Intensive biomass removals and site productivity in Canada: A review of relevant issues[1]

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ABSTRACT

A renewed interest in the intensive harvesting of forest biomass as a source of bioenergy in North America raises concerns about the impacts that this practice may have on the maintenance of forest soil productivity. In Canada, such concerns were first voiced in the 1970s, and studies were launched to investigate and predict the impact of intensive forest biomass removal on site productivity. Most of these studies focused on static nutrient budgets. In Canada and around the world, more detailed process models were also developed to study carbon, nitrogen and base cation cycles under different forest harvesting intensities. However, the validity of modelling results is still constrained by our lack of knowledge on the capacity of ecosystems to supply nutrients. A few sets of field trials have been established in Canada to gather empirical data on the impact of biomass removal on soil nutrient reserves as well as on tree nutrition and growth. Although still fairly recent, these field trials, along with the older ones established in other countries with similar site conditions and climates, provide opportunities to refine our understanding of the resilience of ecosystem processes and of the impacts of intensive biomass removal on ecosystem functions. Although numerous knowledge gaps and questions remain, some jurisdictions around the world have nevertheless issued policy directives and developed guidelines for biomass harvesting. As described by the concept of adaptive forest management, ecological monitoring of harvesting operations, scientific field testing and modelling can all interact to produce better knowledge that could then help improve policy directives.

Key words: bioenergy, biomass, intensive harvesting, environmental sustainability

RÉSUMÉ

L'intérêt renouvelé pour la récolte intensive de biomasse forestière comme source de bioénergie en Amérique du Nord soulève des inquiétudes quant aux impacts de cette pratique sur le maintien de la productivité des sols. Au Canada, ces inquiétudes ont été émises pour la première fois dans les années 1970 et des travaux de recherche ont été entrepris pour étudier et prédire les effets de la récolte de biomasse sur la productivité des sites. La plupart de ces études étaient basées sur des budgets nutritionnels statiques. Au Canada et ailleurs dans le monde, des modèles plus détaillés incluant la description des processus écologiques ont aussi été développés pour étudier les cycles du carbone, de l'azote et des cations basiques sous différentes intensités de récolte. Cependant, la validité des résultats de modélisation est toujours contrainte par notre connaissance limitée de la capacité des écosystèmes à fournir des éléments nutritifs. Quelques dispositifs expérimentaux ont été établis au Canada pour recueillir des données empiriques sur l'impact de la récolte de biomasse sur les réserves nutritionnelles du sol ainsi que sur la croissance et la nutrition des arbres. Bien que relativement récents, ces dispositifs, ainsi que des dispositifs plus anciens installés dans d'autres pays aux conditions de site et de climat semblables à celles du Canada, nous offrent l'opportunité de raffiner notre compréhension de la résilience des processus écologiques et des impacts de la récolte de biomasse sur le fonctionnement des écosystèmes. Bien que les incertitudes et les questions restent nombreuses, certaines juridictions dans le monde ont tout de même fourni un cadre politique et développé des lignes directrices pour la récolte de biomasse. Tel que décrit par le concept d'aménagement forestier adaptatif, le suivi écologique des opérations de récolte, les études sur le terrain et la modélisation peuvent interagir afin d'améliorer les connaissances scientifiques qui pourront par la suite être utilisées de façon à ajuster le cadre politique.

Mots clés : bioénergie, biomasse, récolte intensive, durabilité environnementale

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"*Woodman, spare that tree, touch not a single bough!*"
George Pope Morris (1802–1864)

Introduction

Recently, we have seen a renewed interest in the intensive harvesting of forest biomass as feedstock for bioenergy in North America and around the world. Globally, the main driving force behind the increased use of biomass for energy is concern about climate change, with forest biomass being considered as a sustainable, renewable energy resource and a sound alternative to fossil fuels (Stupak *et al.* 2007). It also increases the diversity of energy sources and, for some countries, improves the security of energy access.

In Canada, the forestry sector is the major source of bioenergy and it currently produces about 6% of Canada's energy needs, largely from mill waste produced within the sector (Bradley 2006). This helps diversify forest products, reduce energy costs and raise environmental stewardship within the sector. For example, since 1990, members of the Forest Products Association of Canada (FPAC) have increased their use of forest bioenergy and thereby reduced fossil fuel use by 45%, greenhouse gas emission intensity by 54%, and landfill waste by 40% (FPAC 2007).

It has recently been estimated that Canada could produce an additional 0.72 EJ yr^{-1} of forest bioenergy by converting 50% of the slash from conventional forest harvesting into energy. This represents about 6% of Canada's current annual energy consumption of 12.6 EJ yr^{-1} (Wood and Layzell 2003) and would double the current forest bioenergy production to 12% of national consumption. However, compared with conventional stem-only harvesting, more intensive forest biomass extraction such as whole-tree harvesting, in which stems, branches, twigs and foliage are all removed from the harvest site, may affect environmental sustainability by altering site productivity, biodiversity and water resources (see overview by Lattimore *et al.* 2009 and reviews in Dyck *et al.* 1994, Richardson *et al.* 2002, Röser *et al.* 2008).

The most obvious impact of whole-tree harvesting is that it results in increased losses of nutrients from the ecosystem. For example, Paré *et al.* (2002) estimated for species commonly found in the boreal forest of Quebec that whole-tree harvesting would export 200% to 350% more nitrogen (N), 150% to 650% more phosphorus (P), 150% to 300% more potassium (K), 150% to 200% more calcium (Ca) and 200% more magnesium (Mg) than stem-only harvesting. Such nutrient losses, as well as changes in other nutrient cycling processes, raise concerns about the long-term sustainability of site productivity with whole-tree harvesting.

Assessment of Impacts

In Canada, concerns about site impacts were first voiced in the 1970s when the oil crisis pushed fossil fuel prices to then-record levels and alternative sources of energy were sought, such as underutilized forest harvesting residues (delimbed tree branches and tops). In response to these concerns, the Canadian Forest Service initiated the ***En****ergy from the* ***For****est* program (ENFOR), which included the development of tools to define sustainable levels of organic matter and nutrient removals in biomass. Through ENFOR, allometric equations were defined for the estimation of tree biomass (e.g., revised equations in Ung *et al.* 2008), large amounts of data on nutrient concentrations and contents of different tree components were generated for a variety of species (e.g., Freedman *et al.* 1982), and forest nutrient data were collated (e.g., Kimmins *et al.* 1985) for use in model development (e.g., FORCYTE; Kimmins and Scoullar 1979). This early Canadian work undertaken in the 1970s and 1980s, along with more recent studies by a range of agencies, has been used to estimate carbon and nutrient removal for various combinations of levels of biomass extraction with different stand/site conditions. Coupled with estimations of nutrient supply from atmospheric and weathering sources, simple input-output nutrient budget models can be built (Fig. 1). Although only a crude representation of forest ecosystem processes, nutrient budgets may give an indication of which nutrients could become limiting and the extent of the nutrient deficit under various levels of biomass harvesting. They have, therefore, been useful in making broad recommendations on biomass harvesting at a regional or national scale in several jurisdictions, including the boreal forest of Quebec (Fig. 2) (Paré *et al.* 2002), Minnesota (Grigal and Bates 1992) and Sweden (Akselsson *et al.* 2007).

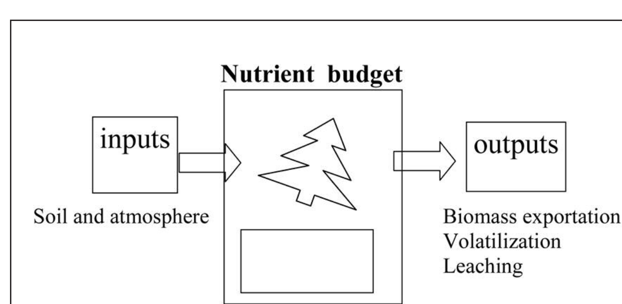

Fig. 1. Schematic view of a nutrient budget.

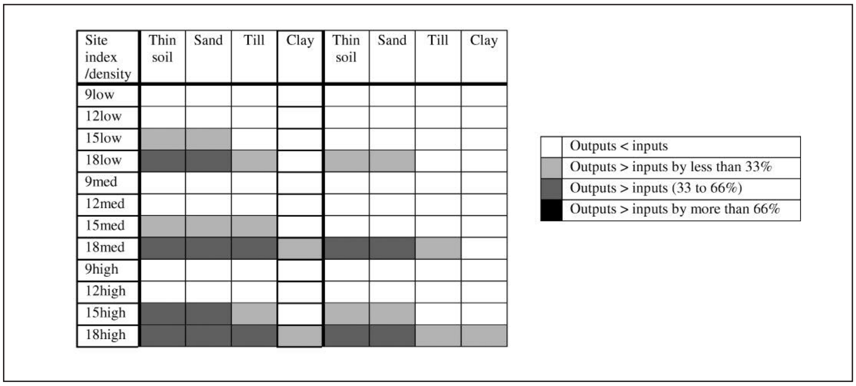

Fig. 2. Risk rating of nutrient depletion for forest stands: Example for Jack pine (from Paré *et al.* 2002).

Budgets are also the cornerstone of the concepts of critical loads of acidity and exceedances, which are used to quantify the maximum amount of acidity from atmospheric deposition (the critical load) that a forest soil can receive without being negatively impacted, by accounting for inputs (e.g., deposition, weathering) and outputs (e.g., leaching, denitrification) of acidity and alkalinity in the soil:

[1] Critical load of acidity from sulphur and nitrogen depositions = (Deposition of base cations + Soil weathering of base cations – Export of base cations) + (Soil immobilization of nitrogen + Export of nitrogen + Denitrification) – Deposition of chloride – Critical alkalinity leaching rate

Critical loads estimate the capacity of a given soil to buffer acidity from atmospheric deposition and the sustainability of its acid–base status by comparing them to actual or projected levels of atmospheric sulphur and nitrogen deposition, and evaluating whether they are in exceedance of the critical load. Results can be used to create maps that predict soils sensitive to acid deposition (i.e., cation leaching), as it has been done for Eastern Canada (Ouimet *et al.* 2006). The model of critical loads has been used successfully to inform and guide international negotiations to reduce emissions of atmospheric pollutants in Europe and North America. Most calculations of critical loads of acidity and exceedances assume no forest harvesting. However, the effect of forest biomass harvesting on the soil acid–base status and on its capacity to buffer acidity from deposition can be tested by varying the two export terms in eq. 1 using values corresponding to the amounts of base cations and nitrogen removed in the harvested biomass. Different levels of biomass removal (e.g., stem-only harvesting vs. whole-tree harvesting) can thus be compared relative to their contribution to soil acidification.

Such models make it possible to estimate the upper and lower bounds of the magnitudes of expected nutrient depletion or soil acidification under different harvesting scenarios at a large scale. However, although it is tempting to use these models at a smaller scale because of their ease of application and clear outputs, they may be inadequate as a management tool for making site-specific predictions. For example, whereas the uncertainty surrounding the estimates of nutrient removal in harvested forest biomass is relatively low, the uncertainty in estimating nutrient inputs into the ecosystem from atmospheric deposition and soil mineral weathering is large (Fenn *et al.* 2006). Akselsson *et al.* (2007) also indicated that leaching of nutrients contributes to much of the uncertainty in nutrient budgets because specific measurements of leaching from forest sites are scarce. Moreover, input–output nutrient budgets are static in nature and therefore do not capture within-site nutrient cycling processes. As stated by Stone (1979), there is no such thing as "nutrient supply" for tree growth in the same useful sense that there is a "moisture supply", and no rule of thumb about "nutrient supply" is useful beyond the grossest generalization. Each nutrient has its own unique chemistry within the soil, its own relationships to lithology and atmospheric inputs, and its own cycling patterns through soil and vegetation (see Thiffault *et al.* 2008 for an example of different cycling patterns between base cations). Furthermore, the importance of different nutrient cycling processes (e.g., for nitrogen) within the same plant species assemblages can vary with site quality (Yamasaki *et al.* 2002). Theoretical quantitative assessments of the impacts of forest disturbances and management may therefore be misleading since the ecological implications for forest ecosystem functioning may not be adequately captured by the simple budgeting of the amount of organic material and nutrients removed or left on site.

In Canada and elsewhere, dynamic models with more detailed descriptions of ecological processes have been and continue to be developed to study carbon, nitrogen and base cation cycles (e.g., FORSAFE, Wallman *et al.* 2005; FORCYTE-11, FORECAST and FORCEE, Kimmins 1997). However, the validity of modelling results is still constrained by our knowledge and understanding of the capacity of ecosystems to supply and cycle nutrients. For example, Palosuo *et al.* (2008) compared several models for predicting the results of biomass harvesting and found different results with each. Making long-term quantitative predictions with models is therefore risky—as stated by Millar *et al.* (2007), "A healthy scepticism leads us to use models to help organize our thinking, game different scenarios, and gain qualitative insight on the range of magnitudes and directions of possible future changes without committing to them as forecasts." Instead, models should be used to generate patterns and trends through multiple scenarios, which can then be used to make forest value trade-off analyses and identify new hypotheses from which to direct future research (Morris *et al.* 1997) using empirical-based field experimentation. (For further background, see Kimmins (1997) for a review of methods for predicting the sustainability of biomass harvesting, including models, with comments on their usefulness and limitations, and see reviews by Korzukhin *et al.* (1996) and Landsberg (2003) for forestry models.)

Assessment of Impacts Using Field Trials: Case Study

Field trials have been established on over 50 sites across Canada from which empirical data on the impacts of biomass removal on soil nutrient reserves, tree nutrition and growth can be gathered (Titus *et al.* 2008). Although still fairly recently established, these field trials, along with older ones established in other countries with similar site conditions and climates, provide opportunities to refine our understanding of the resilience of ecosystem processes to disturbance, and the impacts of intensive biomass removal on ecosystem function. A case study using field trials located in the Haute-Mauricie region of Quebec can be used to demonstrate how nutrient budget model predictions produced hypotheses that could be tested experimentally. The results enhanced our understanding of ecological processes, which were then used in a more complex model to provide further insights by comparing different scenarios, and to develop new hypotheses on potential drivers of soil fertility.

The study area was located in the western portion of the balsam fir–white birch bioclimatic domain of Quebec's Canadian Shield. The experiment, initiated in 2001, included harvested plots that had been established in the 1980s as part of a province-wide comparison of stem-only harvesting (SOH) and whole-tree harvesting (WTH); adjacent plots that had been burned by large crown wildfires of high severity were also included to compare harvesting with natural disturbance. These disturbances occurred over a period of six years (between 1980 and 1986). Harvested plots were clearcut by either (i) WTH, performed by felling and hauling all above-stump biomass using a feller-forwarder and delimbing trees at the roadside, or (ii) SOH, performed by motor-manual felling and delimbing trees on site, with stems hauled off-site with cable skidders and all logging residues (foliage, branches and twigs) left scattered across the site. The initial stands (before harvest or wildfire) were mature jack pine (*Pinus banksiana* Lamb.) and were regenerated back to the same species. Soils were humo-ferric podzols, developed from relatively deep (>1 m) and rapidly drained outwash sand deposits, with a texture of more than 85% sand and a mineralogical composition similar to that of the granitic gneisses of the Canadian Shield.

According to the input–output nutrient budget model developed by Paré *et al.* (2002), jack pine stands of medium density growing on sandy deposits with a site index of 12 to 15 (i.e., similar to those in the Haute-Mauricie field trials) would theoretically be at low risk of nutrient depletion following intensive forest biomass removal from whole-tree harvesting (Fig. 2). We therefore hypothesized that these sites would not be negatively affected by whole-tree harvesting. However, field results showed that the intensity of harvesting at clearcutting (SOH vs. WTH) was still influencing soil and foliar variables 15 to 20 years after harvesting (Thiffault *et al.* 2006). The upper soil layers of the whole-tree harvested plots had a lower cation exchange capacity and lower organic carbon concentrations relative to the stem-only harvested plots. Whole-tree harvesting also lowered foliar Ca and Mg concentrations. These effects appeared to be linked to the initial levels of soil organic matter and the geochemical composition of the soil, as stands were grown on soils with very low organic matter and elemental contents of Ca and Mg. Organic matter content, as well as total elemental content of Ca and Mg in mineral soil horizons, which is an indicator of the soil's ability to provide these nutrients as weathering products, therefore seem to be good indicators of the sensitivity of soils to nutrient depletion by whole-tree harvesting—when trees need to rely on soil reserves, intrinsically poor soils or soils with imbalanced nutrient proportions may quickly cause dysfunctional tree nutrition.

Jack pine height growth reductions of 18% were also measured on whole-tree harvested plots relative to stem-only harvested plots[6]. A number of hypotheses have been raised to explain these reductions after whole-tree harvesting, such as lower soil moisture availability and lower nutrient availability (base cations, N, P, or micronutrients). Jack pine, as a tree species with attributes that allow rapid acquisition of soil nutrient resources (e.g., fast juvenile growth rate, deep rooting system, high foliage turnover), appeared to react more to the differences in the soil environment created by the different levels of biomass harvesting than other more conservative species such as black spruce. This implies that the use of intensive biomass removal would have a more pronounced negative impact on tree nutrition and growth in stands of acquisitive species such as jack pine and aspen than for species such as black spruce (Thiffault *et al.* 2006 and D. Paré[7]).

This shows that conclusions based on simple static input–output nutrient budgets, such as the ones in Paré *et al.* (2002), could be misleading. In this case, the amount of slash and nutrients removed was low in jack pine stands because jack pine does not bear an important branch and foliage biomass—this type of stand was thus theoretically classified at low risk, but the actual impact observed in the field was great. Thus, the small amount of biomass left on-site could be important for the ecosystem, not because it generates a great supply of nutrients, but perhaps because this small biomass input makes a crucial difference in the soil's nutrient retaining capacity or in other soil properties such as soil moisture availability and microclimate (Zabowski *et al.* 2000). Another issue with static nutrient budgets is that greater stand productivity implies a greater nutrient drain and a greater soil impoverishment at harvesting because of the large quantity of nutrients stored in the tree biomass and removed at harvesting. While this is true for short-rotation harvesting, such as in agriculture, it may be questionable in forestry. The impact of vigorous tree growth over several decades may in fact enrich the soil, as illustrated by Bélanger *et al.* (2004). In some cases, vigorous tree growth is therefore an agent of soil improvement, and not degradation.

On the other hand, the field trials showed that harvesting these sites *per se*, irrespective of the harvesting method used (either whole-tree or stem-only), did not emulate the biogeochemical effects of wildfire on forest floor carbon, nutrients and acid–base status or on jack pine foliar nutrition (Thiffault *et al.* 2007a, 2008). The emulation of natural disturbances through the use of appropriate harvesting practices is an important tenet of sustainable forest management. Wildfire is the major natural disturbance in the boreal forest of Canada. It is a benchmark for evaluating the impacts of harvesting, based on the rationale that the survival, recovery and productivity of boreal forest ecosystems have evolved in response to wildfire and are therefore well adapted to the conditions created by this natural disturbance. Although stem-only harvesting retains slash on site and therefore appears to be a more ecologically sustainable practice than whole-tree harvesting on these sites (Thiffault *et al.* 2006), it did not reproduce the

[6]David Paré, Natural Resources Canada, unpublished data.
[7]David Paré, Natural Resources Canada, unpublished data.

conditions caused by wildfire. It is uncertain, however, whether the differences found two decades after harvesting and wildfire disturbances will be maintained over the course of a full rotation, and whether they portend long-term nutrient availability problems on the harvested sites.

Then again, a modelling exercise using the dynamic biogeochemical model SAFE, parameterized with the data from the field trials, suggested that whole-tree harvesting of jack pine stands growing on these sandy soils would not lead to soil base cation depletion in the long-term (Thiffault *et al.* 2007b). According to the modelling results, any kind of forest disturbance, either anthropogenic (harvesting) or natural (wildfire), influences base cation availability to different extents for periods of one to five decades. However, neither one of these types of disturbance, regardless of its return interval or intensity, seems to be the main driving force of soil chemistry in the long term (i.e., over a period of many stand rotations); the more important driver rather appears to be acidity from atmospheric deposition of sulphur and nitrogen compounds.

We therefore conclude, based on the range of approaches used and for the sites studied, that the soil geochemical composition and species in the regenerating stand appear to be good indicators of site sensitivity to intensive biomass harvesting, and that concerns over the negative impacts of WTH and any subsequent mitigation measures should focus on soil nutrient availability and microenvironment in regenerating stands during the crucial first decades of the rotation. However, long-term forest soil base cation depletion and soil acidification may not be at stake in relation to harvesting methods. These concerns appear to be mainly related to acid atmospheric deposition; air pollution abatement policies rather than forest management strategies should first be dealt with to ensure long-term productivity on these sites. Nevertheless, continued field monitoring is required to validate this affirmation and field-based experimentation, such as factorial fertilizer trials, is needed to empirically verify the actual influence of the different driving forces on soil chemistry and potential site productivity.

… Then What?

Despite the large body of research on the subject, numerous knowledge gaps and questions remain surrounding the ecological impacts of intensive biomass harvesting. For example, Earl Stone, at a 1979 symposium on the impact of intensive harvesting on forest nutrient cycling, identified a set of research gaps that still warrant scrutiny. These gaps included (i) the capacity of soils to supply nutrients in the face of removals by intensive harvests, (ii) the nature and magnitude of possible decreases in productivity and mitigation measures to counteract these decreases, (iii) physical consequences of more frequent traffic by harvesting equipment and lower returns of organic matter to the soil, and (iv) unplanned secondary effects resulting from altered nutrient cycling on, for example, species composition, habitat diversity and pest problems (Stone 1979). Almost three decades later, considerable progress has obviously been made towards a better understanding of these issues (see review by Burger 2002). However, these four knowledge gaps have yet to be entirely filled, especially when applied at a site level for guideline development, and hence are still priorities today.

Of all the unanswered questions, one of the most important is: "When and how do we know that the observed results of intensive biomass removal reflect the 'complete' impact, and that no further impacts will be observed in the future?" In other words: "How long do trials and operations need to be monitored before we know the full long-term impacts of biomass removals?" Unfortunately, we can never know for sure until a full rotation is completed. Even after 24 years, some authors cannot confidently conclude that the growth losses observed with biomass harvesting are temporary or permanent, and still recommend further monitoring (Egnell and Valinger 2003). On the other hand, modelling alone cannot make definitive predictions.

Notwithstanding the history of research and the current state of knowledge, policy-makers, land managers and scientists in Canada and around the world are still asking: "How can we use existing scientific knowledge to make decisions, and what indicators can we use to predict site sensitivity to intensive biomass removals?" Some countries have taken a proactive stance and developed guidelines for forest biomass harvesting based on their local knowledge and understanding of the issue. For example, the United Kingdom has produced a classification of soil types according to their risk for soil fertility following harvest residue removal (United Kingdom Forestry Commission 2008; Fig. 3). The Swedish National Board of Forestry also provides recommendations for the extraction of forest fuels to preserve the nutrient balance of forest sites (Swedish National Board of Forestry 2002). For example, they stipulated that branches and tree tops can be harvested once per rotation provided that most of the needles are left and spread out, or else compensatory fertilization should be carried out (see Lattimore *et al.* 2010, this issue, for a discussion on the role of guidelines; see Stupak *et al.* 2007 and 2008 for reviews of guidelines).

In Quebec, an initiative was undertaken by academic and government researchers to use scientific knowledge to develop harvesting guidelines adapted to the province's forest conditions. Based on results from field trials, soil physical and geochemical characteristics were chosen as prescriptive indicators of site sensitivity to biomass harvesting. Sites with very coarse-textured soils and low base cation geochemical content would be considered highly sensitive and at risk of productivity loss, and

Risk Category	Soil Types
Low Unaffected by residue removal	Brown earths (except podzolic type (1z)), Surface-water gleys (except podzolic type (7z)), Ground-water gleys, Limestone soils, *Juncus* bogs.
Medium Leave most of foliage	Podzolic brown earths (1z), Podzolic surface-water gleys (7z), Integrade ironpan soils (4b), Peaty gley soils, *Molinia* bogs (9a,b).
High Unable to sustain residue removal	Unflushed peatland/bog soils, *Molinia* bogs (9c-e), Ironpan soils (except integrade type (4b)), Podzols, Littoral soils, Rankers and Skeletal soils.

Fig. 3. Guidelines for residue harvesting in the United Kingdom.

thus should not be subjected to intensive biomass removal. This initiative has built on the work done in the province during the past decades on the ecological classification of forest sites, and used this to link these indicators to information that is already known and mapped for Quebec. Research to validate the indicator and test its ability to predict the impacts of intensive harvesting on site productivity is ongoing.

Conclusion

Existing scientific information on the impacts of intensive harvesting is moderately abundant, but further synthesis and generalization is needed for wider applicability. Obviously, generalizing findings so that they can be applied means making decisions based on less knowledge than many scientists are comfortable with. To be useful for policy-making and forest management, science must, in the face of much uncertainty, deal with scaling up research results and drawing lines between areas that are different shades of grey rather than black and white. There will never be enough good long-term research field trials to validate and fine-tune harvesting guidelines and harvesting operations, and regulation will inevitably proceed without perfect certainty of future impacts. However, systematic monitoring of harvesting operations also allows for the accumulation of ecological knowledge that will help reduce uncertainties. This does not mean that there will not be a need for more field trials as evolving forest operations and identification of knowledge gaps will doubtless necessitate their establishment, and this may come sooner rather than later. Paraphrasing the old African saying, "the best time to establish field trials was 30 years ago, and the next best time is now". All this fits neatly within the concept of adaptive forest management (Fig. 4), in which policy direction produces guidelines for forest management operations and the monitoring of these operations fosters ecological data collection and generation of new hypotheses that can be tested with field trials and enriched by modelling, the results of which are then used to adjust forest management and policy direction.

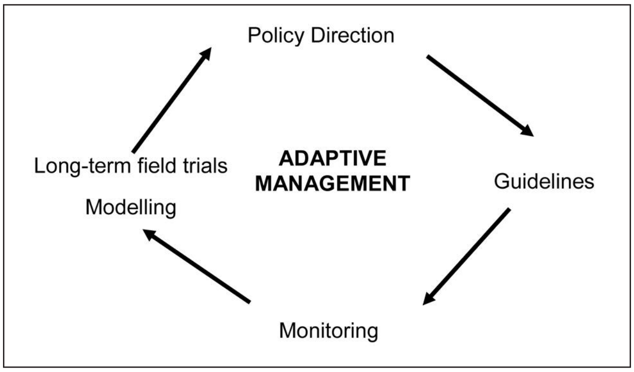

Fig. 4. The concept of adaptive management.

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