doubt that leaving only the tops is enough to reduce removal to 50% in thinnings.) Limiting to a corresponding percentage of nutrients instead of biomass would be easier to comply with.

Removal limited to once during a rotation. This is an important quantitative restriction that complicates planning. Registration of activities in private forestry is poor, treatment areas change and the best choice between harvesting the biomass in thinnings or final felling will probably change several times during a rotation. Considering the long timespan between cutting operations, there is a risk that this restriction might be forgotten or not taken seriously.

Ash recycling or nutrient compensation required on certain areas. This means higher costs, which may be partly compensated for by greater freedom at harvesting. Ash recycling is not yet practical, although it seems to be quite feasible.

The type of constraints introduced will certainly affect harvesting methods and techniques. Areal restrictions will interfere with the desire for standardized methods. Limited removal will require flexible methods. Most restrictions will affect costs and ability to harvest biomass. The question is how to impose ecologically necessary constraints with the least effect on harvesting possibilities. I do not have the final answer, but I am convinced that, together, harvesting people and ecologists can find solutions.

Harvesting Methods

Practically all roundwood harvesting in Sweden is done with shortwood systems where the logging residues are more or less concentrated in heaps along and on logging trails. For harvesting wood fuels, there are basically two different methods, depending on felling form.

On clearcut areas, logging residues are extracted in a separate operation after conventional harvesting. When residues are going to be harvested, the operating method of the harvester is slightly modified, in order to concentrate the slash in larger heaps and facilitate extraction (Wigren, 1992). The heaps of tops and branches, or more correctly the easily collectable part of the heaps, are picked up by forwarders or chipped directly with chip-harvesters (forwarder with chipper and transport bin). Unchipped residues are then stored in larger piles on the cutover or at the roadside for later chipping. Residue collection is done in the spring/summer, after the clearcutting, when the residues are dry and chipping is done later in the fall or winter, when there is a need for heat. The methods are very flexible and the degree of removal does not depend on technology but is controlled by the operator and can be varied within the same site according to local conditions. Naturally, all biomass can not be removed when collected from the ground. Maximum removal is about 70% but usually lower for reasons of efficiency (Danielsson, 1991). It is simply too costly to spend time on smaller, scattered quantities. (Skidding is not practised in Sweden, but would reduce removal to approximately 60-70%.)

In thinnings, tree section systems or whole-tree systems are used to harvest wood fuels, without any storage in the forest. These methods are less flexible and there are fewer opportunities to adjust the degree of biomass removal. A smaller amount of needles, twigs and branches will always break off and be left behind on the ground at harvesting and maximum removal is estimated to be 80-85%. If it is desirable to leave more material, removal can be limited to about 50% by leaving tops and smaller trees. Another way to reduce removal is rough partial delimbing, which can be done by a variety of technologies, *e.g.*, chainsaw, flails, loosely set delimbing knives, etc.

Leaves, needles, and twigs are less desirable (less valuable) tree components in wood fuels, because of problems both in terms of storage and combustion. This circumstance has been an equally important deterrant, in combination with ecological aspects, to some minor development of methods intended to leave a greater proportion of needles and other fines in the forest. Active measures to separate fines are not practised but minor adjustments of the technique and operating methods are made. Chippers are equipped with feeder tables that let fines (as well as sand, etc.) through and because of drying until summer a greater proportion of the fines will be lost at collection and in the consecutive handling (Lehtikangas and Lundkvist, 1991).

In general, it is more difficult to make ecological adjustments in whole-tree systems with processing (chipping) or storage at roadside than in systems with separate wood fuel harvesting. An active process is needed to leave more of the biomass in the forest, because residues of fines from storage or processing fall in the wrong place and the quantities are too small to be easily returned. The situation would be the same for North American systems with roadside processing if the slash, now left at roadside, was recovered for fuel.

Wood Fuel Volumes

Bioenergy accounts for approximately 15% of Sweden's total energy supply (435 TWh/year). Close to 50% of the bioenergy is solid wood fuels and another 45% is lignin, in the form of digester liquids from pulp and paper industries (accounted for as bioenergy but not as wood fuel). The present use of wood fuels is about 30 TWh per year (1 TWh = 3,6 PJ, 10^{15} Joule). Slightly more than 50% comes from industrial by-products (bark, sawdust, etc.), about 8-9 TWh is stemwood and an estimated 4-5 TWh is logging residues.

There is great potential for increasing the use of wood fuels — if the economy and ecology permit. Not all industrial by-products are fully utilized, but the large potential sources are logging residues and stemwood in the form of underutilized growth. Growth far exceeds annual felling and industrial need for wood is expected to remain constant for the foreseeable future. According to the latest calculations, based on a model that maximizes sustainable harvest, it would be possible to increase the annual harvest (of stemwood) immediately by 25 million m^3 per year (from 63 to 88 million m^3) and gradually further increase in the coming decades (Jordbruksdepartementet, 1992). If this potential is used for energy production it would correspond to about 50 TWh per year, from the stemwood alone. One implication is that wood from final fellings alone can supply the total industrial wood demand; industry is not especially interested in wood from thinnings, because of higher costs and generally lower quality in most respects. Therefore, it is highly likely that a large proportion of the thinnings will be for wood fuel, or that an increased market for wood fuels is necessary for continuing our forest management by thinnings, aimed at producing good quality saw logs.

Because of demand for higher wood quality from pulp and paper industries, partly as a result of less chlorine bleaching, a few million m^3 of rotten or decayed wood per year is expected to be used for fuel instead of for industrial purposes. This volume is, however, interchangeable with a corresponding increased harvesting.

The supply of standing timber potentially available for wood fuels is not directly affected by ecological constraints. There are no restrictions against harvesting all stemwood, but since the most likely and economic way of harvesting this fuel potential will be some kind of whole-tree harvesting in thinnings, ecological constraints can impose more expensive harvesting methods that will reduce the opportunities to exploit the full potential.

The other large wood fuel source is logging residues. The total quantity is about 68 TWh per year (approximately 14 million dry tonnes), which would increase by approximately 50% if the full potential of roundwood were harvested. Of these 68 TWh, about 56 TWh are available for harvesting with today's ecological recommendations. More than 60%, or 36 TWh, of what is available for harvesting are logging residues from final fellings and the remaining 20 TWh are residues from thinnings. Taking into account that the removal is restricted to once during a rotation, the 36 TWh per year (7.3 dry tonnes) from final fellings is regarded as the ecologically available volume. Also including losses of biomass in connection with harvesting and technical aspects (but not economic), the potential is estimated to be 20-25 TWh per year, Table 1.

Table 1 Annual quantities of logging residues, TWh

Availability	TWh/year
Totally	68
Ecologically available	56
in final felling	36
in thinning	20
Technically available	20-25[1]

[1] (one harvest per rotation)

Without going into detail, it is obvious that Sweden has the potential to increase its use of wood fuels by two to three times and that the ecological constraints are important both for physical and economic availability.

Effects of Ecological Constraints

As mentioned, changes to the present recommendations for biomass removal have been discussed. In the study of harvesting potential and volumes of logging residues, the effects of alternative ecological constraints were also calculated (Jordbruksdepartementet, 1992). The percentage of the forest area available for residue harvesting was calculated for three different constraint levels:

1. Present recommendations.
2. Future constraints *with* nutrient compensation.
3. Future constraints *without* nutrient compensation.

The future constraints are based on more recent knowledge about the environmental situation and the ecological effects of biomass removal. They can be regarded as a likely result of a revision of the present recommendations. However, it is pointed out that even these "new" constraints may be too liberal. Furthermore, the recommendation about removal only once during a rotation has been disregarded.

Overall in Sweden, the effects of the new constraints are relatively small (Table 2). Without compensating for nutrient loss, the available area will be reduced from 82% to 73%, compared to present constraints. In southern Sweden, where the environmental load is higher, the effects are much more pronounced. The available area will decrease to only 50% without nutrient compensation, but can on the other hand increase to almost 90% with nutrient compensation. Southern Sweden is perhaps the most important part of the country in regard to wood fuels. This region is a small part of the country in area, but it has about one third of the forest resources, a high population, high demand for fuels, short transport distances, and the most developed market for wood fuels.

In a previous study of wood fuel volumes in southern Sweden, the average, technically feasible removal was 70% of the ecologically available volume (Danielsson, 1991). Applying the new constraints, this means that it is possible to harvest about 60% of the volume, if nutrient losses are compensated. Without nutrient loss compensation, it would be possible to harvest only 35%, before any economic considerations.

Table 2 Area available for harvesting at different constraint levels

Constraint level	Available area, in %	
	Totally	**Southern Sweden**
Present	82	70
Future *with* nutrient compensation	86	88
Future *without* nutrient compensation	73	50

Nutrient Compensation — Ash Recycling

There are basically two methods to replace lost nutrients. Fertilizing with commercial fertilizers or ash recycling. Special fertilizers, produced for nutrient compensation are commercially available and have the advantage of a constant and controlled composition. They have a nutrient content that is about the same as in pure wood ash, except for some additional micro elements. The only disadvantage is that we create an unnatural production system if we use artificial fertilizers.

Ash recycling is a more attractive alternative as it creates a more natural production system. Currently, the ash is a waste product dumped in landfills, an operation that adds a few tenths of a percent to the fuel costs. Ash from wood fuels contains all the natural nutrients of the biomass, except nitrogen, and is an excellent product for nutrient compensation. Studies and practical tests of ash recycling are well under way and recycling seems to be quite a feasible method without major technical problems.

Before spreading, the wood ash should be pelletized or granulated to avoid dust and health problems, to facilitate spreading with helicopter or tractor, and to prevent a too quick release of nutrients. Dry, previously unmoisturized ash has natural binding properties and can be granulated by only adding water. Otherwise, complimentary binders can be added and a mixture with cement powder will produce good strong granules (Falk, 1992).

Of great importance for both the economy and the biological result is the quality of the ash, which to a great extent is decided by the combustion and handling (Hakkila, 1986). Wood ash should not be mixed with other ashes, because other ashes usually contain more heavy metals and will contaminate the wood ash. A good combustion that leaves little unburnt coal is necessary. The natural ash content in wood fuels varies between 1-4% depending on tree species and components, as does the nutrient composition, but the amount of impurities such as sand and unburnt coal can be even higher. This means that more material has to be handled and the costs will increase in proportion to the amount. Residual charcoal powder is also a fire hazard and reduces the self-binding properties of the ash. Water is often used to cool off the ash and to reduce dust problems, but the nutrients are easily soluble and will leach out in the handling process, which is why as little water as possible should be used.

The cost for ash recycling is uncertain but is estimated to be about 400-700 SEK (1 USD = 7.3 SEK) per ton ash. If the ash quality is good, recycling would add a small percent (2-5%) to the fuel price for the user. However, for the forest owner residue harvesting is only marginally profitable and it is questionable if it covers the extra costs of ash recycling.

In most cases, it would be desirable to add more nutrients than have been removed with the wood fuel to restore the nutrient balance of the soil and to counteract the effects of air pollution. A complication is the question about responsibility: who is responsible, who shall pay, and for what? At the moment this is partly a political question; forest owners claim that they should not pay the full costs for restoring damages caused by general air pollution.

Perspective on the Environmental Issues

It is important to have the right perspective on environmental issues (Ekvall, 1992). From a strictly soil nutrition perspective a more intensive use of the forests for energy production can have negative effects. But, if the whole energy production system is taken into consideration and in comparison with the alternative of using fossil fuels, wood is generally the environmentally best alternative. The results of environmental evaluations often depend on system boundaries and it is necessary to broaden the evaluations to include not only the forest soil but as many aspects as possible, like water, lakes, air, vegetation, etc.

The environmental effects of wood fuels do not end until combustion and waste disposal. Emissions from harvesting machines and transportation are examples of often forgotten but important effects of wood fuel production. Energy producers often regard what is coming out of the smoke stack as the only environmental effects, when the whole system in relation to the alternatives must be considered.

The time frame is also important. Over the short term, increased biomass removal might be unacceptable, but in the long term we should, or will have to, base a larger proportion of the energy production on this renewable resource. Drastically expressed, we have to ask ourselves: should the forests be a filter and a dump for pollution from fossil fuels or should forest production be used to reduce the pollution.

Methods exist that claim to handle questions about environment, economy and sustainable development (Costanza, 1989). These methods, *e.g.*, energy accounting, energy analysis, environment impact assessments, position analysis, *etc.*, are connected to the new discipline "Ecological Economics," which can be defined as the study of the interface among ecology, economics, and social sciences. Some methods are under development and may not be fully scientifically accepted but they seem to be very interesting alternatives for environmental evaluation.

Conclusions

Briefly:

- In future, it is desirable and environmentally preferable to base a larger proportion of our energy production on renewable, sustainable resources like wood.
- The basic ecological problem is air pollution and acid rain from the use of fossil fuels, which causes nutrient loss and leaching.
- Not only forest soil but also streams, lakes and other ecosystems are negatively affected by nutrient leaching.
- Intensive use of forests and inappropriate harvesting methods can aggravate the loss of nutrients.
- Too strict ecological constraints can be difficult to comply with and can be a severe setback to the use of wood fuels.
- To a certain degree, there are good opportunities to adapt harvesting methods to ecological needs and it should be possible to find ecologically acceptable solutions.
- A large part of the potential wood fuel volume in Sweden is unutilized growth of standing timber, and is not directly affected by ecological constraints. But, the most efficient harvesting methods are whole-tree harvesting systems, which are affected.
- Ash recycling can be one way of preventing harmful nutrient leaching and maintaining the storage of essential nutrients in "nitrogen-saturated" areas.
- A wider perspective on the environmental effects of wood fuels is necessary. Not only the forest soil but also water, air and the total environment — in relation to alternative energy production, should be included.
- Methods from Ecological Economics, together with a good basic knowledge, might be useful for broad environmental evaluations.

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LOGGING STRATEGIES FOR COMPLYING WITH ENVIRONMENTAL REGULATIONS UNDER ADVERSE WEATHER CONDITIONS

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Abstract

Environmental regulations are nothing new to loggers and logging activity in the southern United States. Some laws, such as Virginia's seed tree law, which specifies minimum standards for restocking, have been in place since the 1950s. The drive for more intensive regulation began in 1972 when Section 208 of the Federal Water Pollution Control Act required that pollutants entering the nation's waters be controlled at the source. Most states developed sets of guidelines for forest activities ranging from harvesting to wildfire control known as Best Management Practices (BMPs). Compliance with the guidelines is voluntary, but the operation can be shut down and the operator fined for any activity that results in contamination of a water course or serious abuse of the site. The last 2 years have been among the wettest in recent memory and have served as a laboratory for compliance strategies. Loggers working in sensitive areas have moved to wider tires and high-flotation equipment. Increasing use of logging residues to strengthen skid trails, landings, and truck roads is expected, decreasing the by-products available for energy production. Operations in hardwood forests, which yield the largest volumes of forest residues, are coming under increasing scrutiny. Consuming mills are allowing larger inventories to reduce the necessity of operating under severe conditions. Three primary operating strategies are emerging: (1) maintain a large number of tracts in progress and move between them as weather permits or demands; (2) be prepared to stop operations when conditions become marginal and then capitalize on any production opportunity that presents itself; or (3) continue to operate to the limit of the regulations. System characteristics of mobility, flexibility, and elasticity are becoming increasingly important.

Key Words: harvesting, contractor, rutting, BMPs, SMZs, elasticity, mobility, cost, landowner, environmental

Introduction

Environmental regulations are becoming increasingly entangling for production forestry everywhere in the world. The southern United States is no exception. The issue becomes really interesting when one remembers that politics is one of the top three sports in the region, right in there with college football and stock-car racing. The environmental restrictions will affect all forest products, commodity or amenity, solid wood, fiber, or energy.

Before proceeding too deeply into the subject, it is perhaps useful to spend some time on a non-technical discussion of the various types of environmental constraints that are arising across the region.

Commercial forest land in the southern United States is largely (91%) privately owned, 18% of which is industrial ownership. Public ownership of all types comprises the remaining 9%. The original timber was fully exploited by the 1930s, leaving some stands of virgin timber in industrial reserves and in national and state parks across the region. The area is completely settled. Even the most remote regions of the Smoky and Ozark Mountains have been populated since the mid-19th century.

The region has become urbanized. A majority of the population lives in centers that fall broadly into three bands:

1. Coastal cities — Norfolk, Wilmington, Charleston, Savannah, Jacksonville, Mobile, New Orleans, and Houston.
2. Cities on the fall line — Washington, Richmond, Raleigh, Columbia, Augusta, Macon, Columbus, Montgomery, and Jackson.
3. Inland cities, often complexes of cities — Lynchburg, Danville, Roanoke; Greensboro, Winston-Salem, High Point; Charlotte-Rock Hill; Greenville, Spartanburg; and Atlanta, Birmingham.

The American taste prefers scattered, single-family housing over the compact and structured styles of Europe. Consequently, each of these population centers is surrounded by a band of urbanites in a rural setting. The depopulation of the rural areas has slowed but is still taking place. These urban populations find it difficult to distinguish between privately held and publicly held forests. They are less accepting of practices such as timber harvesting and more willing to abridge private property rights in pursuit of what they see as necessary efforts to protect the environment.

The pressures to convert the National Forests from production to amenity forestry is expected to put added pressure on the region for the production of both solid wood and fiber products. Ecologically, a pine stand planted in the 1960s on a cotton field that had been under cultivation for a century or more lacks the complexity and allure of old-growth timber. So production forestry from plantations enjoys a broader acceptance.

This does not mean that environmental concerns can be ignored or that the pressure will not increase over time. Challenges will be mounted for any land-use practice; forestry will not be an exception. The challenges are taking several forms. For simplicity, let's segregate these into four broad categories:

1. Obstructionist.
2. Endangered species.
3. Wetlands.
4. Water quality.

Obstructionist challenges are among the most unpredictable. They often use environmental arguments and reasoning in an attempt to control forest practices on private lands for reasons that have little to do with the environment *per se.* Root causes are commonly 1) general resistance to change; 2) a desire to preserve off-site amenities such as vistas, screening, or shade that are considered to increase the value of adjacent property; and 3) an evangelical belief that any tree cutting is wrong. These challenges may take the form of tree-cutting ordinances, attempts to get injunctions to stop an operation, or assured enforcement of any applicable regulation to the utmost. These practices have led several states to consider and pass "right-to-practise" legislation, granting landowners the right to practise forestry.

A second and more pernicious level of challenges to harvesting comes from applications of broadly based federal and state legislation. Probably the best known examples of this are the lands being withdrawn from production under the Endangered Species Act. The Red Cockaded Woodpecker is the Spotted Owl of the South, although other species can serve equally well as necessity arises.

The legislation has the potential to become the Armageddon of economic use of natural resources. The Act covers all species, including one-celled plants and animals and, as the Spotted Owl controversy demonstrates, the Act can be stretched to cover sub-species as well. It is likely that a skilled taxonomist coupled with extensive lobbying power could identify a unique sub-species of protozoa or better occupying any site on earth.

The sixth reauthorization of the Endangered Species Act was due October 1, 1992, but has been delayed. There is hope for legislation that more equitably balances the requirement of species conservation and the economic and social needs of the human community.

Wetlands legislation is particularly entangling. Even the definition of exactly what constitutes a wetland is under intense discussion. Forestry enjoys many exemptions, without which many silvicultural practices could not be undertaken. Wetlands are of particular interest to the southern forest industry; the better pine and hardwood sites fall within the current definition of wetlands, and the ability to keep these sites in production depends on the ability to retain these exemptions. This legislation is also open to revision.

The bill that has created the greatest stir in timber harvesting has been the Federal Water Pollution Control Act. The Act, passed in 1978, authorized the Environmental Protection Agency (EPA) to require individual states to develop Best Management Practices (BMPs) to prevent or reduce nonpoint source pollution to achieve water quality goals. A BMP has been defined by the EPA as *"a practice or combination of practices, and appropriate public participation to be the most effective, practicable (including technological, economical, and institutional considerations) means of preventing or reducing the amount of pollution generated by nonpoint sources to a level compatible with water quality goals."*

Each state has followed the letter of the law and has put its own set of BMPs in place. These do, however, share a similarity of content, construction, and even comma placement that indicates that large sections of the manuals were copied from those of other states, often with only passing regard to the match between the text and the topography and practice within the target state. BMPs for harvesting address: pre-harvest planning; haul road, skid trail, and log deck construction and maintenance; streamside management zones; and tract closure. Other BMPs cover the full range of silvicultural practices, controlled burning, and even grazing of cattle in woodlots.

The BMPs are voluntary in most states, which means that no formal structure is in place to ensure that each provision is followed, but any problem arising from failure to follow the recommended practices can result in prosecution. For the most part, BMPs are common-sense recommendations and include those things good loggers were already doing without legislation. The existence of the BMPs levels the playing field, forcing the logger who attempts to cut costs by cutting corners to play by the same rules as everyone else.

The guidelines also cause the better loggers to forego opportunities that they might have otherwise undertaken. The impact is especially important to forest energy production. Most of the energy wood-harvesting operations currently active in the region use hardwoods from low-lying lands or on steep slopes. Both land forms require special care under the BMPs. Adoption of these guidelines will also require increased use of residues for road and trail pavement, filtration, and other uses, thus reducing the availability of residues for fuel.

Two of the more controversial recommendations are those for streamside management zones and rutting. Streamside Management Zone (SMZ) recommendations restrict logging in a band ranging from 16 m either side of a warm-water stream flowing through relatively flat terrain to 77 m on either side of a stream serving a municipal water system flowing through steep terrain.

Removals within these bands should leave at least 50% of the crown cover and 50 ft^2 of basal area in place. The forest floor must be left undisturbed and any harvest litter must be removed from the streams.

The first problem arises in defining exactly what constitutes a stream. Perennial streams, those with a constant flow, are easily identified and should be protected. Because of the topography, geology, and weather across the region, there is a second echelon of water courses that flow irregularly. Attempts are being made to differentiate intermittent streams (those that flow continuously for an extended period of time, weeks, or months, and would require the same protection as a perennial stream) from an ephemeral stream (one that flows only after heavy rains, during snow melt, or periods of high water tables and then dries up). These ephemeral streams require limited or no protection.

These distinctions are relatively easily drawn in the uplands, where much of the streamflow originates from springs or rock outcroppings. The distinctions become murky as one moves toward the coastal plain. A perennial stream during one weather cycle may be intermittent during the next. Stream boundaries are not well-defined and the question becomes — "50 feet from where?" The problem is acute in the bottomland hardwood forests along the coast, typified by braided stream channels. Loggers, wood procurement foresters, and consultants are doing their best to follow both the letter and the intent of the BMPs, but they recognize that what is permissible and acceptable today could be considered a violation tomorrow.

Even though harvesting is permitted in Streamside Management Zones, most contractors stay completely out of them. Crossing an SMZ is permissible if the crossing is protected by logs or if culverts are installed. Crossing improvements must be removed immediately after the harvest on all but permanent roads. Most loggers prefer skidding around the SMZ if at all possible. The risk of being cited for disturbing the forest floor, or being required to remove debris, both natural and man-made, from the stream is usually greater than the value of timber.

Landowners are just beginning to realize that these costs are not being passed forward to the industry and consumer but are returning to the land. A recent study in South Carolina found that SMZs are removing large amounts of private property from commercial forestry. Estimates were that aggressive interpretations of the regulations could result in the removal of areas ranging from 10% in the mountains to as high as 50% in the lowland swamps. The commercial value of timber will go to zero, which is bound to distress landowners, who will in turn petition for tax relief, which will distress local governments dependent on *ad valorem* taxes for their revenues.

Rutting restrictions are the second area of concern with the BMPs. Most BMPs contain some language about rutting, usually in a form that specifies the maximum depth and length of rut the contractor can leave. Again, interpretation becomes important, especially how and under what soil-water conditions the rut is measured and whether closed end ruts constitute a threat to water quality on- or off-site.

The greatest concern is knowing where the boundaries lie between acceptable and unacceptable practice. The BMP guidelines are written in very general terms to cover an entire state. Timber harvesting is extremely localized, and the application to that spot requires interpretation, adjustment, and, often, compromise. A statement as simple as, "Harvesting should be halted when water is flowing over the surface of the tract," while appropriate for the uplands, will effectively halt timber production in black river bottoms. Adaptation of the broad guidelines to local conditions is now being done by "gentlemen's agreement."

Industry Reaction

Logging contractors have, for the most part, adopted a positive view of the BMP process. The better contractors were voluntarily following most of the practices before the guidelines were put in place. The adjustments for full compliance were relatively easy. The problem has been complicated by the regional climate entering an extremely rainy phase just as the revised guidelines were being published.

Loving (1991) found that over-capacity in the logging force was a significant problem during the period of 1988-1990. The contractors he surveyed were losing from 15-25% of their production capacity due to quotas — the markets' restricting the amount of wood they would buy or accept. LeBel and Stuart (1992), in a similar survey for the 1991-1992 period, have found a similar level of loss, but the loss is due to weather.

Contractors have become much more cautious about wet-weather operations. Many have or are in the process of re-equipping to allow extended operations on wet or soft soil. This usually involves going to wider, or dual, tires on skidders, excavator-based feller-bunchers, and the purchase of wooden mats for building temporary roads. Residues are being used to pave skid trails, landings, and other "soft spots" on the tracts. Previous estimates of potential volumes available for energy or other uses will have to be revised downward as this adaptation expands.

Contractors are altering their operating strategies as well. Figure 1 (not supplied) shows the pattern of weekly deliveries for a contractor from 1989 through 1991. Hurricane Hugo, which hit the area in which this contractor operates during week 90, also tended to make a major change in operating strategy. He lost 41 workable days during 1989, 20 days to weather, 21 to quota. During the most recent year, his days lost have increased to 75, most due to weather.

As the pattern shows, he has adopted a conservative operating strategy during the second half of the period. His crew will not go out unless there is a very good chance that they will get a complete day's work. He feels that the risk of BMP violation on top of the additional wear and stress on his equipment operating in marginal conditions mitigate against operating. He has purchased wide tires, an excavator-based feller-buncher, and mats. These have probably allowed him to increase his ability to operate from 100 to 140 days over the last year.

He does attempt to take maximum advantage of days when he can operate. In 1989, his goal production was in the range of 400 to 450 tons per day, which lay close to his maximum for the period. In the past year, 400 to 450 tons per day has become the median production for those days when he was able to work. His distribution of days lost to rain shows two distinct populations: one with a mode of 50 loads, representing those days when he was rained out during the work day; and a second with a mode of 425 tons, representing those days when the crew did not work. His maximum production has been as high as 675 tons per day. The operation is considered upwardly elastic. Given an opportunity, the job can produce wood at levels close to twice its normal level of production for periods of up to a week. Upwardly elastic jobs usually have poor downward elasticity. In this instance, he does not go to the woods unless he can produce at least 300 tons per day.

A second contractor, working in the same area as the one above and contracting with the same company, has adopted an entirely different strategy. He tends to put a crew in the woods any day he can and take the production losses as they occur. He lost only 25 days of production over the same period in which the first contractor lost 75 days.

His modal productivity was around 450 tons per day, but the variability was much greater, ranging from 175 to nearly 900 tons per day. He had invested heavily in new equipment to meet the BMP requirements, wide-tired skidders, tracked feller-bunchers, and the payments necessitated maintenance of his cash flow. His loss pattern shows a high frequency of partial days lost. He also maintains a great upward elasticity.

Logger 306 represents a different strategy. Working in the Sand Hills region of South Carolina, where the forests are usually found on deep, well-drained sands unsuitable for shallow-rooted agricultural crops, rain generally impacts his operation by making access roads impassable. He may have five or six tracts "open" at any one time and can move between them as weather demands. A high-ground tract located on a high-standard road is as good as gold, to be worked only in the worst of conditions. A tract on several miles of clay road is worked whenever weather permits.

This contractor moved his operation 39 times in 39 weeks. This minimized his losses to rain and even the combined losses due to rain plus moving generally were less than three loads. This system's elasticity is less than that of the other two. The operating area and his operating strategy do not require the extra capacity. These savings in excess capacity must be balanced against the cost of keeping the tract inventory necessary to make this operating strategy work.

Costs

What is the cost of these heightened environmental considerations? No one knows for certain — the process is still in the "shake-out" phase — but some figures are becoming available. A recent survey in South Carolina estimated that protecting Streamside Management Zones added roughly $0.25 US per ton to the cost of logging in the form of locating and flagging tract boundaries and taking additional care during the harvest itself. The additional roading standards were considered to add another $0.25 US per ton to logging costs in excess of the productivity gains realized from better road quality.

In addition to the $0.50 US in direct operating costs from above, the contractors and wood procurement personnel estimated that BMP compliance would cause the contractor to lose 30 operating days per year that would otherwise have been worked. The average cost for a lost day for an operation of this size equipped with environmentally benign equipment is $2,900 a day. The contractor is faced with $87,000 per year, or $1.74 per ton, that he must recoup from operations, bringing the total increase in operating costs to about $2.25 US per ton.

Wood-consuming industries are accruing larger inventories, both of cut timber and stumpage. Interest in wet storage — storing wood under sprinklers — is high. The capital cost of providing the additional inventory space, the operating cost of running the sprinklers coupled with the cost of putting material in and retrieving it from off-site storage can range from $1.00 US to $5.00 US per ton. Wet-weather wood is commanding stumpage premiums. The interest costs associated with these inventories are mitigated by the fact that borrowing rates in the United States are at a 20-year low, but they are still significant.

Landowners are beginning to recognize that a major share of the increased costs for environmental protection will devolve to them, and they are beginning to react. Pine lumber prices enjoyed a surge as a result of concern over the withdrawals of stumpage on the West Coast, which allowed stumpage purchasers to pay premium prices when necessary. The wet weather also drove up stumpage prices for pulpwood on accessible tracts. These premiums tended to mask the effect of increased operating costs.

The market is now beginning to adjust to more traditional levels, and the environmental costs are becoming more apparent. A seller of mixed pulpwood and sawlog stumpage at an assumed pre-BMP stumpage value of $20 per ton will likely see 10% of that lost to increased operating costs for the logger. If his timber is located in the uplands, SMZs will probably pull a minimum of 10% of his stumpage from the market. His receipts from the sale will be 80% of what they would have been a few years ago. This could drop to as little as 40%, depending on the percentage of his land lost to SMZs. Landowner rights movements are cropping up quickly across the region.

This decrease in value will affect attitudes toward forest management, taxation of real property, and private property rights. Many owners of property or timber that they consider to be "at risk" environmentally (such as pine trees over 60 years of age and bottomland hardwood forests) are choosing to liquidate those holdings before the threats become real.

Conclusion

The impact of environmental pressures on production forestry are real and pervasive. Many of the changes brought about have been beneficial and easily adopted. The leveling of the playing field by insisting that every stumpage purchaser and harvesting contractor leave tracts in good conditions has been especially important.

The major problem is one of uncertainty. Being a litigious society, our legislatures do not determine the ultimate meaning of the legislation they enact. The courts do. The process of suit, counter-suit, and appeal may take years. Turf wars between agencies are also to be feared. Many environmental impacts of forest management can fall within the purview of several agencies simultaneously: the state forest service, the Corps of Engineers, the Environmental Protection Agency, the U.S. Fish and Wildlife Service, and others. Satisfying one does not necessarily satisfy them all. As issues are resolved, both forest owners and forest industry can focus on playing by the revised rules.

The industry is adaptive. The future will likely see more intensive management of sites that pose the least environmental risk. This will likely involve searching for alternatives to mechanical and chemical site preparation — increasing the supply of woody fuels. Rotations on these tracts will likely be shortened and improvements to the land in the form of higher standard roads increased.

Harvesting contractors will continue to move toward equipment that minimizes soil disturbance. The next changes are likely to be in machine suspensions and drive trains. The number of work days per year will decrease for most contractors. Elasticity to take advantage of those days when the job can work and ability to move quickly between tracts will be priority considerations in system design.

Most importantly, the industry must play an active role in shaping the future. Forestry and the forest industry are regarded positively across the region. Willingness to adapt and work with those desiring to make necessary changes and to work with landowners and others in making the risks of unnecessary regulation known will be crucial in the long term. This is not the time to stand in the background and hold the coats while others fight. Remaining uninvolved is the quickest way to lose.

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FOREST MANIPULATION. IMPACTS ON FOREST ECOSYSTEM SUSTAINABILITY

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Abstract

A world population approaching 6 billion and a rapidly growing public awareness of, and concern for, the environment is requiring major changes in forest management in many countries. Sustainable development of forests, whatever this popular phrase means, is steadily replacing sustained yield of timber as the paradigm for forestry. Soil nutrient and organic matter conservation, maintenance of various measures of ecosystem biodiversity and integrity, the stability of forest-dependent communities, and maximizing employment per cubic meter of wood harvested are becoming major issues that are challenging the more traditional concepts of efficiency and economics. Consideration of the impacts of forest management practices on ecosystem function, diversity, integrity, and stability will become a routine activity of the forest manager in many of the world's forests.

The forestry-environment debate has had many beneficial consequences for the practice of forestry, as well as posing many challenges and, sometimes, threats. In many cases, it has created a political environment in which foresters can practise forestry the way they were trained to, and would like to, rather than merely serving the logging division of their company or government ministry. On the other hand, eco-fundamentalism is on the rise, and green religion has claimed the moral high ground in the environmental movement, displacing the original forest environmentalists: foresters. It is time for foresters to become worthy of reclaiming their status as environmentalists. This will require a commitment to the principles of sustainable management and use of forests and the use of ecologically-based planning tools such as site classification and GIS, and ecosystem management models of the FORCYTE and FORECAST genre as well as ecological models such as the gap-model genre.

Currently, the public has difficulty distinguishing among ecology, green religion, and environmentalism. Both the science of ecology and faith-systems about the environment have important contributions to make to the design of sustainable forestry policies and systems. But it is environmentalism, defined in terms of the original goals of forestry and ecosystem conservation, that should be the paradigm on which sustainable forestry is based. This will require that foresters truly act as professional environmentalists, and this will in turn require consideration of the impacts of forest manipulation on ecosystem sustainability as one of the most fundamental and routine activities of forest management.

Introduction

War, famine, disease, and changes in education, economic status, and religious beliefs have always made prediction of the growth of the human population a difficult task. Nevertheless, human numbers are approaching 6 billion, and predictions of as many as 16 billion humans within the next century no longer seem unrealistic, even in the face of disease epidemics like AIDS and the threatened resurgence of proven killers like tuberculosis. If population growth is brought under control, there is a good chance for a significant per capita increase in standard of living and resource consumption in the third world. Consequently, it is predicted that pressure on global resources and environment will continue to increase, even if the population growth predictions prove to be pessimistic.

There is nothing new about the present concern over the environment. Thomas Malthus, an English vicar, warned in the 18th century about the inability of resources to provide for a geometrically increasing population. The Club of Rome study of the 1960s (Limits to Growth) quantified Malthus' concerns, and concluded that radical changes in population growth, consumption, pollution, and overall attitudes towards the environment are necessary if we are to avoid cataclysmic environmental alteration and population reduction. The World Commission on Environment and Development in their report "Our Common Future" concluded that, in the long run, poverty and its consequences constitute the greatest long-term threat to the environment. Only by raising the standard of living of the majority of the world's population which currently lack the most basic of human needs — security, shelter, and sustenance — can we develop a sustainable relationship with our environment and avoid the scenarios suggested by the Club of Rome study. This conclusion led the World Commission to propose that the solution to the global threat posed by population growth is *sustainable development* of the world's resources.

There is as yet no single widely accepted definition of sustainable development. However, the general idea is that resources should be used in a manner that satisfies the needs of today's human societies but without mortgaging the future. Sustainable development focuses on "inter-generational equity" to ensure that satisfying our needs and desires will not prevent future generations from achieving their goals. One of the consequences of this concept for forestry is that there must be a switch from a focus on sustained yield of timber products to a focus on sustaining the supply of a wide variety of material and environmental values in our forested landscapes: in short, a focus on sustaining forest ecosystem condition and function.

There is great public concern in many western countries about issues such as biodiversity, carbon storage, old-growth, ecosystem integrity, clearcutting, and the use of management chemicals such as herbicides. These concerns pose both a support for, and a threat to, forestry. The criticisms of forestry by the environmental movement have led to a critical re-examination of forest practices in many parts of the world and have created a climate in which significant improvements can now be made. Foresters in these ares will finally be able to practise a style of forestry that is much closer to what they would like to do, or were trained to do, than has been possible or permitted in the past. However, there is a threat that in their concern for the environment, environmentalists will persuade politicians to replace unacceptable old style methods of forest management with new methods that are equally inappropriate in many types of forest.

Foresters have a moral obligation to manage forests according to the objectives of management of the landowners, who in Canada are mainly the public. They also have a professional responsibility to ensure that the methods of management used will in fact achieve the public's vision of what type of forest condition they want to pass on to future generations. To satisfy both of these requirements, careful evaluation of the impacts of forest manipulation is necessary, and forest harvesting and other management practices must be designed to ensure sustainability of desired values.

In this paper, I start by defining a variety of the terms that are commonly used in discussing the impact of forest management systems on ecosystem sustainability. The impacts of various management practices are then examined. Ecologically-based management planning tools that can help identify risks of unacceptable impacts are described, and the paper concludes with a discussion of three alternative paradigms for the design of sustainable forest management.

Definition of Terms

The forestry-environment debate has become greatly confused by the inconsistent use of terminology. It is important that technical terms be defined prior to their usage in this debate to ensure accurate communication among the participants.

Forest Ecosystem - A terrestrial ecosystem dominated by plants with a tree growth - form. "Dominated" means that the microclimate and the soil conditions in the ecosystem are determined by the trees: there is a forest microclimate and a forest soil. The habitat values for animals are created largely by the trees.

A terrestrial ecosystem is any non-aquatic ecological system that has a physical substrate and an atmosphere that support plant, animal, and microbial communities. In addition to this structural requirement, ecosystems have the following attributes: function (e.g., energy storage and exchange, nutrient cycling), complexity (diversity), trophic organization (food webs), interaction and interdependency of its components, and change in all of these attributes over time.

Sustainability - In the context of this paper, sustainability is being used to imply the maintenance of a long-term average condition. It does not mean no change

Sustainability at the local or stand level means a cyclical change caused by disturbance and ecosystem recovery back to some condition that is maintained over the long term. In temperate forestry, the long term frequently refers to three or more tree crop rotations, implying at least 200 years. Sustainability at the landscape level means the maintenance of a mosaic of individual stands of various areas and ages arranged in a pattern that in aggregate provides a sustained supply of a variety of desired resource values at the landscape spatial scale being considered: a watershed, a region or some other landscape scale. The different components of the mosaic change their geographical location over time as the stand-level cycle of disturbance and recovery continues, but in aggregate the composition of, and values provided by, the mosaic remains constant. The long-term average condition that is sustained at the stand and the landscape levels may approximate the unmanaged forest condition, or may be some new condition desired by society.

In uneven-aged forestry, sustainability at the stand level is not very different from sustainability at the landscape level; at neither level will there be dramatic management-induced alteration in ecosystem form and function over time. However, this condition will not be the same as that in an unmanaged or old-growth forest. In even-aged forestry, there will be fluctuations in ecosystem condition in a given stand within the stand cycle, but the composition of the regional mosaic should remain unchanging. Depending on rotation length and management philosophy, the forest condition achieved in a given stand prior to the subsequent harvest may be quite similar to, or very dissimilar from unmanaged or old-growth forest.

Ecosystem integrity - There is a popular view that the only forest ecosystem with integrity is an old-growth forest. In contrast, the term ecosystem integrity is used in this paper to refer to a range of ecosystem conditions within which the ecological processes responsible for recovery from disturbance are operating at rates considered to be "normal" for that ecosystem. In some old-growth forests, ecosystem processes operate at rates not dissimilar from those in younger forests. However, a "decadent old-growth" forest ecosystem can be said to have reduced integrity if stagnation of ecosystem processes is leading to reduced net productivity and a break-up of the forest canopy. A young forest developing after fire, windthrow or clearcutting has integrity if the soil resources, the local range of genotypes, and the climatic conditions all permit the successional recovery to proceed at rates considered "normal" for that ecosystem type. If there has been soil damage, a loss of locally adapted plant genotypes and/or "key" microbe and animal species, or a loss of critical microclimatic control, or if a particular seral stage has become dominant and is resisting the normal operation of autogenic successional processes, the integrity of the ecosystem can be said to have been damaged. If the ecosystem has been altered in a way that watershed-level hydrology has been negatively impacted, there has been a temporary loss in this aspect of integrity.

Impacts of Forestry on Ecosystem Sustainability

These impacts will be reviewed briefly in terms of the major phases of even-aged stand management. The impacts of uneven-aged management may be less, equal or greater, depending on circumstances and the ecosystem condition being considered.

Harvesting

Of all the things foresters do to forest ecosystems, forest harvesting is probably the single most dramatic one, especially if clearcutting is used. By definition, clearcutting is a timber harvest system in which the "forest influence" is temporarily removed. The effects of trees on energy capture and storage, on hydrology and microclimate, on nutrient cycling and miscellaneous soil processes, and in providing a variety of habitat features for wildlife are removed. This loss persists until the new forest closes the canopy, and full recovery of many of these attributes may await the self-thinning phase of the stand cycle. If reforestation is delayed on steep slopes with unstable soil and high rainfall events, there may also be a loss of slope stability.

In a sustainably managed forest, the loss of "forest conditions" persist for only a small portion of the crop rotation period, and preharvest conditions should be restored before the subsequent harvest, except where unmanaged or old-growth forests are being converted to managed second growth. However, if too much of the biomass and nutrients are removed, such as may occur in commercially thinned and whole-tree harvested stands operated on a short rotation, forest productivity may decline. If this occurs, the ecosystem may not have recovered its former inventory of organic matter and nutrients by the time it is harvested again and the potential productivity of the ecosystem may begin to decline. There can also be a loss of ecosystem integrity even without any decline in potential productivity. This can occur if early seral, non-crop vegetation is permitted to occupy the site and exclude tree regrowth. This would constitute a loss of forest ecosystem integrity, but it might create a shrub or herb ecosystem that has integrity in terms of that type of plant cover. Clearcutting in hot dry climates may convert savanna forest to grassland, with a loss of forest integrity but a gain in grassland integrity.

In terms of environmental impact, the greatest effect of forest harvesting is often from the roads. Areas with steep slopes or compactable soils may be clearcut harvested by helicopter, balloon or tight-line cable yarding with minimal negative impacts, whereas even partial harvesting systems on such sites may cause unacceptable soil damage if ground-skidding is used to extract the timber.

All ecosystems undergo change. Climate change, the activities of animals (*e.g.*, insect epidemics) and natural disturbance events (fire, wind, flood) frequently disturb forests; subsequently, successional processes result in ecosystem recovery. Harvesting can mimic, though rarely does it exactly duplicate, "natural" disturbance effects. Where harvest-related disturbance is high (large-scale with intensive disturbance, such as clearcutting large areas with ground skidding), the successional condition is pushed back to an earlier stage of ecosystem development. This may be desirable if it promotes the growth of desired species, creates desired wildlife habitat, and/or speeds up ecosystem processes and increases productivity. It may be undesirable if the new ecosystem condition favors unwanted species, has lower productivity and lacks desired wildlife habitat conditions or aesthetic values.

Clearcutting in areas with a humid climate causes successional retrogression that favors light-demanding, early or mid-seral species. In contrast, partial harvesting in humid climatic areas or on moist sites will accelerate succession towards the climax seral stage. Depending on which tree species and seral stage is desired and the type of forest being harvested, either clearcutting or partial harvesting can be either good or bad.

Harvesting a forest region too rapidly can lead to a loss of sustainability at the landscape level even though the harvest practices may not cause any loss of ecosystem integrity at the stand level. Unacceptable alteration of hydrology and wildlife habitat can occur from sustainable stand level practices if they are applied over too large an area too rapidly. The bad reputation that "progressive" clearcutting of old growth in western Canada has earned has more to do with these landscape level issues of sustainability than with stand level problems. However, the concentration of logging caused by the use of this method has resulted in many areas remaining unroaded and unlogged, giving us land-use options today (*e.g.*, parks, wilderness, ecological reserves) that would not have been available had logging been dispersed in small patches over the whole area, or if partial harvesting had been carried out, as some have advocated in the past.

In summary, forest harvesting that is insensitive to the ecological characteristics of the forest being harvested can negatively affect ecosystem integrity and reduce ecosystem sustainability. In contrast, harvesting designed with respect for the ecology of the local species and both the soil and local hydrology need have no negative effects on sustainability. Removal during harvesting of all standing dead trees (snags) may remove critical shelter and feeding habitat for certain species of birds and mammals. Retention of snags, where this is consistent with worker safety, can sustain these values where the character of standing dead trees provides the necessary habitat. Sustainability of some aspects of biodiversity may require a modification of harvesting to retain these structural elements of the forest ecosystem. Sustainability of aesthetic and recreational values may require altered rates and patterns of harvesting, shape, and layout of harvested areas, and type of silviculture system.

Site Preparation

A harvested area is often not in an appropriate condition for prompt and successful reforestation. Inappropriate seedbed conditions, excessive logging debris (slash), competing vegetation, cold or wet soils, or excessive accumulations of organic matter may prevent or delay regeneration or the subsequent growth of the new forest. Similar regeneration delays may follow natural disturbance of forests. The use of fire, mechanical or chemical methods to achieve desired site conditions has the potential to improve reforestation, but it can also threaten ecosystem sustainability if done incorrectly, and in many cases of ecosystem damage attributed to forest harvesting, the problem was actually caused by post-harvest site preparation.

Slashburning is an excellent silvicultural tool with which to reduce logging slash to improve access and ease of planting or to promote natural regeneration. It can reduce insect and disease problems, and provide temporary relief from competition between seedlings and non-crop vegetation. It can improve soil chemistry, result in soil warming and promote improved seedling growth. It may be necessary to slashburn to achieve prompt regeneration and good growth of certain species on certain sites in certain climates, and this may be necessary to maintain biologically diverse forests in the long term.

Slashburning is a very powerful site preparation tool but, unfortunately for its reputation, it has often been poorly applied. It is capable of doing substantial soil damage if applied to the wrong site, at the wrong time of year, or under inappropriate fuel and weather conditions.

The complex interactions between site, site condition, weather, fuel conditions, and slashburning technique preclude any simple relationships between slashburning and sustainability. Its effects can be good, bad or neutral with respect to ecosystem sustainability.

Mechanical site preparation (MSP) has become increasingly popular as slashburning has declined in public acceptability or popularity among foresters and as herbicides have essentially been lost as a vegetation management tool due to public protest. It can facilitate regeneration, reduce the risk of growing season radiation frost damage, reduce competition from non-crop vegetation, and improve soil temperature and drainage. Unfortunately, mechanical methods of site preparation have often been as badly applied as has slashburning, and in many instances it, too, is falling into disfavor.

Windrowing and "scalping" are two MSP techniques that have significantly reduced site productivity by removing too much organic matter and nutrients. While they may reduce competition from shrubs and herbs in the short term, they can sometimes result in increased competition from non-crop deciduous trees over longer time periods.

Herbicides are hardly worth discussing anymore due to their rejection by many sectors of the public. Used as a "chemical bulldozer," they can have a significant negative impact on ecosystem integrity and sustainability. Non-crop vegetation may provide important shelter to crop seedlings from herbivores and undesirable microclimatic conditions. Competing vegetation may help retain nutrients on-site, may reduce erosion and contribute to slope stability, may be nitrogen fixers, and may have beneficial effects on soil organisms and soil fertility. Short-term negative effects on crop species may be more than compensated for by the long-term benefits of non-crop vegetation. On the other hand, used appropriately, selective herbicides with low toxicity to animals, no known adverse effects on soil microbes, rapid degradation, and low mobility in the environment can be much more "environmentally friendly" than mechanical methods of "weed" control, and more effective than manual methods. Used with an understanding of the ecological role of non-crop vegetation and the behavior of the herbicide being applied, herbicide use can be very consistent with ecosystem sustainability. The loss of this silvicultural tool is, therefore, to be regretted, past cases of over-use or misuse of herbicides notwithstanding.

Stand tending

Natural regeneration generally enriches single species plantations when they are established in mixed species, managed forests. Foresters frequently plant only one species in these forests even though they anticipate, and want, a mixed species forest. They plant the species that is desired but is least likely to be provided by natural regeneration, allowing this process to provide for the other species' regeneration. However, if in stand tending, these other species are removed, monocultures may result. This may or may not be a threat to ecosystem sustainability. Nature frequently indulges in monocultures. However, removal of deciduous trees, especially where these are nitrogen fixers, may have a long-term negative effect on sustainability because of their role in maintaining soil fertility and their contribution to wildlife. A period of time under deciduous forest may be necessary to control root rots of conifers that may threaten achieved site productivity (*e.g.*, red alder — Douglas-fir systems in coastal B.C.), and early seral hardwoods may play an important non-crop protection function for spruce in boreal and sub-boreal ecosystems. Removal of hardwoods during stand tending may thus have a negative effect on sustainability of coniferous crops. Removal of other species of conifers that have invaded the site may be appropriate if these are not ecologically suited to the site, but may be a poor choice both environmentally and economically if mixtures promote ecosystem productivity and sustainability, and if uncertain future timber markets favor a mixture of timber species at time of harvest. Mixtures are also a good idea in the face of risks posed by climate change, and in some cases they may be our insurance against insect or disease outbreaks. Conversely, it may be necessary at some point in the rotation to control stand density and species composition in order to achieve management objectives, including a sustainable supply of desired wood products and habitat conditions for wildlife.

Fertilization

Many forests are grown on nutrient poor soils, and the climatically-controlled growth potential is only achieved if the trees are fertilized. Nitrogen is usually the most limiting nutrient, but phosphorous, potassium, iron, sulfur, and various micronutrients limit tree growth on some sites and in some regions. Even forests on moderately fertile soils may experience nutrient limitations if various combinations of short rotations, whole-tree harvesting, slashburning or mechanical site preparation, and control of non-crop trees that contribute to site fertility, result in lowered nutrient availability.

Forest fertilization can result in spectacular increases in tree growth if based on a good understanding of tree physiology and nutrition, production ecology, and the ecosystem processes that determine nutrient cycling and nutrient availability. However, results of field fertilizer applications are often variable because they have often been conducted without this necessary knowledge base.

Fertilization has relatively few environmental risks. Eutrophication of rivers and lakes can occur, but is rare. Usually, the productivity of the recipient aquatic ecosystem is limited by lack of nutrients, and there is a benefit from such nutrient additions. Fertilized forests are denser and darker than unfertilized forests, and this can result in the loss of understory vegetation, which may negatively affect some wildlife species. However, fertilization improves the nutritional quality of browse species and, because it is usually done only after a thinning, often improves the food of browsers.

Because forest fertilizers are applied infrequently and at relatively low rates, the environmental concerns over agricultural fertilization are not usually applicable.

A recent trend in forest fertilization is the recycling of organic wastes in forests. Urban sewage sludge, fish farms and fish processing water, pulp sludges, and wood ash are all being used on an increasing scale, improving forest growth while recycling these "wastes." There may be some public health concerns about the use of primary sewage sludge that has not been sterilized, or where it has high loadings of heavy metals. The latter may also raise environmental concerns over effects on soil organisms. However, insufficient research has been done to fully explore these issues. Results to date suggest that careful use at rates that do no overload the soil's capacity to absorb the added material should not be a problem. More long-term monitoring is needed, however.

Ecologically-Based Tools Required for Sustainable Forestry

Achievement of sustainability in forestry in physically diverse environments (variable climate, topography, geology, and soils) requires that this physical diversity, and the biological and ecological diversity that it produces, are explicitly recognized. This is achieved by ecological site classification.

Perhaps the single most important prerequisite for sustainable forestry, site classification is well developed in some countries, but is not yet well integrated into all aspects of forestry. For example, the biogeoclimatic classification of British Columbia's forests, although one of the most developed in the world, is still not well integrated into the B.C. forest inventory system and various aspects of forest planning in the province. More work is needed to get such systems of forest classification operational.

Site classification give you a method of stratifying the landscape into productivity classes, and treatment response classes. However, it does not usually provide predictions of productivity and other ecosystem values under alternative management systems and practices. This can be achieved on the basis of experience, but where this is lacking, incomplete, or inappropriate for future conditions, computer simulation models can provide a best estimate. Ecosystem management models of the FORCYTE and FORECAST genre can help forest managers to rank the probable outcomes of alternative management strategies for site productivity, sustainability, wildlife habitat, soil fertility, carbon budgets, energy-use efficiency and benefit/cost rations, and economics. These models were specifically designed to analyze the sustainability of bioenergy plantations, and the various tradeoffs involved in this energy option.

One of the ecological concepts that is useful in the discussion of sustainability is *ecological rotations*: the time taken for a particular ecosystem value or condition to return to its predisturbance condition (or some new desired condition) following some particular change when subjected to a disturbance. For example, soil fertility on a site with a deep, fine-textured, organic-rich soil will not be easily changed by management. Others are easily changed, such as a site with a nutrient-poor mineral soil that has good productivity because of a well-developed forest floor containing sufficient nutrients to support adequate tree growth. Such a site can easily be degraded by burning, mechanical site preparation, or whole-tree harvesting on short rotations. Ecosystem stability can also be considered in terms of the rate of its recovery if disturbance has changed it significantly. Fore example, if the fertile soil is depleted in organic matter and nitrogen, and the processes that replace these are prevented from operating, then the former fertility may recover slowly. Conversely, if successional recovery processes are permitted to operate on the poor soil (*e.g.*, if nitrogen-fixing primer plants are able to grow and fix nitrogen efficiently on the site), the site may recover quite quickly.

The complexity of the issues involved in assessing ecological rotations and sustainability requires the use of ecosystem simulation models. In forests, one of the main applications of such models is to determine ecological rotations: to answer the question, "what combinations of frequency, type, scale, and intensity of disturbance are consistent with sustainability in a particular forest ecosystem?"

A problem with many ecosystem models is that they are not very user friendly: they were designed by, and for, researchers. But the problems of sustainability are largely determined by field foresters. There is an urgent need to make such ecologically-based tools available to field foresters, and also to the general public to help them understand the tradeoffs that foresters must make. FORTOON is an example of a user-friendly ecosystem management "game," based on the FORECAST ecosystem management simulation model designed for use in schools, colleges, and by both forest researchers and forest managers.

What Should the Paradigm for Sustainable Forestry Be?

The media and concerned citizens frequently use the term "ecologically-sound management." Should the science of ecology be the paradigm from which we develop sustainable forestry?

Deep ecology is a belief system about ecosystems: it is a green religion based on faith rather than fact and empirical evidence. It suggests a very different approach to forest management. Should ecological-faith systems be the basis for forestry?

In designing sustainable forestry, we need to understand the contributions made by both ecology and green religion, and what the role of environmentalism should be.

Ecology is a science. It describes, explains, and provides a basis for predicting future states of ecosystems. It does not provide a basis for judging what is a good or a bad ecosystem condition, nor how ecosystems should be managed. Ecology is essential as one of the foundations for sustainable forestry but, on its own, it does not provide a workable paradigm.

Green religion, like other religions, identifies ethical responsibilities and moral values that are absent in the science of ecology. Like any religion, it can lead to fundamentalism and intolerance if divorced from secular considerations. Thus, green religion makes an important contribution, but cannot be the paradigm for sustainability.

What then should be the basis for sustainable management? It is environmentalism. Not the environmentalism as currently described in the media — green religion has, to a great extent, taken over the environmental movement or, where this is not the case, it is the part of the environmental movement that is reported. But environmentalism as defined by the common origins of both forestry and the forest conservation movement: the desire to sustain a desired set of values and conditions in particular forested landscapes.

Foresters, the original forest environmentalists, have lost the "moral high ground" to preachers of green religion, riding under the banner of environmentalism. It is time for foresters to organize their forest management to be truly sustainable of the values that all of society wants from its forests, and thereby to earn their place once more as the leading forest environmentalists. To do this, they must understand much more about ecosystems than most foresters presently do.

Conclusions

1. Forest management constitutes one of the major disturbance factors in many of the world's forests; in others, wildfire, wind, insects, and disease continue to be the dominant forces. Where management does have a dominant effect, foresters must learn enough about the ecosystems they are managing to ensure that the values they are managing for are sustained at the landscape level. Many practices common today are questionable in terms of long-term sustainability and need to be re-evaluated.

2. To achieve sustainable management, foresters must use ecological site classification and, where appropriate experience does not provide reliable predictions about the long-term consequences of management, they should use ecosystem management simulation models.

3. Foresters must decide on a paradigm for sustainable forestry. They must understand the contributions made by ecology and green belief systems, and must achieve the status of forest environmentalists, in the original and broad sense of this term. To fail to do so is to risk that forest management decisions will increasingly be controlled by green fundamentalism.

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CANADA'S MODEL FOREST PROGRAM: EXPERIMENTS IN THE SUSTAINABLE MANAGEMENT OF FORESTS

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Abstract

Canada's model forest program is based on the common interest of Canada's provincial and federal government agencies to explore a working level definition of the sustainable development of forests. The ten model forests were created through a nation-wide competition during the past year and a half. The projects include participation by all major stakeholder groups, who work together to develop a common vision statement, objectives, and the activities necessary to make a transition to sustainable development in the forest area concerned. The model forests, covering over six million ha in total, are making early progress on such diverse activities as defining biodiversity, examining the diversification of local economies, developing environmental education programs, and re-establishing a cultural connection with the forest. While many activities are now underway, the challenge will be to ensure that the diverse projects are integrated and lead towards a workable concept of sustainable development. Based on the early success of the program, Canada is now working with three other countries to create an international network of model forest projects. The goal is to work cooperatively towards the definition of sustainable development and to support further progress towards regional and global forest institutions and agreements.

Introduction

The definition of sustainable development or sustainable management of forests has been a subject of most recent forest policy debate. Sustainable development, as defined by the Brundtland Commission, was a seductively simple concept that could be readily accepted by a large segment of the public. It seemed on the surface to be a balanced approach to maintaining economic growth while ensuring that all functions and features of the natural environment would be conserved. Yet, the concept of sustainable development runs the risk of fading into obscurity like so many other catch phrases, simply because it has not been translated into a working definition with implication on how forests are managed.

To be implemented globally, the concept of sustainable development of forests must be defined at different levels of resolution. At a global level, conservation of forests requires international financial cooperation to ensure all countries are equally able to reach minimum targets. International mechanisms require a common definition of sustainable development as a basis for financial cooperation and to maintain a level playing field in forest products trade. At a regional level, countries often share responsibility for the management of distinct biomes, and activities in one country can affect the environmental integrity of neighbors. Within countries or large ecosystems within countries, there is a need to define objectives and measures of environmental, economic, and social sustainability that form the basis for public policy and guidelines. Finally at the forest or working-scale ecosystem level, there is a need to plan activities and balance among competing interests. It is at this lowest level that a philosophy of sustainable development must be implemented. An examination of current examples of multilateral processes should serve to illustrate the difficulties found in translating the very general goal of sustainable development into something quantifiable and implementable. The first was the call for, and negotiations towards, a global forests convention as part of the preparation for the UN Conference on Environment and Development in 1992. Because of political self interest, fear of trade implications, and a general mistrust of the motives of developed countries by developing countries, the negotiation process failed. The result was a somewhat confusing patchwork of 'principles' that included too many riders and qualifications to be meaningful.

On a regional basis, the current negotiation towards a European Ministerial Resolution on the Sustainable Management of European Forests is making better progress. In this case the difficulty has been to reach an agreement on specifics, and there has been a tendency to push the level of discussion to more general principles. While any refinement of the concept is worthwhile, the European Resolution, if adopted, must be followed by another process to lead to measurable objectives, possibly at the country level.

Canada can serve as an example of a country-level initiative. An important meeting was held in February of 1990. The federal and provincial government ministers responsible for forests met and agreed to collectively pursue the goal of sustainable development. Following that meeting, a year-long process was established to create a national forest strategy, aptly entitled "Sustainable Forests: A Canadian Commitment". This document led to over 80 specific recommendations in support of 11 principles of sustainable development. The Canadian Strategy provided a very broad definition of sustainable development, and included such things as conservation of environmental quality and biodiversity, economic and social development, rights of indigenous peoples, and public participation in forest management planning. The success of this document was illustrated by the companion signing of the Canada Forest Accord, a brief statement of principles and objectives. This document was signed by governments, industry, environmental groups, native leaders, labor organizations, and academics. Despite the strong consensus found in the national forest strategy, however, provincial forest legislation still differs dramatically, forest information is scattered and of uneven quality, and there are different codes of practices for similar ecosystems in different jurisdictions.

At the level of the forest ecosystem or regional forest landscape, there are really no clarifications of what sustainable development means. Yet it is interesting to reflect how the concept of sustained yield arose in Germany in the late 18th century. A visionary forester pioneered the concept at the working scale and it was slowly accepted around the world. Possibly a similar mechanism is needed to define the concept of sustainable development of forests. While there is general agreement that all values in the forest should be recognized and sustained, and that goals for forest management should be set with the participation of major interest groups and stakeholders, there is little understanding of the implications of this for actual forest management programs. In the absence of such a working definition, forest management must still rely on the traditional sustained yield philosophy, with non-timber values identified as constraints on the production of timber.

The Challenge of Defining Sustainable Development at a Working Scale

The conflict over forest management in Canada has occurred less at the national or provincial policy level, and more on a 'valley by valley' basis. This reflects the fact that broad provincial objective statements mask the critical tradeoffs required when forest harvesting operations are actually planned for specific sites. Yet, it is at this landscape or ecosystem level that sustainability will be implemented or will fail. As the controversy over the spotted owl in the Pacific Northwest has shown, there is a great difference between making the general commitment to biodiversity and the implications when it comes time to trade off between habitat and harvesting.

Therefore, the challenge to defining sustainable development in Canada is at the working scale, rather than at the broad policy scale. This was recognized by both the 1990 meeting of Canadian Forest Ministers, and the 1992 National Forest Strategy, which have called for working models of sustainable forest management to be established.

To address this need, the federal government proposed a new program under the Canadian Green Plan. The Green Plan was the major program initiative of the current government, and promised up to $3 billion over 6 years to fund a wide-ranging series of programs to foster sustainable development and to ensure a healthy environment. The forest program, called "Partners in Sustainable Development of Forests," was designed to lead the transition from the conventional sustained timber yield philosophy to the broader concept of sustainable development. The 6-year, $100 million program was designed to include three elements: the establishment of a network of ten model forests where sustainable development could be explored at the working scale, and the expansion of scientific and information programs on the forest. The model forests, however, funded at $54 million over the 6 years, would be the greatest challenge and the centerpiece of the program.

The Concept of the Model Forests

Immediately after the announcement of the Green Plan, Forestry Canada (now known as the Canadian Forest Service) created an internal task force to examine the results of the Canadian Council of Forest Ministers 1990 meeting and to translate these into criteria for the establishment of the model forests. The task force recommended that the model forests be established through an open competitive process, that the goals for forest management in the model forests would be established through a consensus-based process including all interested stakeholders, and that forest management would be guided by an integrated planning process that would sustain all critical values. The model forests would also be expected to support scientific research, to use the most ecologically sensitive forestry practices, and to make efforts towards communications and technology transfer to areas outside of the model forest areas. Finally, the model forests would be of a working scale, in the order of 100 000 to 1 500 000 ha in size. The federal government contribution to model forests would be in the range of $1.0 to $1.5 million per year each, and this funding would provide support for those activities necessary to make the transition from conventional forest management programs.

The model forest competition with associated documentation was announced in September of 1991, and proved to be a lively affair. Not only was the government saying that the working-level definition of sustainable development was an open-ended and flexible concept, but it was suggesting that groups including naturally opposing views form partnerships and enter into competition with one another. Yet the result was impressive, with over 100 groups submitting letters of intent to the program within 1 month of its announcement. The magnitude of the response caused some difficulties. Provincial government agencies were swamped with requests for assistance to develop proposals, and the process of developing a thorough technical review of up to 100 proposals was worrisome.

The federal Minister of Forestry had established a National Advisory Committee to administer the competition. This committee created a technical review sub-committee to undertake the detailed proposal review. These committees included representatives from industry, native groups, environmental groups, academics, and government. They encouraged groups to coalesce into larger partnerships and made it clear that only serious efforts would have a chance of succeeding. The result was the submission of 50 proposals by the February 28, 1992 deadline.

The review process was approached in two stages. First, each proposal was read by three reviewers and a consensus evaluation developed. The reviewers used a fairly mechanistic approach, based on the weighting and selection criteria announced at the start of the competition (Table 1). Then, based on the consensus 'grades' given each, the full technical committee discussed each proposal and adjusted the ranking where necessary. Finally, all the proposals were given to the National Advisory Committee with a one-page critique, a rating of excellent, good, fair, or poor, and a ranking. The advisory committee had spent considerable time reviewing the proposals and were very satisfied with the results of the technical review. In developing their recommendation to the Minister for the successful sites, the Advisory Committee first accepted all excellent and good proposals, and then chose three extra from the 'fair' category to complete the coverage of major ecoregions of Canada. The Minister accepted the recommendations of the Advisory Committee, and announced the ten model forest projects in June of 1992.

Establishing the Model Forests

After the announcement of the successful sites (Figure 1), Forestry Canada officials had to negotiate contribution agreements to control the expenditure of public funds in the model forests. After the initial euphoria, the negotiation process was a tough exercise. The model forests found it necessary, in most cases, to incorporate and establish a board of directors, by-laws, and administrative systems (Figure 2). This took about 3 months, and during that time secondary issues were often causing fractures in the partnership groups. The proposals accepted were also generally for much more than the $5 million per site available, and the partner groups had intensive negotiations among themselves to pare budgets. One of the Model Forests, located in the Clayoquot Sound area of Vancouver Island, also drew a very negative response from environmental groups, who saw the program as a justification for continued logging of the area. Finally, however, the administrative matters were settled for nine of the projects, and the contribution agreements were signed between December of 1992 and April of 1993. Funds were quickly made available to groups to start project activities after each agreement was signed.

The tenth project, from Vancouver Island, was held in abeyance until the recently announced land use decision of the provincial government. All stakeholder groups will now be asked whether they wish to proceed with the project.

A national model forest network committee was also established, including representatives from all model forest projects, three provincial government agencies on a rotating basis, and from Forestry Canada. This committee is a basis for the exploration of common problems in different regions of Canada, and for the sharing of experiences and techniques developed. In its first year of operation, the committee will sponsor workshops and conferences on environmental education in schools, and on the definition of indicators of sustainability that can be measured to evaluate progress in Model Forests.

Table 1 Evaluation Criteria for Model Forest Proposals

	Item	Weighting(%)
1.	The objectives and management philosophy proposed for the Model Forest and how they support the concept of sustainable development and integrated resource management - the goals and objectives of the Model Forest and the balance between differing objectives; - he management concepts, structure and decision-making process proposed; - the nature of the partnership proposed and the involvement of key stakehoders; - the relevance of the proposal to the objectives of the Model Forests program; - a long-term commitment to the principle of sustainable development.	40
2.	The activities and results proposed for the Model Forest using "best forestry practices" - the activities, outputs and results proposed over the 5-year period; - how these support the objectives and goals of the Model Forest; - how these activities differ from present practices.	25
3.	The use of the most advanced technology and the demonstration of techniques and results - how any gaps in the technology, expertise or knowledge needed to implement the Model Forest proposal will be addressed; - how the Model Forest will link into existing research programs, including the new Forestry Canada funded Green Plan research initiatives, and the collaborators involved in the proposal; - how the results achieved in the Model Forest will be transferred and diffused to others, nationally and internationally.	25
4.	How the results will be communicated to the public and the general financial and administrative management of the proposal - the proposal for general public communications activities; - the feasibility of the budget; - the degree of leveraging accomplished with the aid of federal funds.	10

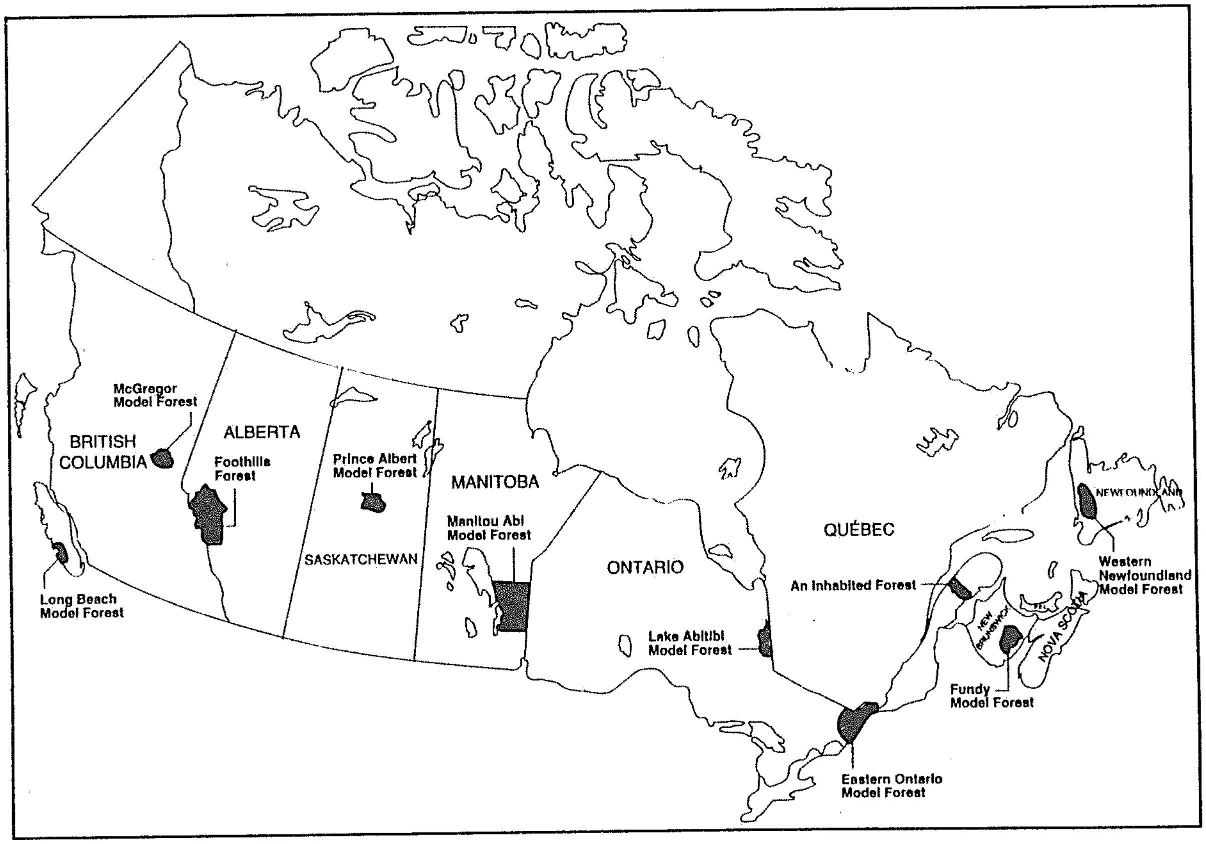

Figure 1 Map showing location of Canada's ten model forest sites

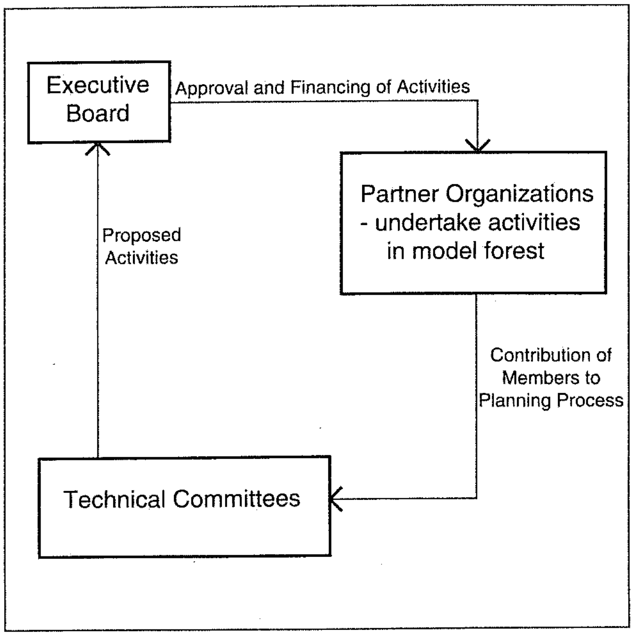

Figure 2 Generalized decision-making structure of model forest projects. Each project differs in specific organization, but most have these key components

The Issues being Addressed by Model Forests

Biodiversity

There are two major approaches to the conservation of biodiversity, and the two must be developed in concert. The first is in identifying and maintaining specific areas of natural ecosystems intact. These ecosystems may be large representative examples of forest landscapes, or smaller areas of critical or rare habitat. Protected areas are incorporated in or adjacent to most of the model forests. But the great majority of protected areas are not of sufficient size to conserve all aspects of biodiversity. Therefore, it is important that the commercially available forest also be managed with the objective of biodiversity conservation. Model forests are approaching this issue in several ways. Many used ecologically meaningful criteria in establishing their boundaries, thus allowing better planning for habitat conservation. All of the model forests are trying to map, to varying degrees, the ecological site types on their areas, to study the major plant communities, and to take a census of the animal species present. In most cases, the objective is to understand the ecological diversity of the model forest area and to be able to evaluate the impacts of different forest management programs on biodiversity.

Water Quality and Soil Conservation

In most of the model forests there is the objective of improving forestry operations to conserve soil and water quality. In the case of soil conservation, the two most important aspects are the location and construction of roads and the design of harvesting operations. In some projects, the construction of new roads will be modified and roads will be taken out of service immediately after completion of use. Also the location of roads on hillsides will be undertaken with greater concern about water flows and potential for erosion.

Harvesting operations can also lead to soil erosion, compaction, and water table fluctuations. Most model forests will include research projects to study hydrology and soil physical properties and the demonstration of more careful logging techniques. These techniques can include skyline yarding, use of smaller vehicles with lower ground pressure, and even the use of horse logging. In model forest areas with mixed forest types, selection harvesting will be undertaken at an operational scale.

Economic Diversification

The past heavy reliance on the forest industry in many of the communities associated with the model forest projects has led to problems of cyclical employment and increasing uncertainty about the future. Most communities want a stable future and see economic diversification as a positive objective. In model forest projects, the emphasis is on studies related to expanding tourism, traditional first nations products and crafts, value-added manufacturing, training centers, and specialty products such as maple syrup. These grassroots activities build a broader economic base, and may lead to more dynamic and entrepreneurial communities.

Public Education and Worker Training

Even in the rural communities associated with model forest projects there is a recognition that people are becoming less connected to the forest in their daily lives, and less aware of the nature and complexity of forests. There is a widespread desire to implement more environmental education in schools and more education relating to forests, forest ecology, and wildlife habitat. Most model forest projects include support for outdoor education centers, curriculum development, and teacher training programs. It is believed that better education will lead to better future understanding of the role of forests in society.

Worker training is another area where environmental education has been lacking. While most companies will train their workers in the operation of equipment, safety practices, and even interpersonal skills, there is a new awareness that workers are the cornerstone of environmental conservation. Model forest groups are proposing to provide training in environmental ethics, forest ecology, and forest conservation to forest workers.

Cultural and Spiritual Renaissance

Most model forest projects encompass a mix of communities, including first nations, industrial towns, and, in some cases, associated urban centers. Over the last few decades, these societies have become less and less culturally attached to the forest. While most rural people still hunt, fish, canoe, and hike in the forest, there has been a slow loss of understanding of regional history, folklore, and the traditional land ethic. Many model forest groups are hoping to rebuild this cultural connection to the forest. Projects have been approved to map archeological and cultural sites of first nations, to rediscover traditional medicines, to cultivate trees and plants with special purposes in handicraft arts, and to establish educational and cultural centers. Like the education and training activity, it is expected that a stronger understanding of the forest and human relationship to it will benefit resource management attitudes in local communities.

Scientific Research and Development of New Technologies

In defining sustainable forest management, many of the decisions that must be made founder on questions that are currently difficult to answer. What minimum size of population of pine martin is needed to ensure its survival? What should be the range of sizes for harvest blocks and what shape should they take? Science, therefore, must be an integral part of the model forest projects. In all cases universities, federal and provincial government agencies, and private technology companies are active partners in the model forest groups. In most cases the research is supported not only by the operating funds of the model forests, but by the $33 million enhanced science programs associated with the 'Partners in Sustainable Development of Forests' program. These associated science programs include new studies of the ecological impacts of forestry practices, alternatives to chemical pesticides, the role of fire in forests, ecological classification and the role of ecological reserves in resource management, forest landscape simulation systems that allow futuristic views of the potential results of different forest management programs, and a national genetic conservation center.

The science programs in model forests must be driven by two interacting forces. The first is the definition of the actual questions needing answers to support management decisions in the model forests, and the second is the need for broad scientific cooperation and interaction among projects and with the outside scientific community. Therefore, most of the science programs are nationally coordinated, with peer review and evaluation, but are focused on the issues identified by the model forest sites.

Integration of Programs in the Model Forests

Reading through the list of activities and issues above leads one to question how it is all put together into an integrated program that addresses some higher level objectives. There is obviously a danger that each partner will develop specific proposals and activities that are approved each year and carried on in parallel with one another. The mechanism to avoid this is the linkage of the projects to the original proposal and the management decision-making structure in place.

In the original proposals the partner groups had to follow a hierarchical development process. First, the groups had to agree on a common 'vision' statement that captured the land ethic or philosophy that the group held in common. Then, this vision statement had to be broken down into defined objectives. The project activities within the model forests, then, were designed to achieve the objectives. Science projects were identified where there was an inability to agree on a course of action in fulfilling the objective. In this way, every activity undertaken would lead to fulfillment of the vision statement.

There was one piece of the puzzle missing in this framework. That was the measurable definition of what things would look like when sustainability is achieved. There is a need to develop a series of quantified indicators that tell whether the results of the activities undertaken are in fact leading to some 'good' condition. In challenging the model forests to address this, they became somewhat uncomfortable. Defining how much wood, biodiversity, jobs, and cultural awareness is enough is a daunting task. But the need is understood, and a major workshop will be held during the next 6 months to address this problem and try to find a mechanism to define these indicators.

The decision-making framework of model forest groups also leads to integration of the activities undertaken. In almost all cases the model forests operate on the basis of consensus rather than voting. This means that no one group can be continuously isolated and overwhelmed. The majority of model forests also work in a two-tiered structure. There are a series of technical or working committees with involvement of different partner representatives. These committees may have a mandate to develop specific project statements within the area of communications and public education, or biodiversity and habitat conservation. They take the original proposed activities and develop full project statements and then submit these to a higher level board of directors or executive board. This board must look at all the proposed activities and identify weaknesses, holes in the program, and the philosophical orientation of the overall effort. In general, the system seems to work fairly well.

This broad and detailed planning system is clearly breaking a lot of new ground. Never before have such a wide range of stakeholders had such a meaningful opportunity to exchange views and try to hammer out a vision of what constitutes sustainable management of forests. There will be problems along the way, many of them caused by the fact that the partners may have irritants and disagreements with each other outside the model forest activities. These have a tendency to spill over into the working relationship in the model forest. Yet patience has been the key to date, as most problems are resolved with time and negotiation.

International Model Forests

The role of model forests in working towards an operational definition of sustainable development has been an important part of the recent evolution of forest management in Canada. The individual projects are all unique and yet among them they explore a wide variety of critical issues. Over time there is an expectation that the model forest projects will set a course for the future of Canadian forest management.

At the same time as the model forests have been developed, there has also been an urgent and expanding call for closer international cooperation on forest issues. Particularly based on the difficulty found in negotiating a global forest convention, there is a need for countries to work cooperatively in defining sustainable development. Like the original Germanic concept of sustained yield, which served forest managers for almost two centuries, working level agreement on philosophy may be an important and necessary first step. Based on Canada's success with the model forest concept and based on Canada's desire to be active in the ongoing international debate over forests, Canada's Prime Minister announced at the UNCED meeting a commitment to provide funding to expand the model forest network internationally.

The work has begun on the expansion of the model forest network. As an initial step Mexico and Russia were invited to participate in the network and to establish their own model forest projects with Canadian assistance. The response has been positive and projects will be established with the same high technical standard and degree of innovation found in the Canadian projects. There has been a very positive response from the Canadian model forest groups to this opportunity as well. They see the internationalization of the program as providing them with a new pool of ideas and a new understanding of the context of their own problems. The early steps taken in the program have included workshops in Mexico and Russia that allowed Canadian model forest representatives to explain their projects to their counterparts and engage in wide-ranging discussions about sustainable development.

Canada will support the development of model forests in three countries in the coming year and hopes that the success of the initiative will lead other countries to establish compatible projects and contribute to the operation of a global network of these model forests. The objective is to establish a network of projects that includes all the major ecoregions of the world by the year 2000.

Conclusion

The actual implementation of sustainable development occurs at the working level where ecosystems are impacted by human activity and where social and economic stability are created for communities. Yet at this level the concept of sustainability has been most difficult to define. The Canadian model forest program, while still in its early stages, has shown indication of being an important step towards defining sustainability at the working scale. Only time will tell if the model forest groups will find a stable co-existence and common purpose. And only time will tell if the results of their efforts are in fact sustainable for the environment, the economy and the Canadian society.

INTENSIVE HARVESTING OF FORESTS: A REVIEW OF THE NUTRITIONAL ASPECTS AND SUSTAINABILITY IMPLICATIONS

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Abstract

Whole-tree harvesting increases both the biomass and nutrient output from a forest site when compared to stem-only harvesting. The proportional increase in nutrient output is, however, greater than that of biomass output. The concern is that the increase in nutrient removal will lead to an impoverishment in site quality and a reduction in future tree growth. This paper reviews some of the more recent literature on this topic. In particular, research carried out to examine the balance between nutrient inputs by atmospheric deposition and weathering, and outputs by leaching and harvesting, is examined. An example of a nutrient balance is given by using data from a Sitka spruce plantation in North Wales, UK. The interpretation of the information available from nutrient balance studies is discussed. The difference between the objective of maintaining a site's nutrient capital, and the objective of maintaining a site's timber production is considered. It is concluded that there is great variability among forest ecosystems in their response to an intensification of harvesting, which limits the extent to which conclusions derived from any individual study can be generalized to other areas.

Introduction

In the forest industry, there is pressure to increase productivity, which stems not only from the need to maximize financial returns, but also from the increasing demand for biomass. This demand is both as a raw material for industry and as an alternative to fossil fuels (e.g., Forestry Canada, 1991), as the emphasis increases on using renewable forms of energy. Such an increase in productivity can be achieved by a greater utilization of the forest biomass on site at harvesting.

At the same time, there is increasing awareness that any operation or development should be sustainable in the long term. In the draft of the Rio Declaration on Environment and Development, principle 4 states that "....to achieve sustainable development, environmental protection shall constitute an integral part of the development process..." and principle 8 states that "....to achieve sustainable development....States should reduce and eliminate unsustainable patterns of production...." It is, therefore, important that the sustainability of all forestry practices is addressed, and this is especially important when potentially site-damaging operations, such as harvesting, are being considered.

Harvesting after clear felling can be divided into two categories, depending on the intensity of biomass removal from a site. The convention has been to remove only stemwood from the harvested site, with the branches and top (referred to as slash or brash) of the trees being left on site as harvest residues. This will be referred to as conventional harvesting (CH). In recent years, the demand for forest biomass together with increasing mechanization of harvesting operations, has led in many places to the adoption of whole-tree harvesting (WTH) systems. During WTH, slash material, in addition to stemwood, is removed from the site, either with or without foliage. In some instances, non-timber tree and shrub biomass will also be harvested. In an increasing number of regions around the world, WTH has become the normal harvesting method (e.g. Mahendrappa, 1990).

The "residues" harvested during WTH can be chipped either on or off site before further processing or burning. However, not all residues harvested during WTH will be used. With advances in harvesting machinery, it is often easier to transport the whole tree to roadside before delimbing. Where there is no market for the slash, the large slash piles will be left at roadside. Markets for slash are still developing. For example, in

Table 1. Biomass and nutrients (kg/ha^{-1}) present in stem wood in differnt forests and percent increase if slash material is included.

Forest type	Biomass		N		P		K		Ca		Mg	
	Stem	Slash	Stem	Slash	Stem	Slash	Stem	Slash	Stem	Slash	Stem	Slash
Sugar maple[1] pole-stage	87000	59	123.0	197	11.3	232	46.2	239	177.1	117	15.6	165
White birch/[1] red maple pole-stage	55600	65	92.0	197	7.7	288	34.8	137	137.7	96	12.7	113
Sugar maple[1] mature stand	113000	37	159.4	123	15.0	156	84.6	116	256.4	75	23.5	93
Red spruce[1] balsam fir pole-stage	106700	45	120.5	178	13.9	214	55.2	180	188.7	101	16.9	141
Red spruce[1] balsam fir mature stand	167100	34	191.7	145	24.3	158	93.2	138	278.2	87	27.7	107
Radiata pine[2] 23 years	337300	26	149.0	191	24.0	176	194.8	138	171.7	94	51.8	97
Sitka spruce[3] 50 years	216900	33	209	236	14	329	107	183	nd	nd	nd	nd
Aspen[4] 40 years	14660	14	199	50	26.2	77	198	45	606	45	39.2	47
White spruce[4] 40 years	9880	53	102	274	13.2	335	63	263	264	179	13.6	196
Red pine[4] 40 years	16040	24	155	123	15.3	173	84	108	185	101	34.2	68
Jack pine[4] 40 years.	11840	24	118	119	9.3	166	52	87	128	55	22.2	70

nd - not determined 1 - ref. 27 2 - ref 108 3 - ref 15 4 - ref 3

the U.K., two power stations are currently proposed that would use slash material from local large spruce plantations as part of their fuel input. The harvesting and utilization of stump and root material can further increase biomass harvesting from a site, although this option will not be considered in the current review.

There has been concern that timber harvesting in general will result in a decline in site quality, with subsequent decrease in the growth of future crops. There are two main concerns: soil damage by compaction and nutrient removal. Both of these may be affected by the intensity of the harvesting operation. For example, it is well established that the concentration of nutrients in fine branches, bark, and foliage is higher than in stemwood (Table 1; see also Maliondo, 1988). The increase in biomass harvested from a site during WTH will, therefore, increase the removal of nutrients disproportionally. As a result, the impact of WTH on the nutritional quality of a site has been the subject of a number of research studies, and the literature on the subject is now extensive.

This paper reviews this literature and attempts to derive general principles that may be useful to the forest manager. Nutrient fluxes into and out of a forest ecosystem will be discussed, together with the influence of slash removal on these fluxes. Difficulties in deriving estimates for these fluxes will also be highlighted. The paper will then discuss the usefulness of nutrient balance sheets in considerations of the sustainability of WTH as a management practice. The importance of rotation length will be explained. The review will concentrate on temperate forest systems where the primary objective of management is sawlog timber production. Hence, short-rotation forestry of less than about 25 years will not be considered. Most of the literature considered derives from the U.S.A., Canada, New Zealand, and Europe.

Preparing a Nutrient Balance Sheet

For research purposes, it is, in principle, simple to determine the effect of harvesting on the nutrient status of a site. What is required is a "budget" of nutrient inputs to and outputs from the forest system under study, as illustrated in Figure 1. In order to gain an indication of the significance of the fluxes, estimates of the nutrient status of that site in terms of its "available" and total nutrient pools are also required.

Inputs to the system can be estimated by analyses of rainwater chemistry and N fixation processes. The weathering of soil minerals will also provide inputs to the system and requires evaluation.

Harvesting outputs can be calculated in one of two ways for any given intensity of slash removal. Either the component parts of a tree of mean diameter at breast height (dbh) are measured in detail (*e.g.*, Teller, 1988), or trees are taken from the range of diameter classes and divided into component parts, measuring the wet weight of these components, and then taking a representative sample from each component for dry weight and chemical analyses. The total allocation of nutrients to different parts of the tree can be calculated by multiplying the concentration by the dry weight of that component. Relationships can be derived between tree diameter and biomass (*e.g.*, Johnston and Bartos, 1977; Mitchell *et al.*, 1981; Pehl *et al.*, 1984) and an assessment made of the nutrients removed from the system by either CH or WTH. Leaching losses of nutrients can be measured by analyses of soil water chemistry in lysimeters below the rooting depth (*e.g.*, Johnson *et al.*, 1988; Mann *et al.*, 1988), or in ditch or stream water leaving the site (*e.g.*, Adamson and Hornung, 1990; Likens *et al.*, 1969).

The balance between the input and output fluxes will indicate if the ecosystem is undergoing a net gain or loss in the capital of any particular nutrient over a given time period. However, although such a nutrient balance sheet is simple to conceive, it is both difficult to produce and to interpret.

INPUTS		OUTPUTS
Atmospheric deposition		Leaching and surface run-off
Fixation (N only)	FOREST ECOSYSTEM	Harvested biomass
Mineral weathering		Gaseous losses (N only)
Fertilizer		Erosion

Figure 1. Nutrient inputs and outputs to a forest ecosystem.

Inputs

Atmospheric Deposition

Inputs to a forest via wet deposition can be measured by chemical analyses of rainwater (*e.g.*, Stevens *et al.*, 1988). However, many of these inputs (especially N) have changed over time as a result of pollution, and to predict future inputs from this source necessitates making large assumptions. Dry and occult deposition of nutrients will increase as forests grow and the filtering effect of the tree canopy increases. There is also evidence that atmospheric deposition varies with tree species (Hornung *et al.*, 1990). Most studies, however, use bulk precipitation for estimating inputs, as the quantity of nutrients in throughfall chemistry either leached from, or taken up directly by, the foliage is unknown (Hornung *et al.*, 1990). This can lead to substantial underestimates of inputs, especially where pollution is high (Johnson, 1992b). Indeed, including an estimate for dry deposition can turn net losses of some nutrients into net gains (Mann *et al.*, 1988).

Nitrogen Fixation

In the case of nitrogen (N), fixation of atmospheric di-nitrogen can contribute to inputs. This source is considered to be minor (approximately 0.1 kg/ha^{-1}/yr^{-1}) but may be substantial (50-80 kg/ha^{1}/yr-$^{1)}$ where plants with N-fixing associations occur, *e.g.*, alder, broom, or lupins (Miller and Miller, 1991) and may have a significant effect on productivity of low quality sites (Dyck and Skinner, 1988).

Mineral Weathering

Weathering of soil minerals is also often included in the input side of the equation, although whether this is a true "input" or a transformation of nutrients already within the forest ecosystem, is debatable. To overcome this problem, some studies use a threshold size of particle, with only weathering of particles greater than this size being included as input. Such a system was used by Federer *et al.* (1989) in their summary paper of a number of North American studies. These authors stressed the uncertainty associated with their estimate of weathering inputs and the need for further research to improve them.

Outputs

Harvested biomass

The potential increase in output of both biomass and nutrients in the form of harvested boimass as a result of WTH has been illustrated in Table 1. There is a great deal of variability associated with these increases over CH that depends on site, species, stand age, and structure.

As the total quantity of crown material does not alter much after full canopy closure is achieved, the proportion of above-ground biomass and nutrients that are present in the slash material at harvesting will decline as tree size increases, so that the proportion of slash to stemwood decreases as a stand matures (Anderson, 1985). A change from CH to WTH will, therefore, be potentially most serious in small, comparatively young, crops. In the U.K., many of the forest crops that are grown on exposed sites, vulnerable to windblow, are felled prematurely. These crops often also occur on nutritionally poor soils, and this combination of poor soils and premature felling will make the sites more vulnerable to the consequences of WTH.

The species of tree being harvested also affects both the increase in biomass and nutrient depletion that occurs as a result of WTH. This is partly due to differences in nutrient concentrations between species, but mostly because of variations in the weight of crown components (Miller and Miller, 1991; Hendrickson *et al.*, 1987). In general, WTH of broadleaved species will remove more nutrients than coniferous species as the nutrient concentration of broadleaves tends to be higher, even if the foliage is allowed to drop prior to harvesting (Wells and Jorgensen, 1979). However, this difference may be overturned when harvesting losses are expressed on an average annual basis (Johnson and Todd, 1987) as rotations for broadleaves tend to be longer than those for conifers (*e.g.*, Johnson and Todd, 1987; Phillips and van Lear, 1984).

While outputs in harvested material would appear to be one of the most easily quantifiable fluxes, small sampling errors in nutrient concentration analyses, and biomass dry weight can lead to large errors when scaled up to the tree and hectare level. In addition, the actual amount removed from a site will be less than the calculated total biomass in the slash material due to breakage of branches and scuffing off of bark (Madgwick and Webber, 1987). Freedman *et al.* (1982) found that the estimate of nutrient output during any harvesting operation could be greatly overestimated (84% for N, 58% for P, 28% for K, 45% for calcium (Ca), and 41% for magnesium (Mg)) by estimates derived from either biomass regression or a stratified mean-tree approach when compared to measurements derived by sampling the chips actually harvested from plots. They considered that this overestimate was attributable partly to incomplete recovery of the biomass but also due to a tendency for regression techniques to overestimate standing crop biomass. Of particular importance to this review, this study also found that the estimated increase in nutrient depletion caused by WTH in comparison to CH was greater using the regression method than that actually measured in direct sampling of harvested biomass.

It is assumed throughout this paper that slash produced during a CH operation will be retained and spread fairly evenly on site for the next rotation. However, for a number of reasons, this may not be the case. Ease of cultivation, planting and regeneration, or hygiene reasons, may lead to slash being burned and/or being physically moved into windrows after a CH operation. Where this is the case, the loss of nutrients in the areas between the windrows caused by such intensive methods is often many times larger than the loss of nutrients in harvested biomass during WTH, due to the physical removal of the forest floor (Dyck and Beets, 1987). Therefore, if the presence of slash itself on a site after a CH operation subsequently results in the need for intensive site preparation, WTH may actually result in less nutrient loss if the forest floor is also retained (Tew *et al.*, 1986).

Leaching

Nutrients are transformed within the soil from "unavailable" reserves of soil and litter organic matter by the process of decomposition and mineralization undertaken by the soil microorganisms. Weathering of minerals will also contribute to the "available" pool of nutrients (except in the case of N), but will usually be a minor flux when compared to that from organic matter mineralization. Once in the "available" pool, nutrients are subject to immobilization, by plant or microbial uptake, in organic matter. "Available" nutrients will, however, also be subject to loss from the ecosystem by leaching and, in the case of N, through gaseous emissions. A major factor controlling leaching losses appears to be conversion of ammonium (NH_4+) to nitrate (NO_3-) by the process of nitrification. The NO_3- anion produced is only weakly held in the soil and, when leached, requires a balancing cation to also be lost (Wells and Jorgensen, 1979).

Leaching of nutrients will occur in all forests where there is a net movement of water through the soil profile. However, as mineralization and nitrification are mediated by microorganisms, they, and consequently leaching, will be strongly influenced by the soil microclimate and the energy value, nutritional quality and quantity of organic matter. Harvesting influences all these factors and leaching losses have often been shown to increase as a result of disturbances such as clear felling (Vitousek and Melillo, 1979; Bormann and Likens, 1979; Adamson and Hornung, 1990).

The retention or removal of slash from a site will further modify the factors influencing mineralization activity on a clear-fell site. Smethurst and Nambiar (1990a), for example, found that the litter beneath slash in a harvested radiata pine site with a sandy soil in southern Australia, had a considerably higher water content than that in the plots where slash had been removed. Removal of the slash and litter reduced mineralization of N, which in turn reduced N leaching (Smethurst and Nambiar, 1990b). Entry *et al.* (1987) found that the insulating effect of slash on a felled lodgepole pine site, with a cryochrept soil type, in Montana, U.S.A. allowed winter decomposition by microorganisms to continue in plots where slash was retained. Where slash was removed, microbial activity was inhibited by the freezing soil conditions. This was reflected in higher extractable soil nutrients in the slash plots. They also found that a slash cover protected the soil from desiccation during the summer and stimulated decomposition rates of litter.

Emmett *et al.* (1991a) found similar results in a study at Beddgelert in north Wales, U.K. Here, a stand of 49-year-old, first rotation, Sitka spruce growing on a ferric stagnopodzol was felled using both WTH and CH techniques. Leaching losses of NO_3 from lysimeters were increased twofold over a 15-month period in the presence of slash compared to where no slash or vegetation was present. As these losses were also observed where artificial slash had been placed on the soil surface, the increase in leaching was attributed to the effect of slash in producing microclimatic conditions that stimulated mineralization and nitrification, rather than increased inputs of N to the litter/soil system in the form of slash. In contrast, Hendrickson *et al.* (1985) found little evidence that nitrification activity was affected in the first year following either CH or WTH of a mixed conifer and broadleaved forest on a podzolic soil in Ontario, Canada. Production of NH_4^+ in the litter layer of the Ch plot was not significantly different from that of the unfelled control while in the WTH plot, NH_4^+ production was significantly decreased. Although both the extractable pool and production of NH_4^+ in the mineral soil was higher in both the harvested treatments than in the control, this was relatively less important as it was estimated that 75% of the NH_4^+ production activity occurred in the litter layer.

Although most studies do show an elevated leaching loss as a result of felling, its importance varies and may be small in some circumstances. For example, in a Douglas fir clear-felling study in Oregon, U.S.A., Martin and Harr (1989) found only small absolute increases in NO_3 leaching and could not detect any changes in the pH or concentration and net losses of cations.

Mann *et al.* (1988) compared average annual inputs and outputs from a number of studies investigating WTH in North America. They concluded that elevated leaching losses attributable to felling were short lived and insignificant when considered over a whole rotation and so only used the leaching data from uncut forests in their calculations. However, it has been shown that leaching losses can vary as a result of stand age (Stevens *et al.*, 1990). It may, therefore, not always be valid to use data only from mature crops as an average leaching value over the whole of the rotation.

In contrast to Martin and Harr (1989) and to the studies considered by Mann *et al.* (1988), Goulding and Stevens (1988) reported large increases in both potassium (K) and NO_3^- dependent on the type of harvesting employed. Leaching losses of K from the CH plots were increased in magnitude compared to the WTH plots, with the difference almost cancelling out the differences in K removal in harvested biomass from the two treatments. At the same site, Stevens and Hornung (1990) observed a lengthening of the period over which elevated NO_3^- leaching losses occurred in the CH plots compared to the WTH plots, so that again the differential removal of N in the biomass was partly offset by differences in leaching fluxes (see Table 2). In such a situation, it would obviously be important to include these additional leaching losses in the nutrient rotation length balance sheet.

The rate at which a site is recolonized by vegetation has been recognized as a major factor affecting the magnitude of leaching losses following disturbance (Vitousek

Table 2. Nutrient inputs and outputs (kg/ha^{-1}) for a 50-year rotation at Beddgelert forest. (Data from Stevens *et al.*, 1988 and Fahey *et al.*, 1991.)

	N (kg/ha^{-1})		P (kg/ha^{-1})		K (kg/ha^{-1})		Ca (kg/ha^{-1})	
	CH	WTH	CH	WTH	CH	WTH	CH	WTH
INPUTS								
Bulk deposition	520	520	7.5	7.5	223	223	375	375
OUTPUTS								
Harvested biomass	128	428	12.3	43.5	38	144	151	279
Leaching	624	624	0	0	198	198	952	952
Harvesting leaching	208	148	0.7	0.1	108	32	66	44
BALANCE	-440	-680	-5.5	-36.1	-121	-151	-794	-900
Percent increase by WTH	55		556		25		13	

[1] Additional leaching losses resulting from the disturbance at time of clear felling.

Table 3. Differences in leaching losses and nutrient accumulation between the conventionally harvested and whole-tree harvested plots at Beddgelert. (Totals for 4 years after felling.) (Data from Fahey *et al.*, 1991.)

	N (kg/ha^{-1})	P (kg/ha^{-1})	K (kg/ha^{-1})	Ca (kg/ha^{-1})
Leaching	60	0.6	76	22
Vegetation accumulation	-35	-4.1	-23	-5

and Matson, 1985). At Beddgelert, it has been estimated that the uptake and immobilization of N in vegetation biomass in the 4 years after felling can account for a significant proportion of the difference in leaching losses between the WTH and CH plots (Table 3) (Fahey *et al.*, 1991). In a lysimeter study at the same site, grass growth occurring in the absence of slash reduced leaching losses of NO_3- to 19% of the losses from the lysimeters with no slash or vegetation, and to 10% of the losses under slash (Emmett *et al.*, 1991a). An experiment in New Zealand compared NO_3- loss after forest disturbance in different ecosystems, including both Douglas fir and Radiata pine crops. Rapid vegetation regrowth was thought to be responsible for the reduced NO_3 leaching from the clear-felled plots in comparison to the plots that had been trenched to eliminate root uptake without disturbing the canopy (Dyck *et al.*, 1983).

Fahey *et al.* (1991) discussed a number of studies that have examined vegetation regrowth following CH and WTH. They concluded that although there are examples to the contrary, in general, vegetation growth is higher following WTH than CH, probably due to the effect of logging on light and temperature at the soil surface. The removal of slash during WTH operations can, therefore, have a strong effect on the magnitude and longevity of increased nutrient leaching losses simply through effects on the rate at which the site is subsequently recolonized by vegetation. Smethurst and Nambiar (1990b) suggested that the management of ground vegetation should take this into account with minimal weed control resulting in reduced leaching losses. This suggests that sites where the rate of vegetation regrowth is slow, even in the absence of slash, may be less suitable for WTH.

The effect of clearfelling and slash removal on leaching losses is not, therefore, consistent between studies and does not appear to be related to nutrients left on site after harvesting, nor any easily measurable soil nutrient pool (Mann *et al.*, 1988).

Gaseous Emissions

In the case of N, gaseous losses by denitrification and volatilization can occur. The acidic nature of many forest soils means that volatilization of NH_4+ is usually extremely low, even after the application of urea fertilizer (Hulm and Killham, 1988). This acidity has, in the past, also been considered to result in insignificant nitrification, and hence denitrification, rates. There is now, however, substantial evidence that nitrification can occur in these soils, and can increase significantly after felling (Bormann and Likens, 1979; Adamson *et al.*, 1987). Similarly, there is now increasing evidence that denitrification also occurs in forest soils (Robertson and Tiedje, 1984; Goodroad and Keeney, 1984; Davidson and Swank, 1986). It is difficult to obtain field estimates of denitrification rates and very few harvesting studies have included such measurements. There is, however, evidence that at some sites, such losses can be of the same order of magnitude as leaching losses (Dutch and Ineson, 1990). It is reasonable to assume that if a treatment such as slash removal affects microbial activity and either increases or decreases NO_3- production, N outputs via denitrification may be affected in the same direction.

Erosion

Nutrients are also lost from a site as a result of erosion and surface water run-off, especially after harvesting (Powers, 1989) and this again can be affected by the intensity of harvesting. Depsite this, such losses are rarely included in budget studies.

Examples of Budgets and Results

An early example of a whole-tree harvesting budget study is that of a 40-year-old aspen/mixed hardwood stand in Wisconsin, U.S.A. (Boyle and Ek, 1972; Boyle *et al.*, 1973). Actual nutrients removed in the harvested biomass were measured and compared to input from precipitation, mineralization, and weathering. Leaching and erosion losses were considered minimal on this site and were, therefore, not included. Calculations indicated that the supply of the major nutrients, N, phosphorous (P), and K were sufficient to replace the losses for an indefinite number of rotations, but that Ca showed a negative balance and was predicted, therefore, to be the nutrient most likely to become limiting in future rotations.

The suggestion that Ca is the nutrient most susceptible to depletion by intensive harvesting is supported by other studies (*e.g.*, Freedman *et al.*, 1986; Hopmans *et al.*, 1987; Mann *et al.*, 1988; Federer *et al.*, 1989; Hornbeck *et al.*, 1990). Alban *et al.* (1978) noted that the large drain of Ca during forest harvests resulted from the large accumulation in trees compared to agricultural crops. They observed that this may point to the need to study a wider range of nutrients than the normally considered N, P, and K. Indeed, some studies have indicated that micronutrients, *e.g.*, boron (Ballard and Will, 1981) may at certain sites be more susceptible to depletion than major nutrients.

In the U.K., one of the most intensive harvesting studies was that carried out by the Institute of Terrestrial Ecology and the Forestry Commission at Beddgelert forest, already mentioned above. Input and output data were collected for both the CH and WTH treatments and are summarized in Table 2.

From this, it would appear that the cumulative balance sheet over a 50-year rotation at Beddgelert is in deficit for all four nutrients studied, at both intensities of harvesting. However, there are a number of points that need to be noted before such conclusions can be drawn.

The input side of the balance has considered only bulk precipitation and so dry deposition will have been underestimated (Stevens *et al.*, 1990). The fact that N, usually considered to be tightly conserved within a forest system, is being leached prior to felling at a rate greater than the inputs in the bulk precipitation, together with the occurrence of nitrification on site, indicate that N is not limiting tree growth. Using an estimate for dry deposition derived for a different forest ecosystem, of 308 $kg/ha^{-1}/yr^{-1}$ (Mann *et* al., 1988) could substantially reduce this perceived imbalance. Similarly, although probably not to the same extent, inputs of other nutrients are likely to have been somewhat underestimated by the bulk precipitation measurement.

No estimate for weathering inputs has been included in the above balance. Goulding and Stevens (1988) examine the data available for the site on K reserves, and conclude that although short-term reserves are small, long-term reserves would be weathered at a rate sufficient to meet tree demand for the short to medium term (up to 1500 years). Whole-tree harvesting has the most dramatic effect in increasing outputs of P. However, P is often added as a forest fertilizer and one application of P at standard rates (50-60 kg P/ha) would more than balance outputs. The high leaching output of Ca is explained by bedrock weathering beyond the reach of most tree roots (Stevens *et al.*, 1988). When the soil reserves of Ca within the rooting zone are considered, it was estimated that the total reserve was approximately equal to the quantity of Ca removed by the WTH. Therefore, in this study, it appears that Ca is again the nutrient most susceptible to depletion by harvesting.

Some studies of inputs/outputs have shown a net loss of nutrients, even before the forest is felled, *e.g.*, Federer *et al.* (1989) listed a number of sites in the eastern U.S.A. where Ca, Mg, and K leaching losses exceeded gains by wet deposition. Even after estimates of weathering and dry deposition were included, losses of Ca by leaching were still greater than the inputs in precipitation, a theory also discussed by Johnson *et al.* (1988). It is not within the scope of this paper to discuss the effect of acidification on leaching. However, the possibility that forest systems may not be in balance even in the absence of felling should be borne in mind. In such cases, intensification of harvesting may bring forward site degradation.

Limitations of a nutrient balance sheet

Interpretation of perceived imbalances

Internal processes do not need to be understood in order simply to determine the net effect of any harvesting operation on the total nutrient capital of a site. However, as discussed above, an understanding of the internal processes can help in predicting how the fluxes may change over time and between sites or treatments. This may be useful in estimating the likely validity of measurements taken only over a short time period.

The discussion has concentrated on looking at the difficulties associated with compiling a nutrient balance sheet for any particular site. However, even where such information is available, there remains a problem of interpretation. In order to evaluate the importance of any predicted imbalance, an estimate must be made of the site's reserves of nutrients and the likely availability of these nutrients over the numbre of rotations of interest. Deriving such an estimate is very difficult. Authors have used both the "available" pool or the total site capital of nutrients for comparisons with any imbalances. There are problems with both approaches.

For example, incubating soil in the absence of roots and measuring extractable inorganic N is a common procedure for estimating the "mineralisable" or "available" soil N pool. However, such a proceudre will only measure net mineralization as uptake and immobilization by microorganisms of inorganic N is not accounted for. There is evidence that net mineralization is not well related to gross mineralization, and hence availability (Vitousek and Andariese, 1986). Johnson (1992b), in his review of N retention in forest soils, argues that chemical soil extraction procedures designed to estimate the "available" nutrient pool will underestimate long-term nutrient availability, as trees appear to have the ability to effectively "mine" the soil for nutrients making them good competitors for resources in the long term. The lack of a model for predicting the outcome of competition between heterotrophic microorganisms, plants, and nitrifiers for the mineralisable N pool is highlighted.

Other studies have concentrated on comparisons with total soil reserves of nutrients. In a study of nutrient losses as a result of leaching and WTH in a mixed oak wood and loblolly pine forest, Johnson and Todd (1987) found that atmospheric inputs of N approximately balanced outputs by WTH and leaching over the rotation at both sites. Although, by contrast, phosphorus inputs were far short of compensating for the outputs, only a small proportion of the large total soil reserves of phosphorus was required to allow sustained growth for several more rotations. The comparisons with total soil reserves may, however, be misleading since, even though trees contain relatively small amounts of phosphorus compared to reserves, phosphorus is relatively slowly available for plant uptake (Smith *et al.*, 1986). Comparison of the net flux of nutrients from a forest ecosystem with total soil nutrient determinations will, therefore, give an overestimate of nutrient supply capacity as not all the total will be mineralized, even in the long term.

Other confounding effects of slash removal

Harvesting, especially WTH, will have effects on a site other than just nutrient removal, such as loss of organic matter and soil damage. In terms of overall site quality, these may be just as important, or more so, than the nutritional effect. In addition, they may themselves have an impact on nutrition so that it is difficult to isolate one effect from another (*e.g.*, Dyck and Beets, 1987).

Harvesting has generally been linked to a loss in soil organic matter (Covington, 1981; Federer, 1984) with WTH exacerbating the decrease. Soil organic matter is important not only as a source of nutrients during its decomposition but also for its role in maintaining soil structure and in helping to retain soil moisture. For example, in a study reported by Ballard and WIll (1981), the loss of organic matter resulting from the removal of logging debris at harvest, and by repeated removal of the developing litter layer in the next crop, was considered to cause unfavorable moisture and temperature conditions within the rooting zone. This was thought to be of equal importance to nutrient depletion as the likely explanation for the observed decrease in growth in comparison to the control plot.

However, a recent review by Johnson (1992a) questions the evidence for the loss of soil organic matter as a result of harvesting. Johnson suggests that this link has been overstated, and that there is little firm evidence of such a decrease. Even after a WTH operation, Huntington and Ryan (1990) found no detectable change in N or C content in the forest floor or mineral soil 3 years after the harvesting, although the variability associated with their estimates was increased. This was considered to be largely due to the mechanical mixing of the forest floor with the mineral soil (Ryan *et al.*, 1992). Organic matter decomposition and mineralization have been suggested to either increase (Smethurst and Nambiar, 1990a) or decrease (Huntington and Ryan, 1990) as a result of such mixing.

The use of heavy machinery during a modern harvesting operation will result in some degree of soil damage (a possible exception being where cable-crane extratction is used). This is likely to be increased during WTH as more produce is being removed from the site, necessitating an increase in the number of passes over the ground. Additionally, the slash left in CH operations is often placed so as to provide a mat for the machinery to pass over. If no such mat is available, then compaction and rutting can increase (Smith and Dickson, 1990). In a number of studies, soil compaction has been shown to reduce tree growth (Pyatt, 1983; Tuttle *et al.*, 1988; Corns, 1988). Compaction will limit root spread, and decrease oxygen diffusion and water drainage. This will not only affect the trees themselves, but can decrease microbial activity and hence mineralization.

On the other hand, the absence of slash during site establishment can sometimes remove the need for site preparation (Nelson and Dutch, 1991). This can reduce compaction by eliminating the need for heavy machinery at this stage.

Slash may also affect tree growth without apparently affecting the overall quality of the site. For example, in a lysimeter study at the Beddgelert site, the growth of Sitka spruce trees planted with slash was significantly increased compared to trees planted without slash (Emmett *et al.*, 1991b). This observation repeated that of Titus and Malcolm (1987), where Sitka spruce was found to be significantly larger at 3 years when planted through slash strips than when planted between these strips. The differential in growth observed by Titus and Malcolm was maintained even where NPK fertilizer had been applied and it was, therefore, considered to the due to improvements in microclimatic conditions rather than soil fertility. However, as Emmett *et al.* (1991b) found Sitka biomass to be reduced in the presence of grass, the effect of slash in suppressing weed growth can be a further mechanism whereby tree growth may be indirectly improved.

When trying to predict the effect of intensifying harvesting operations on future timber production, it is thus important not only to include measurements of nutrient transformation processes within the forest system, but also to consider other effects of slash removal that may influence tree growth and, in turn, nutrient uptake and immobilization within the tree.

Nutrient sustainability vs. productivity sustainability

Despite these difficulties of interpretation, compiling a detailed balance sheet of nutrient inputs and outputs from a site should provide a valuable basis from which to evaluate the importance of an intensification in harvesting on the nutrient capital of a site. However, the important factor is not the total nutrient capital of a site but the pool of nutrients available to a tree throughout the rotation. Making sure that nutrient inputs balance outputs does not imply that the productivity of a site for biomass production will be sustained. Immediately after clear felling, there is commonly a "flush" of nutrients into the available pool withing the soil. This increase in nutrient mineralization may not match the timing of nutrient uptake by the developing stand which is at a maximum just before canopy closure (Smethurst and Nambiar, 1990b).

Determining the availability of nutrients for tree growth is complex. Chemical analyses of soil water collected in lysimeters or streams can give an estimate of the nutrients lost from the system but do not imply much about their availability to plants. Frazer *et al.* (1990), using a chronosequence approach, found a continued effect of clear felling in increasing soil N mineralization for up to 17 years after regeneration. However, this effect could not be detected using conventional lysimetry. They concluded that the continued additional N being made available as a result of the disturbance at the time of clear felling was being incorporated into the rapidly growing forest vegetation.

As discussed in the section on leaching losses above, the presence or absence of slash on a site can strongly affect both the timing and size of fluxes of nutrients into the available pool. Whole-tree harvesting can, therefore, influence the nutrient availability and hence productivity of the next crop in addition to its more general effect on nutrient output from a site.

Extrapolating from the above, it is perfectly possible for the nutrient capital of a site to be depleted, but for this not to be reflected in nutrient availability in the short to medium term (possibly extending for a number of rotations). Tree growth would not be affected until the reduction in the soil capital was eventually translated into a reduction in the available pool of the nutrient. Conversely, it is possible for the nutrient capital of a site to remain in balance over a rotation length, but for the available nutrient pool to be depleted and thence for tree growth to decline.

Defining Sustainability

From the above discussion, it can be seen that the question as to whether or not any particular intensity of harvesting is "sustainable" is not simple to answer. The question must be more closely defined, both as to what is being "sustained" and at what level.

Firstly, what is being sustained? Sustaining a site's nutrient capital will not necessarily ensure that timber productivity will be maintained or vice versa. Indeed, managing for the sustainability of one of these aspects may, at some sites, necessitate sacrificing the other.

Secondly, the level at which either the nutrient capital of a site, or its timber productivity, is to be sustained must be considered. The FAO Forest Resources Division Director is quoted as saying:

"it must be accepted from the start that utilization of a given forest ecosystem implies some change in its structure and composition, and that sustainability cannot mean the identical reproduction of the ecosystem in its original state" (Anon. 1992).

It should, therefore, not be expected that when a largely natural forest is harvested, the output of nutrients at its harvest will be balanced by inputs before its next harvest. Similarly, the productivity of a forest may be radically altered by management. It is only once a forest is established in a management regime that a balance of nutrients, or the maintenance of a production level, could be viewed as an aim.

The Effect of Rotation Length

If the aim is to sustain a certain nutrient capital at a site, then as already discussed in this paper, inputs must balance outputs. An intensification of harvesting will normally increase outputs from the system. However, due to the linkage at certain sites between some losses, *e.g.*, leaching, and the intensity of harvesting, it is very important that net outputs be considered rather than simply the increase in outputs in harvested biomass.

Increasing harvesting intensity may also have an effect on inputs. For example, differences in soil moisture, temperature, and chemistry as a result of slash removal may affect mineral weathering rates, and atmospheric deposition will be affected by any residual tree canopy left after CH or by large piles of slash. These effects are, however, likely to be both small and short lived (Wells and Jorgensen, 1979), so that, in contrast to outputs, inputs can be considered to be largely independent of harvesting intensity (Maliondo *et al.*, 1990). The implication from this is that, as long as inputs are exceeding outputs during the main growing period of a rotation, harvesting outputs can be balanced by simply adjusting the rotation length. In theory, therefore, where intensifying harvesting increases net outputs, this can be offset against any financial gain from reduced restocking costs on a comparatively "clean" site or from the sale of harest residues. The importance of rotation length in influencing the nutrient balance has been highlighted, sometimes using computer simulation models, by many authors (*e.g.*, Aber *et al.*, 1978, 1979; Gordon, 1983; Phillips and van Lear, 1984; Sachs and Sollins, 1986).

Such an increase in rotation length to balance nutrients may fit in well with the current reappraisal of how forests are valued in many developed countries. Until recently, "products" from forested areas have largely been seen as timber. However, other forest "products", such as recreation, landscape, and conservation are increasingly being seen as being at least as important as timber. The value of most of these other "products" increases with rotation length. This, together with the public pressure to limit areas of clear felling (*e.g.*, Forestry Canada 1991), will increase the pressure to maximize biomass output at each harvest, but will also help to offset the effect that this will have on the long-term nutrient capital of a site. To many forest managers, however, the more immediate practical aim is to sustain the level of timber production from a site. A nutrient balance sheet exercise is of only limited value here as productivity is not directly dependent on the nutrient capital of a site. Nutrient availability itself is only one of a number of factors that may be determining growth. Predicting the effect of an intensification of harvesting on timber productivity necessitates knowing in detail what is limiting growth at any particular site and how this, and other potentially limiting factors, will be affected by slash removal. In the case of nutrient availability, the presence of slash can have a major effect, that will vary greatly depending on site factors. To predict this effect requires an increased knowledge of the complex processes controlling nutritional requirements of different species and an understanding of the interaction between these two. At present, these effects cannot be predicted for any given site with much degree of certainty and it is necessary to carry out individual studies on different site types to evaluate these processes.

Again, fertilizer inputs may be an option to sustain timber production but here it may not simply be enough to add the nutrients removed by harvesting. Rather, fertilizer applications should be timed for when nutrient availability does not meet the nutrient demand of the crop.

Conclusions and General Principles

There have now been a large number of studies examining the effect of whole-tree harvesting on nutrient dynamics and many papers have been written on the subject. Despite this, however, "solid evidence of its consequences on long-term productivity is surprisingly meagre" (Powers, 1989). This is largely due to the tremendous variability between forest ecosystems in the inputs, outputs, and nutrient transformation processes. Only very general principles can be derived from the literature.

a. There is no immediate simple link between sustaining a site's nutrient capital and sustaining its timber productivity.

b. In the long term, if fertilizer additions are not used, a site's nutrient capital will affect nutrient availability and hence timber productivity.

c. There is no simple way to predict the effect of whole-tree harvesting at a site on the sustainability of either the nutrient capital or the timber production.

d. Studies suggest that Ca is likely to be the nutrient most susceptible to depletion by harvesting at a variety of sites.

e. The effect of increasing harvest intensity on a site's nutrient capital will be greatest where soil reserves of nutrients are low and are of a similar size to reserves within the tree crop, *e.g.*, on sandy soils low in organic matter.

f. In terms of sustaining a site's nutrient capital, whole-tree harvesting is most suitable where forest rotations are long and least suitable where rotations are prematurely shortened due, for example, to windblow.

g. Rapid vegetation regrowth of a clear-felled site will minimize leaching losses and should be encouraged to maximize the sustainability of the nutrient capital. This may, however, decrease the timber productivity of sites where weed competition is important.

h. Fertilizer inputs can be used to sustain either nutrient capital, or timber productivity where nutrition is the limiting factor.

i. Sustaining a site's nutrient capital is only feasible where inputs of nutrients exceed outputs in the absence of felling.

j. Whole-tree harvesting may be beneficial where large quantities of slash material would necessitate intensive site preparation to establish the next rotation.

k. Whole-tree harvesting may be advantageous where leaching losses to water courses are particularly sensitive and where slash removal has been shown to reduce leaching.

l. Areas of high pollution leading to acidification will be more sensitive to losses of cations by whole-tree harvesting.

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CUMULATIVE EFFECTS OF SILVICULTURAL TECHNOLOGY ON SUSTAINED FOREST PRODUCTIVITY

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Abstract

The feasibility of using significant amounts of wood for bioenergy will ultimately depend on whether or not intensive harvesting and forest management are consistent with sustainable forestry. In addition to producing high wood yields, forest management must ensure the potential of forest sites to produce a persistent amount of biomass through time. Biomass removals from forests must not exceed levels that would compromise long-term conservation and cycling of energy, nutrients, water, and air. Furthermore, silvicultural practices should be used that speed production without reducing site carrying capacity. The cumulative effects of silvicultural practices are difficult to model empirically because of an infinite number of site-treatment combinations. Process models based on fundamental growth deteminants are needed that predict production functions based on treatment effects on system conditions and processes. Preliminary process work on natural, agricultural, and forest systems suggest that silvicultural approaches should build complexity into forest systems in order to conserve and cycle energy, water, nutrients, and air. Foresters should balance high yields of preferred forest components with biological processes that confer sustainable conditions.

Introduction

Assessing the "Environmental Consequences of Intensive Harvesting" is the stated purpose of the International Energy Agency/Task IX - Activity 4 (IEA-IX-4) Working Group. This activity is a 3-year project that began in 1992. Once per year, the project brings together forest scientists from around the world to study, deliberate, and develop recommendations pertaining to the feasibility and use of wood for bioenergy.

From a biological standpoint, the feasibility and use of wood for bioenergy will ultimately depend on whether or not whole-tree harvesting and intensive forest management are activities consistent with sustainable forestry. The general publics of most developed countries are demanding the conservation and wise use of natural resources to ensure the integrity of long-term life-support systems. In response, a primary goal of the forestry communities in most developed nations is forest management that ensures the long-term sustainability of forests while simultaneously providing forest products and amenity values. This goal is broader than the traditional goal of sustained harvests or sustained yields. This broader view of sustainability, as defined by a professional group of American foresters (SAF 1991), incorporates management impacts on ecosystem processes, and the long-term capacity of ecosystems to produce the commodity and non-commodity values demanded by society. Concern for sustainable ecosystems is also being addressed by research organizations: planning documents by the State Agricultural Experiment Stations and Cooperative State Research Service (1992), the Ecological Society of America (Ludchenko *et al.* 1991), and the National Research Council (Gordon 1990) have all identified long-term sustainability of ecological systems as priority research items for the 1990s.

The IEA-IX-4 group's study of forest sustainability issues is specific to biomass production systems. The questions being asked are: What level of biomass harvest is consistent with sustained productivity; and what effect does intensive forest management for biomass have on the ability of the forest to sustain constant levels of production in perpetuity?

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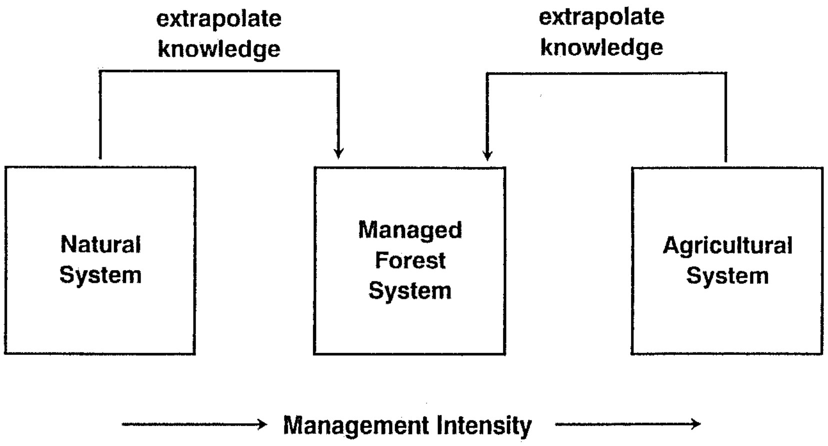

Figure 1 Model depicting the extrapolation of knowledge to managed forest systems

The forestry community has been struggling with these questions because there is no forestry frame of reference against which to seek answers. Forest rotations are long relative to the span of time a person is actively engaged in managing or observing them. Furthermore, except for the last two to three managed rotations in several developed parts of the world, forests have been hunted and gathered instead of cultured. Therefore, in order to more fully answer questions about long-term forest response to cultural inputs, it is helpful to draw on experiences from both natural systems and agricultural systems to make inferences about managed forest systems (Figure 1).

Sustainable Biomass Removal

A fundamental tenet of natural-system development is that, with time, ecosystems move toward maximum persistent biomass regulated by essential nutrients and water and constrained by climate (Reichle *et al.*, 1975). This is demonstrated by primary succession in a variety of ecosystems. A classic documentation of succession toward maximum persistent biomass is a report by Crocker and Major (1955), who characterized a chronosequence of vegetation and soil development following glacial retreat at a site in Glacier Bay, Alaska. Commensurate with succession toward a diverse, productive, and stable plant community was soil development characterized by increasing levels of organic matter, nitrogen, and soil structure. Along with a climax level of production and productivity is an associated level of ecosystem resilience conditioned by perturbations to the system over space and time (Jordan *et al.*, 1972). The evolution and function of natural systems suggests that biomass harvests that perturb system structure and function, to an extent no greater than that caused by natural catastrophes with which the system evolved, should be sustainable. For example, clear-cut harvesting of oak-hickory and mixed mesophytic forests of the eastern U.S. should be sustainable if the forestry operations are no more severe than a hurricane blow-down or a heavy fire. In all cases, rootstocks, seed pools, a portion of the aboveground biomass, and soil structure and function are largely intact for a quick, sustainable recovery of a forest system similar in character, function, and productivity to the one removed.

However, if a forest system is converted to and maintained at an earlier successional stage, production and site productivity will decline to a level commensurate with the productivity level associated with that stage in nature (Lundgren, 1978). Examples of this type of forest conversion include natural, mixed oak-pine to pine plantations in the southeastern U.S., conversion of mixed conifers to ponderosa pine in the Sierra Nevada range of the U.S., and conversion of native eucalyptus forests to exotic pines in Australia. Because the biotic potential of most forest genotypes usually exceeds abiotic carrying capacity, the first rotation of the plantation forest on a site subsidized by soil resources from a climax system is unusually productive. With subsequent rotations of plantations, below-ground condition will equilibrate to a level commensurate with the above-ground condition. In the case of the forest conversions mentioned above, soil organic matter, nitrogen, and structure will decrease along with productivity. Presumably, the less productive system imposed is of higher economic value for reasons other than net primary production (e.g., wood type, fiber type, piece size and structure of the biomass, management and harvesting efficiency).

As nearly all forest type conversions are toward earlier successional stages, site productivity will invariably decline. This decrease in productivity due to forest type conversion is predictable based on our understanding of the development of natural systems. Productivity shifts will occur because soil productivity is a function of soil organic matter, nitrogen, and structure, all of which are autogenically tied to the vegetation successional sequence. After reaching a productivity equilibrium consistent with the successional stage found in nature (usually after one or two rotations), this new productivity equilibrium can be maintained if biomass harvests do not significantly interfere with the new system's ecological condition. Again, a rough measure of allowable levels of biomass removal is the amount removed by natural processes. For example, southern pine forests have a natural history that includes light to severe fire several times during a stand rotation. A plantation-management parallel might consist of complete tree removal every 20 to 40 years depending upon site quality. Removals may be more frequent if residual site organic matter is conserved and nutrients are subsidized via fertilization.

Components of Forest Productivity

The second question is whether or not the productivity of intensively managed plantation forests is sustainable. Agriculturists have long concentrated on sustaining yields through technological advances while the inherent productivity of the land declined. Using this lesson from agriculture, it is important for foresters to distinguish between sustained forest productivity and site productivity in the context of biomass production. Sustained forest productivity means maintaining a certain level of harvest or *yield* through time; sustained site productivity means maintaining the *potential* of a forest site to produce a persistent amount of biomass through time. The difference between forest and site productivity is shown in the model below:

Forest Productivity	=	**Biotic (Plant) Factors**	+	**Abiotic (Site) Factors**	+	**Cultural Factors**
		• genotype		• climate		• water control
		• ecophysiology		• topography		• nutrient control
		• community		• soils		• pest control

Sustained Forest Productivity Versus Sustained Site Productivity

First Rotation	harvest yield 100%	=	wild genotype 25%	+	site carrying capacity 50%	+	cultural treatments 25%
Second Rotation	harvest yield 100%	=	improved genotype 30%	+	degraded carrying capacity 40%	+	improved treatments 30%
Difference	0	=	5	-	10	+	5

Figure 2 Hypothetical comparison between first and second rotation yields (forest productivity) shown as a function of genotype, site carrying capacity, and cultural treatments. This example shows that forest productivity was sustained over two rotations, but site productivity (carrying capacity), one component of forest productivity, was reduced by 10%

Forest productivity is a function of a combination of factors, as shown. Site productivity is a function of the subset of abiotic factors. The maximum production attainable on a site, given unlimited time, is the site's carrying capacity, which is controlled by abiotic factors. Any change in carrying capacity is due to a change in abiotic factors. Both increases and decreases in the carrying capacity of forest or agricultural ecosystems are usually associated with a change in soil condition, since climate and topography are relatively fixed.

This model shows that forest productivity can be sustained while site productivity declines. In Figure 2, a hypothetical harvest yield (forest productivity) is shown as a function of genotype, site carrying capacity (site productivity), and cultural treatments. In producing the second rotation, compared to the first, improved genotypes and cultural practices enhanced production, but a degraded carrying capacity reduced production by an equivalent amount. This resulted in a zero net difference in forest productivity or yield between the first and second rotations. Site productivity was damaged, but forest productivity was sustained nonetheless. It follows that forest productivity would have been greater in the second rotation had carrying capacity not been damaged.

This tradeoff in productivity components has been the rule in American agriculture. In the past 20 years, the yields of agronomic crops have been relatively constant despite improved genotypes and cultural practices. Chronic soil erosion, and deteriorating soil quality, have neutralized productivity gains made by improving genotypes and cultural practices (Lal and Pierce, 1991). As the costs of marginal gains from improved genotypes and cultural practices continue to increase, maintaining carrying capacity or soil quality will be necessary in order to maintain yields. This agricultural experience should be extrapolated to forestry. Foresters must recognize the components of forest productivity (Figure 2), understand the effects of forest management practices on each component, and appreciate how cumulative management affects the sustainability of forests.

Cumulative Effects of Silvicultural Practices

Switzer (1978) depicts forest productivity figuratively (Figure 3A) showing production (biomass accumulation) as a function of time. A logistic growth curve is shown bound on the left by the trees' biotic potential, and bound on the top by the site's carrying capacity. The time required to attain maximum production commensurate with the site's carrying capacity is a function of what Switzer calls environmental resistance (e.g., deficiency of transient resources such as water and available nitrogen).

Using this general model as a base, the influence of various forest management practices on forest productivity is shown in Figure 3B. Changing the biotic potential is the first general way foresters have increased productivity. For example, an improved genotype would shift the biotic potential curve to the left as

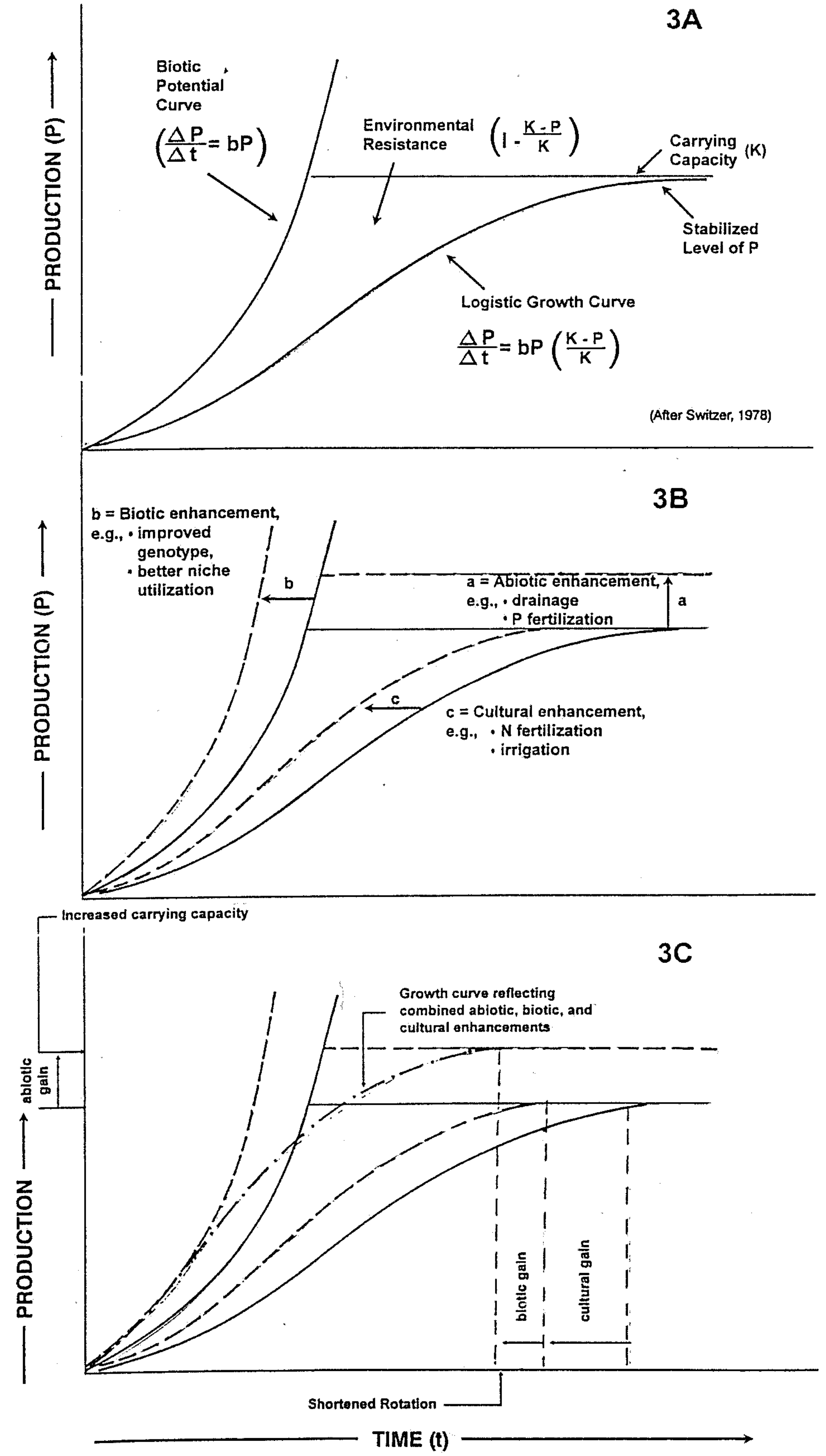

Figure 3 Production function and its determinants (3A); effect of some silvicultural practices on the production function (3B); combined effect of silvicultural practices on the production function (3C)

shown. Timing the lifting and outplanting of seedlings to take advantage of the thermoperiodism of root growth potential (Feret and Kreh, 1985) is an ecophysiologic method of increasing biotic potential. Maximizing niche space with multiple species (*e.g.*, mixed oak-pine stands) is yet another way of increasing biotic forest productivity at the community level. Polycultures are often more productive than monocultures (Vandermeer, 1989). Higher production levels resulting from better niche space utilization by polycultures are expressed as the "land equivalent ratio," or the land area required for a monoculture to produce the same amount as 1 ha of polyculture (Mead and Willey, 1980).

Land drainage (Terry and Hughes, 1975) and phosphorus fertilization (Pritchett and Gooding, 1975) are classic examples of land treatments that confer a more-or-less permanent change in site productivity. These treatment effects are depicted in Figure 3B as the kind that increase site carrying capacity. By contrast, a single water irrigation treatment or application of nitrogen fertilizer has little long-term effect on site productivity; their effects are ephemeral because added water and nitrogen are transient resources. The effect of a pulse of irrigated water is generally understood. The response in the soil of a nitrogen addition via inorganic fertilizer is similar because, unlike P, there are no substantial soil exchange or fixation mechanisms to retain nitrogen added in excess of immediate plant and microbial demand. Therefore, like added water, added nitrogen affects forest productivity by temporarily reducing environmental resistance. That is, added water and nitrogen displace the logistic growth curve to the left (Figure 3B), allowing maximum attainable production (site carrying capacity) at an earlier time (in effect, shortening the stand rotation). The relative response of treatments that change carrying capacity compared to those that reduce environmental resistance is shown in Figure 4. Evidence for this generalization can be found in reports by Terry and Hughes (1975) and Langdon and Trousdell (1978) on drainage responses, and in reports by Ballard (1984) and Pritchett and Gooding (1975) on fertilization responses.

The cumulative effects of forest management practices that enhance forest productivity are shown in Figure 3C. Biotic, abiotic, and cultural productivity determinants, when changed in a positive direction simulta-

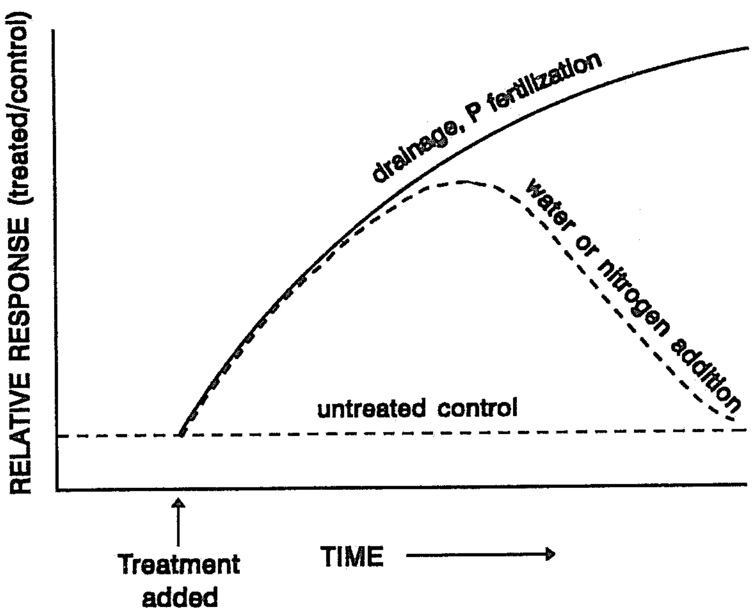

Figure 4 Generalized (drainage, P fertilization) comparison of silvicultural treatments that elicit relatively permanent versus (water, nitrogen) ephemeral responses in stand growth

neously, can increase productivity by both increasing the level of maximum production (carrying capacity) and by reducing the time required to reach this new level of production. The relative gain from cumulative silvicultural effects is depicted as the increased area under the logistic growth curve.

Forest productivity declines, when they occur, are usually attributed to reduced site carrying capacity (negative abiotic changes) (Farrell et al., 1981). Exceptions include biotic decline due to persistent insect and disease damage, and air pollution damage. In forestry, declines due to reduced carrying capacity are usually associated with nutrient and organic matter depletion, and soil physical changes due to harvesting and stand management disturbances. Morris and Lowery (1988), Miller *et al.* (1989), McColl and Powers (1984), and Squire *et al.* (1991) describe and review the positive and negative influences of intensive forest management practices for several major forest types in different parts of the world. Based on their reviews, Table 1 lists several forestry practices that can have both positive and negative effects on forest productivity. These practices can be grouped under stand harvest, stand establishment, and stand management. Within the context of the models in Figures 2 and 3, productivity is increased by increasing the biotic potential and decreasing environmental resistance, but these treatments can simultaneously reduce carrying capacity (abiotic potential). For example, whole-tree harvesting may cause site-damaging nutrient depletion on the poorest sites (Johnson, 1983). Furthermore, site damage can occur if harvesting results in physical soil changes that interrupt normal site drainage, water storage and supply capacity, and soil aeration (Burger *et al.*, 1988).

Nutrient and organic matter depletion is more often due to stand establishment practices (Table 1) used to prepare the site for planting (Burger and Pritchett, 1984) or to reduced interference from unwanted vegetation. For example, short-term gains in early tree growth achieved by controlling herbaceous and woody weeds by harrowing may be counterproductive if the treatment has the side effect of increasing soil erosion, accelerating organic matter decomposition, and breaking up soil structure. Data from O'Connor and Burger (unpublished) from a site preparation study on the Piedmont of South Carolina and Georgia, USA, show that harrowing alone reduced hardwood basal area from 43% on non-harrowed sites to 5% on harrowed sites by age 9 (Table 2). Soil erosion estimates for these treatments were <1 and 40 mg/ha/yr, respectively. Slash raking or windrowing is commonly used to improve the effectiveness of harrowing operations. Harrowing after raking reduced the hardwood basal area by an additional 3% (5% versus 2%), but increased estimated soil loss from 40 to 65 mg/ha/yr (Table 2). Soil-loss estimates were for the year following site preparation. For

Table 1 Intensive forest management operations that can have both positive and negative effects on forest productivity depending on site character and the manner in which the treatment is imposed

		Productivity Component	
Forestry Practice	**Biotic**	**Abiotic**	**Cultural**
Stand Harvest			
clearcut harvesting	+	-	
Stand Establishment			
species conversion	+	-	
tillage	+	-	+
burning	+	-	+
drainage	+	+/-	
Stand Management			
prescribed burning	+	-	+
thinning	+	-	+

Table 2 Site preparation treatment effects on ninth-year hardwood basal area and first-year soil loss potential in pine plantations on the Piedmont of South Carolina and Georgia

Treatment	**Hardwood BA (%)**	**Soil Loss (mg/ha/yr)**
Control	43a[1]	0.2c
Windrow	4b	4.5c
Harrow	5b	39.6b
Windrow + Harrow	2c	64.5a

[1] Values within a row followed by different letters are significantly different (= 0.10).

this site type and treatment, erosion decreases exponentially and returns to a base level after about 4 years (Dissmeyer, 1980). Pine-growth response was initially higher on the raked and harrowed sites following the "assart effect" (Tamm, 1979), but after age 2, relative stand volume of the raked and harrowed plots decreased each year and converged with volume levels of the harrowed-only plots by stand age 9 (Figure 5). This suggests that the small additional amount of hardwood control hardly warrants the cost of the added raking treatments, and it suggests that increased soil erosion, together with the large amount of organic matter removed, could decrease productivity.

In a similar fashion, burning for stand establishment purposes can increase productivity by controlling species and genotype (biotic component) and reallocating nutrient and water resources to preferred plants (cultural component) (Table 1). Hot site preparation burns, however, can adversely reduce organic matter and nutrient reserves and expose steep slopes to higher erosion potentials. Site drainage can positively change species compositions (biotic) and increase soil aeration (abiotic). A negative abiotic effect could occur if drainage greatly accelerated decomposition of organic matter and nutrient release in excess of plant demand. Prescribed burning and stand thinning later in the stand rotation also have benefits that could be negatively

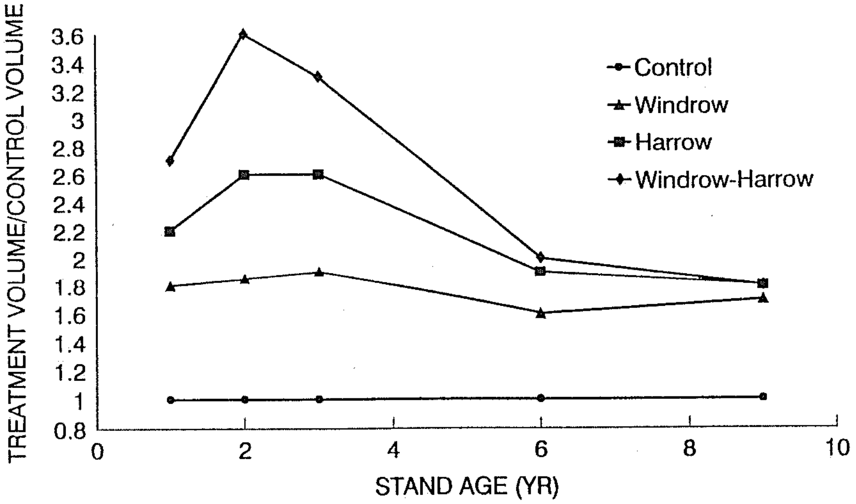

Figure 5 Relative loblolly pine growth response to several site preparation treatments

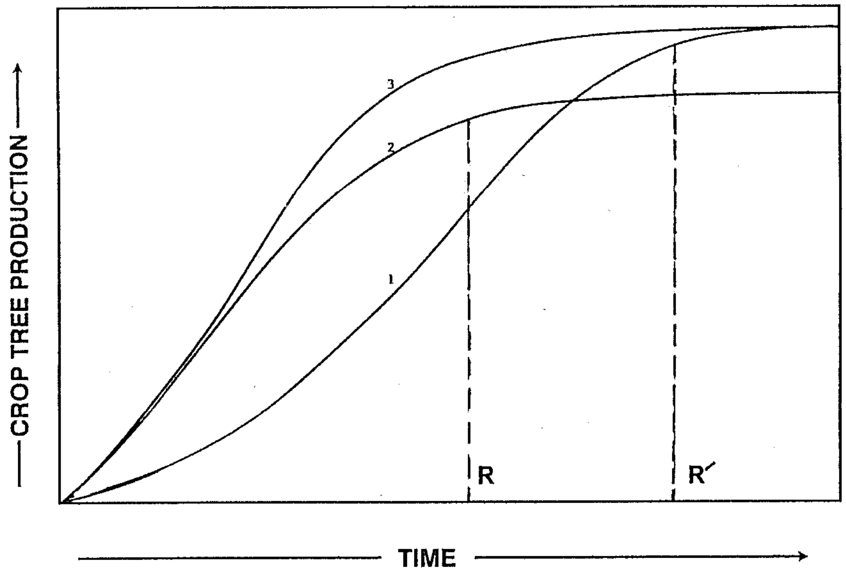

Figure 6 Hypothetical production curves: Curve 1 depicts a treatment control curve; curve 2 depicts a treatment that reallocates resources to desired species but reduces site carrying capacity; curve 3 depicts a treatment that reallocates resources to desired species while maintaining site carrying capacity. R and R' represent alternative stand rotation lengths

countered, respectively, by organic matter depletion or soil physical damage (Table 1). These examples illustrate the way in which a management treatment, intended to positively affect one component of the forest productivity function, can also have a negative effect on a different component.

The effects of any single silvicultural treatment on stand growth are fairly well understood. But an understanding of cumulative response to multiple treatments over time on sites of different character is much more difficult. For example, a pine plantation established by a hot site preparation burn used to control residual hardwoods and clear the site for planting, followed by herbaceous weed control a year after planting, may result in a production curve depicted by curve 2 in Figure 6. Curve 1, a treatment control curve, depicts production without treatment with fire or herbicide. Curve 2 for the treated stand suggests a positive response to herbaceous weed control with harvest at time R, the approximate culmination of mean annual increment. Even if an untreated control plot was left as a check, the danger is that the increased production (achieved by herbaceous weed control) harvested at time R will mask the fact that carrying capacity was reduced by the nutrient-depleting fire (compare curves 1 and 2 at time R'). Carrying the trial to time R' would show that carrying capacity was reduced, but the need for this follow-through is easily overlooked and seldom accomplished. A third treatment consisting of vegetation control without nutrient depletion (curve 3) would show the productive potential if carrying capacity had been maintained. This hypothetical example shows that silvicultural prescriptions must be made with an understanding of site character, how multiple treatments change the condition of sites, and how stands respond to new conditions. Comprehensive trials with adequate follow-through, established on a variety of sites, are needed for accurate empirical evidence of the cumulative effects of silvicultural technology.

Intensive forest management usually includes multiple silvicultural inputs that affect productivity in complex ways. Therefore, predicting the rotation-length cumulative effects of silvicultural technology without process-based models is difficult because responses are very site and treatment specific. Estimates of growth and yield for silvicultural treatments and their site-specific interactions would be very helpful in making prescriptions, but traditional empirical modelling approaches will never adequately capture the numerous permutations of treatment X site combinations. Process models based on fundamental growth determinants are needed that describe the character of forest systems and predict production functions based on treatment effects on system components and processes.

Guiding Principles

Until we learn more from empirical trials and process modelling, several generalizations about the effects of silvicultural technology on forest productivity can be made to guide practitioners as they make necessary decisions. Production of key species can be greatly increased with intensive management. In the process of targeting some early-successional species, however, potential site productivity will be reduced as a trade-off for the higher value of these species. Silvicultural technology has increased forest productivity by optimizing the biotic and abiotic character and function of forest systems. However, cumulative silvicultural effects can be counterproductive when the carrying capacities of forest sites are reduced. An important generalization that can be made for sustaining forest productivity is that no silvicultural treatment should be imposed that decreases abiotic carrying capacity. With this prerequisite, silviculturalists can be relatively certain that their efforts toward increasing productivity via biotic and cultural methods will not be counterproductive.

Evidence from the combined ecological, agricultural, and forestry literature suggests that the key to sustained forest production is maintaining abiotic conditions manifested in soil structure and function as they affect availability of energy, water, nutrients, and air. Ecologists conclude that sustainability of natural plant systems depends on mechanisms for energy storage (Reichle *et al.*, 1975). The energy reservoir is organic detritus which is also critical for nutrient storage and remobilization. Agriculturists conclude that sustained site productivity in agri-ecosystems requires approaches that: (1) conserve organic matter; crop nutrients must come from management of nutrient flow into and out of the soil organic matter; (2) close nutrient cycles; farmers must manage the soil organic matter rather than the soil nutrient solution; and (3) maintain soil macroporosity; management must enhance water infiltration, soil drainage, gas exchange, microbial activity, and root growth (Edwards *et al.*, 1990). Likewise, foresters conclude that sustainable production is highly dependent on sustaining the quality and quantity of the soil resource. In a review of how the Department of Conservation and Environment in the State of Victoria is addressing sustained wood production, Squires *et al.* (1991) report that residue retention with limited weed control is central to a management approach striving to maintain organic matter levels, limit soil compaction, conserve nutrients, and prevent soil loss. In a review of factors causing productivity decline in forests worldwide, Powers *et al.* (1990) also concluded that management that caused losses of soil organic matter and soil macroporosity adversely altered soil processes that regulated the flow of energy, nutrients, water, and air.

Generalizing across the experiences of these natural resource disciplines, one could conclude that the cumulative effects of silviculture on sustained forest productivity at the stand level are positive as long as abiotic carrying capacity is maintained. To maintain abiotic carrying capacity, the recent literature from all three areas suggests that silvicultural approaches should (1) limit biomass removal and site disturbance to levels that will maintain soil condition equivalent to that found in similar undisturbed forests; (2) promote characteristics of natural systems while optimizing the yield of the preferred component(s); (3) build complexity into the forest system in order to effectively conserve and cycle energy, water, nutrients, and air; (4) balance high yields of the preferred forest components against biological processes that confer sustainability; and (5) focus on long-term system optimization rather than short-term exploitation.

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FOREST MANAGEMENT IMPACTS ON LONG-TERM PRODUCTIVITY — EARLY RESULTS FROM A U.S. RESEARCH PROGRAM

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Deborah S. Page-Dumroese, Felix Ponder, Jr., and Marilyn A. Buford

Changes in soil porosity and/or organic matter removal from a site are the forest management impacts most often associated with productivity declines. In 1989, a series of plots was established throughout the U.S. to experimentally manipulate these factors and determine the long-term vegetative growth response. Currently, plots have been established in California, Idaho, Louisiana, Michigan, Minnesota, Mississippi, and North Carolina. The core design consists of nine plots in a full factorial with three levels of organic matter removal (bole only, total above-ground tree, and total above-ground tree plus forest floor), and three levels of soil compaction (severe, moderate, and none). Most installations also have areas of unharvested controls, and extra plots for supplemental or ameliorative treatments. The first installations (LA-1, MN-1, and CA-1) now have results for at least 2 years following treatment.

With the most severe organic matter removal treatment, 97, 286, and 532 Mg/ha of organic matter was removed from LA-1, MN-1, and CA-1, respectively. Soil bulk density in the 0-10 cm soil layer increased by 9, 22, and 28% for LA-1, MN-1, and CA-1, respectively, for the severe compaction treatment. Bulk density was increased in the 20-30 cm layer for CA-1 and MN-1, but only to the 10-20 cm layer for LA-1. Soil strength increased in the 0-10 cm layer by 63, 165, and 224% for sites LA-1, MN-1, and CA-1, respectively. Tree height was generally greatest with minimal treatments, and least with the forest floor removal and the most severe compaction. For reasons as yet unclear, tree height at MN-1 was slightly greater on the treatment with severe compaction and forest floor removal than with either treatment applied separately. Tree biomass at all sites declined as more organic matter was removed under the no compaction treatment. With compaction, the results of organic matter removal on tree growth varied by site, indicating the complex interactions among these factors.

RELATIONSHIPS BETWEEN CONIFER SEEDLING GROWTH AND A VISUALLY DETERMINED STRESS INDEX

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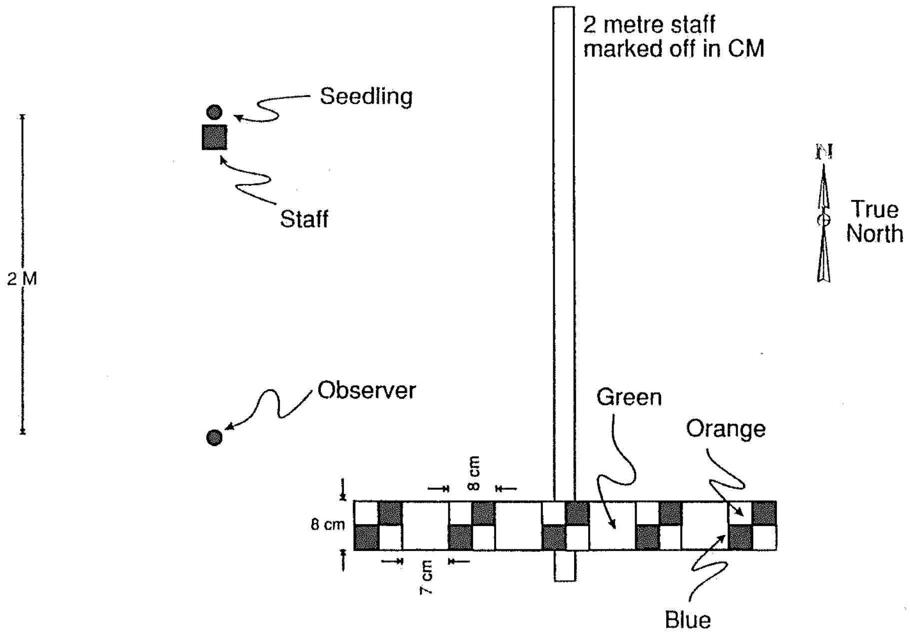
The Stress Index is a simple, accurate, and fast (1.5 minutes per seedling with 3-person crew) method to numerically assess competing vegetation surrounding a seedling. The simplicity of the method makes it applicable for both research and for operational forestry.

Colored squares, set at the base of the seedling leader, are observed through the intervening competitor vegetation from 2 m south of the seedling. The percent of squares not seen is multiplied by the ratio of the mean height of competitor vegetation within 1 m of the seedling to the height of the seedling leader base to produce a numerical unitless Stress Index (SI). The SI for individual seedlings ranged between 0 and 2000 for annual measurements.

The SI was regressed against morphological measurements for individual containerized seedlings. High r^2 were found for height, volume, and height and volume increments in the fifth field season on sites where competitor species diversity was low. The relationships between SI and growth deteriorated when the competitor community became very complex. Various growth measures for seedlings in a series of increasingly stressed groups were plotted against cumulative SI to establish thresholds beyond which growth decreased.

Threshold levels of competition were determined for several coniferous species and these were found to occur at surprisingly low vegetation loadings. Following the development of SI in the post-planting years on individual seedlings facilitated an understanding of the explosive growth of competitors relative to established threshold levels.

If threshold levels of SI are to be avoided as opposed to removing threshold levels after they occur, then many rich sites will require vegetation control before planting because these levels are often reached during the outplanting year before control measures are possible.



AN ECONOMIC EVALUATION OF FOREST IMPROVEMENT OPPORTUNITIES AND IMPACTS FROM THE EMERGENCE OF A BIOMASS FUEL MARKET IN SOUTHWESTERN NOVA SCOTIA

Phase 1. Development of Framework and Methodology

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Abstract

In 1991, Nova Scotia' public power utility initiated a process to purchase privately produced electrical power. A proposal was received to produce 20-25 megawatts from the burning of 350 to 400,000 tonnes annually of wood residue and forest biomass in a co-generation facility in southwestern Nova Scotia, Canada. This proposal has been proceeding and is nearing the construction phase.

As a result of this potential market, there is an opportunity for increasing the scope and extent of forest improvement operations. Options for a closer integration of planning, harvesting, and silviculture activities will emerge. The objective of this project is to assess the effect that this emerging market for forest biomass could have on forest management in the supply area.

This project has two phases. Phase 1, presented here, develops the framework and methodology. Phase 2 will apply a linear programming-based analytical model for evaluation.

Phase 1 accumulated the required data and information for both the current management and marketing situation and that including the emerging biomass market. Growth and yield of the natural stand types were calculated for a mixture of conventional roundwood products and chip equivalents. Management regimes, based on current forest type, site class, and appropriate silviculture treatments, were established. Expected multi-product yields, by regime were estimated. Silviculture and harvest costs along with product revenues were used to calculate standing timber and soil expectation values. In Phase 2, a stand-based optimization model will be developed to explore and evaluate the long-term opportunities and differences between the present and emerging management and market situations.

Introduction

Forest management activities generally are subdivided into three distinct categories: planning, harvesting, and silviculture. Planning generally focuses on locating, accessing, and harvesting stands of size and quality sufficient to meet wood demand. Harvesting activities are more engineering oriented, and focus on cutting and delivering wood in the form required by the secondary processing facility, at least cost. Silviculture activities focus on bringing harvested sites back into production as rapidly as possible, growing timber of the desired species composition and form to meet future demands.

Traditional primary forest products demanded by resource users in southwestern Nova Scotia include softwood sawlogs, softwood and hardwood pulpwood, hardwood fuelwood and small volumes of other specialty products. Due to the nature of this product demand, past harvesting practices, and inroads by fire, insects, and diseases, a number of areas require extensive silviculture treatments to become more productive. But, in many cases, site conditions are not conducive to economically efficient rehabilitation because markets do not exist for "waste" material such as tops and limbs, low quality remnants of desired species, and low quality species.

A real opportunity to assess the effect that a market for waste material could have on forest management could be emerging in southwestern Nova Scotia. In early 1991, the Nova Scotia Power Corporation requested proposals to purchase a total of 50 MW of privately produced electrical power. One of the 12 proposals short-listed was a 21 MW co-generation facility from the Polsky Energy Corporation to be located next to the Bowater Mersey Paper Company (BMPC) newsprint mill, near Liverpool, N.S. BMPC would purchase the steam generated by the plant and would provide up to 50% of the estimated 350-400,000 tonnes of fuel required, in the form of bark and general wood waste. The balance of the fuel requirements would be procured in the area. The total fuel supply would include 20 to 30% whole-tree chips.

Much opportunity for increasing the scope and extent of forest improvement operations could occur if a regional market for low grade material existed. Treatments such as site rehabilitation for older partial cutovers and high-graded sites, mixed stands of silvicultural "junk", and old-field white pine may be greatly increased. The potential for stand improvement through thinning and various improvement cuttings could be enhanced. Utilization of the large quantities of slash might be possible.

The objective of this project is to assess the forest improvement opportunities and economic benefits that could accrue if a regional market for low grade "waste" material were developed. Options for a closer integration of planning, harvesting, and silviculture activities could be greatly enhanced with the widening of the scope and level of primary forest product demand. Optimum end use allocation could occur and overall economic efficiency would be enhanced. The effectiveness of planning and implementing forest management strategies could be substantially improved.

A two-phase approach is being applied to the attainment of objectives. **Phase 1** developed the framework and methodology. This phase is essentially an accumulation and preliminary analysis of relevant and required information. The following is a summary report on the different components of **Phase 1. Phase 2** will develop and apply a linear programming-based analytical model to evaluate the impact of the additional required whole-tree chip fuel supply on forest improvement opportunities and the overall economic value of the forest.

Background Information

The study area encompasses two counties in southwestern Nova Scotia, Lunenburg and Queens. This is roughly equivalent to the potential fuel supply area for whole-tree chips trucked to the co-generation facility. Conversion facilities in the area currently producing conventional forest products include an integrated pulp and newsprint mill, one large sawmill, four medium-sized sawmills, 33 other small sawmills and a large hardboard mill. Other small-scale specialty products are produced and there is a significant consumption of hardwood for domestic fuelwood.

Production of primary forest products in the study area as an average of the most currently available 3-year period shows annual consumption of softwood to be approximately 777,500 m^3/year. Total average hardwood production was over 208,000 m^3/year. Total wood fiber production for the study area averaged close to 1,000,000 m^3/year for the 3-year period. Anticipated additional consumption of whole-tree chips for the new co-generation plant is estimated at 100,000 m^3/year.

The study area lies in the forest section A.11 - Atlantic Uplands of the Acadian Forest Region of Rowe (1972). The forest is dominated by softwood mixtures, mainly red spruce and white pine, with lesser components of balsam fir and eastern hemlock. Red maple and red oak are among the predominant hardwoods.

The current age class distribution for the major covertypes shows a heavy imbalance towards the immature, pole, and mature developmental stages (age classes 41-60 years, 61-80, and 81-100). The forest land ownership pattern shows small private holdings (<400 ha) account for 54% of the area, with large private holdings (>400 ha) at 26%, and provincial Crown at 17%. Lunenburg County is predominantly small private with large blocks of private and Crown land located in Queens County.

Harvesting activities in the study area are mainly a mixture of clearcutting and partial cutting carried out by independent contractors. These may be the landowners themselves in the case of many small private woodlots. Logging systems vary from manual fell, buck, and limb for skidding/forwarding to roadside to the more highly mechanized variations of manual fell and skid for roadside processing. Mechanical harvesters are not currently common. Roadside debarking/chipping is increasing. Harvesting is generally more mechanized on the larger private holdings and less so on smaller holdings.

Silviculture treatments currently practised in the forest types in the area include mechanical site preparation and planting, spacing and cleaning of young stands, and commercial thinning of older stands for volume growth and regeneration establishment. All current silviculture is carried out to enhance the growth and yield of the major softwood species, particularly spruce.

Approach and Methodology

The approach used in developing the framework and methodology is as follows:

1) A detailed sample of the current forest inventory for the study area was obtained. This consisted of data from permanent sample plots distributed throughout the study area. Seven stand level variables and 13 individual tree variables were provided for each of 209 plots and 5500 trees, respectively. These data were analyzed and current forest conditions as well as growth and yield patterns for the major stand types were established. These patterns were established for conventional softwood and hardwood roundwood products and for chip equivalents.

2) Data on type, extent, and cost of silviculture treatments carried out in the study area were obtained and analyzed.

3) Distinct management regimes were established for each of the major stand types in the area, based on silviculture treatments, site capability, and current forest type.

4) Growth and yield estimates were developed for each of the management regimes, for conventional roundwood products and chip equivalents.

5) Soil expectation values (SEV) were established for each management regime. They were based on anticipated costs and revenues for silviculture and harvesting.

6) For each current stand type in the study area, total value was calculated. This was arrived at by summing the present net worth of the existing stand and the SEV of the appropriate management regime. This was done for conventional roundwood products and the chip equivalent.

Forest Inventory, Growth, and Yield

A detailed breakdown of the age class distribution and site capability of the major stand types is as follows. High site areas account for 17% of the productive forest or 70,000 ha. Areas of medium site account for 83% or 346,000 ha. Mixed softwood is the predominant and most commercially important stand type in the area. It makes up 45% of the productive forest or 186,000 ha. Mixedwood stands make up 31% of the area or 130,000 ha. Pine and hardwood stand types make up 5% and 14% or 22,000 and 58,000 ha, respectively. Areas currently classified as NSR (not satisfactorily regenerated) account for 5% or 20,000 ha.

Growth and yield developmental patterns for the major stand types were developed. Growth and yield in volume (m^3/ha) by 20-year age classes was developed for conventional roundwood products, softwood syllogise, softwood pulpwood, hardwood syllogise, and hardwood pulpwood. Growth and yield in weight (green tonnes/ha) was developed for chips for the equivalent of the conventional roundwood products and for softwood crowns and hardwood crowns. The chip equivalents were calculated using the appropriate biomass equations of Ker (1980a, b).

Silviculture

Data on the type, extent, and costs of silviculture treatments carried out in the study area during the past 10 years (1982-1991) were obtained from the N.S. Department of Natural Resources. These data were analyzed and the areas treated and average costs calculated. There appears to be an increasing tendency away from plantation establishment treatments (site preparation and planting) towards intermediate cuttings (thinnings) and natural regeneration treatments (shelterwoods).

Management Regimes

Using a combination of potential silviculture treatments, site capability, and current stand type, management regimes for the productive forest in the study area were established. Eight regimes, for extensive and intensive management, were identified. The regimes most prominent in terms of area are No. 2 - Clearcut - Natural Regeneration - Cleaning, which could cover 192,000 ha or 46% and No. 6 - Clearcut - Natural Regeneration, which could cover 100,000 ha or 24%.

The potential growth and yield developmental patterns for the management regimes were established. Potential yield in terms of conventional roundwood products and of chip equivalents of the roundwood products plus the crown components was calculated. The chip equivalents were calculated using age class-sensitive factors, based on the individual tree inventory data and the biomass equations of Ker (1980a, b).

Soil Expectation Values

Soil expectation values (SEV) for a continuous series of rotations were established for each of the eight management regimes. The SEVs were arrived at by the following process: net values (roadside revenues - roadside costs) were compounded to the rotation age to get future value; future values were then discounted to the present. The interest rate used was 4%. Detailed calculations for each of the management regimes were carried out for conventional roundwood products and for a combination of roundwood and chip products. The silviculture incentives used are 90% of the treatment costs. Local standard operating harvest and silviculture costs and revenues were used in the calculations.

Forest and Stand Evaluation

An initial forest and stand evaluation was completed by summing the present net worth of the existing stand and the SEV of a continuing series of rotations by management regime. The interest rate used was 4%. Present net worth was calculated using the projected yield from natural stands at a rotation age of 90 years. SEV for the management regime was calculated from the point in time the existing stand would be harvested (age 90) and the continuing series of rotations would begin. Initial forest and stand evaluations for conventional roundwood and chip products were carried out.

Summary and Subsequent Activities

The preceding sections illustrate the framework and methodology required for an economic evaluation of forest management opportunities arising from the emergence of a biomass market. Calculation of the growth and yield of multiple products for natural and managed stands is described. Management regimes are established and soil expectation values calculated. A system for base-level calculation of the economic evaluation of stands over time is described. Phase 2 will involve the evaluation, over time, the scope and extent of the harvest, and the investment in silviculture which, taken together, could result in greater economic return.

An algorithm will be constructed to calculate the optimization of economic activity for the supply area, subject to a number of constraints. These constraints will involve: 1) production of the amount of conventional roundwood products presently required; 2) production of the required additional quantities of forest biomass; 3) investment of reasonable and appropriate amounts in silviculture treatments; and 4) requirement to operate on a sustainable basis. Certain price and quantity values will be varied to determine sensitivities.

Parallel analyses will be carried out to project and compare the present management and marketing situation with that which includes the mergence of the additional biomass market. Cross comparisons will enable the economic evaluation of the effects of this new market on forest management options and overall economic activity. It is anticipated that this approach to management planning could have a broad range of operational and policy applications.

Literature Cited

Ker, M.F. 1980a. Tree biomass equations for ten major tree species in Cumberland County, N.S. Canadian Forest Service, Information Report M-X-108.

Ker, M.F. 1980b. Tree biomass equations for seven tree species in southwestern New Brunswick. Canadian Forest Service, Information Report M-X-114.

Rowe, J.S. 1972. Forest Regions of Canada. Canadian Forest Service, Publication No. 1300.

NITROGEN ACCUMULATION BY RADIATA PINE ON SAND DUNES FOLLOWING RESIDUE MANAGEMENT AND FERTILIZATION

C.T. Smith, P.N. Beets, A.T. Lowe, P.D. Hodgkiss, and W.J. Dyck
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The effects of harvesting intensity and urea fertilizer on above-and below-ground accumulation of nitrogen by a second-rotation *Pinus radiata* stand were estimated after 5 years of growth on a coastal sand dune in New Zealand. Four harvesting treatments, with and without additions of urea-N, were applied in a randomized, split-plot design. Main treatments included 1) whole-tree harvest and forest floor removal, 2) whole-tree harvest, 3) stem-only harvest, and 4) stem-only harvest plus extra slash. Sub-plots received additions of 200 kg urea-N/ha annually, with 900 kg N/ha added prior to this study being conducted. Slash retention only increased N concentrations in stemwood, with highest concentrations in the stem-only harvest treatment. Urea fertilizer increased N concentrations in all tree components. Fine-root to above-ground ratio of N contents only varied 2.5% across all treatments. Urea increased branch N contents relative to stem N contents, reflecting similar trends in biomass allocations (Smith *et al.*, 1994). Ecosystem retention of fertilizer N ranged from 11% (whole-tree harvest) to 48% (stem-only harvest plus extra slash). Mineral soils generally lost N since harvest, despite fertilizer additions. The top 90 cm of mineral soil contained 836 kg N/ha at the end of the first rotation, whereas mineral soils contained from 470 to 784 kg N/ha after 5 years in the second rotation. Sand dune mineral soils appear to have poor N retention capacity following harvest. Forest floor and coarse woody slash have an important role in N retention. Fifth-year above-ground N accumulation is from 47% (whole-tree harvest and forest floor removal) to 100% (stem-only harvest plus extra slash plus urea) of that observed in a 42-year-old first rotation stand on the same site. Above-ground N accumulation on fertilizer treatments (about 280 kg N/ha) was lower than that observed on fertile sites in New Zealand (464 kg N/ha) at the same age, although biomass accumulation was comparable (64 Mg/ha versus 72 Mg/ha, respectively). Nitrogen-use efficiency was greater in this sand dune plantation than that observed on a fertile volcanic ash site in New Zealand.

References

Smith, C.T., Dyck, W.J., Beets, P.N., Hodgkiss, P.D., and Lowe, A.T. 1994. Nutrition and productivity of *Pinus radiata* following harvesting disturbance and fertilisation of coastal sand dunes. For. Ecol. and Manage.:

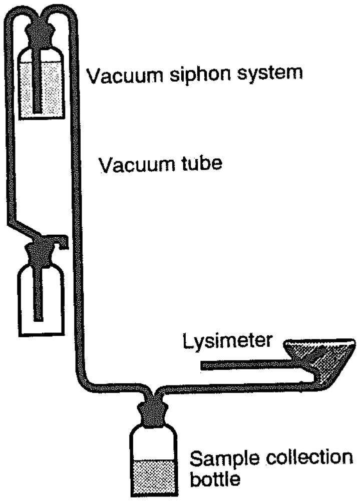
PRELIMINARY RESULTS OF THE IMPACTS OF INTENSIVE HARVESTING ON SOIL CHEMISTRY AND TEMPERATURE

M.K. Mahendrappa and D.G.O. Kingston
Canadian Forest Service - Maritimes Region

Over 80% of clearcutting operations in Canada involve whole-tree harvesting, in which non-merchantable components of tree biomass (slash) are removed from the forests. The removal of slash from the sites leads to a loss of nutrients and faster decomposition of soil organic matter. It sets up a chain reaction leading to increased nitrification due to warmer soil temperature, increased acidity build-up, and subsequent loss of base cations from the solum. The ultimate result is site deterioration and reduced timber yield.

In 1989, a series of lysimeter studies was started on sites representing the major soil types in all three Maritime provinces and including all the commercially important tree species. Whole-tree harvesting, conventional harvesting, and control constituted the three main treatments in each of the studies. Treatment responses in terms of soil temperature at three depths and the chemical composition of soil leachates were characterized.

The diurnal fluctuations in the soil temperatures were most pronounced in the whole-tree harvested plots, followed by the conventional harvest plots. The largest difference in the temperature between the treatments consistently occurred immediately below the organic horizon in the mid-afternoon hours. At lower depths, the patterns were similar but the differential magnitudes were smaller. The temperatures in the whole-tree harvested plots were between 5-6°C higher than those in the control and conventionally harvested plots during the first growing season after the treatments were implemented. During the spring and summer months, soil temperatures were warmer in the whole-tree harvested plots, but after September, the trends reversed. The slash in the conventionally harvested plots acted as insulation to conserve heat. The calculated heat units accumulated were significantly higher in the whole-tree harvested plots over the growing season than in the other plots.



APPENDIX I

IEA/BE WORKSHOP '93
Fredericton, New Brunswick
May 16-22, 1993

May 18th & 19th **FIELD TOURS**

ALL TASKS & ACTIVITIES Groups 1 & 2

Thursday, May 20th

6:30 - 8:00 Breakfast (Buffet)

THEME: Environmental issues in supply and biomass for energy from conventional forestry

Welcoming address: Grand Ball Room, Howard Johnson Motor Lodge
Session Chairman: Paul Mitchell

Invited speakers:

9:00 *Hélène Lundkvist* - Whole tree harvesting: ecological effects and compensatory measures.

09:45 *Bengt-Olof Danielsson* - Harvesting methods and available quantities in the light of ecological constraints.

10:30 Refreshments

11:00 *William Stuart and Luc LeBel* - Logging strategies for complying with environmental regulations under adverse weather conditions.

11:45 *Hamish Kimmins* - Forest manipulation: impacts on forest ecosystem sustainability.

12:40 LUNCH

14:00 - 16:00 Panel Discussion

15:00 Refreshments

16:30 - 18:30 TAC meeting

18:30 DINNER at the Howard Johnson Motor Lodge

EVENING: Poster viewing (with authors present) 19:30-22:00 Ballroom C.

Friday, May 21st - Task VIII & Activity 4 Group 1

AM
1. Grand Ballroom
   Dave Brand - The "Model Forest" - new concepts in landscape level forest management.
2. Janet Dutch - Intensive harvesting of forest: a review of the nutritional aspects and sustainability implications.
3. Jim Burger - Cumulative effects of silvicultural technology on site productivity.

PM Poster discussion (A, related to objective 2 & B, related to objective 3 - 1.5 h each)

EVENING DINNER

Group 1, travels by bus to Gagetown, N.B. to the Steamer Stop Inn

Group 2, travels by bus to the Lord Beaverbrook Hotel.

Activities 2 & 3 combined Group 2

08:30 Introduction

08:40 Session 1, Activity 2: Integrated harvesting systems
Chairman: Barrie Hudson
Three presentations

10:15 REFRESHMENTS

10:45 Session 2, Activity 3: Harvesting small trees and residues
Chairman: Jean-François Gingras
Three presentations

12:20 LUNCH

13:25 Session 3, Activity 6: Transport and handling
Chairman: Alastair Twaddle
Three presentations

15:00 REFRESHMENTS

15:30 Panel Discussion
The implications of ecological constraints on wood fuel harvesting systems
Chairman: Barrie Hudson

17:00 FINISH

Saturday, May 22nd - Task VIII & Task IX Activity 4 Group 1

06:30 - 08:00	BREAKFAST (All groups)
08:00	Panel Discussion
10:00	REFRESHMENTS
10:30	Panel Discussion (Continued)
12:00	LUNCH
PM	Future - IEA Meetings

PROGRAM COMPLETED

Activities 2 & 3 Group 2

08:00	Business meetings of individual activity groups

PROGRAM COMPLETED

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IEA/BE WORKSHOP 1993
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