

Trade-offs between timber production, carbon stocking and habitat quality when managing woodlots for multiple ecosystem services

THEMATIC SECTION
Forest Ecosystem Services

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SUMMARY

Managing for multiple ecosystem services is a growing issue for forest managers. As trade-offs arise between conflicting management objectives, stakeholders must be informed of the possible outcomes of alternative choices in order to facilitate decision-making. We modelled stand dynamics under single-management and functional zoning multiple-management (TRIAD; i.e. three-zone) scenarios in different forest types typical of eastern North America with the Forest Vegetation Simulator (FVS). Timber production, carbon stocking and habitat quality ecosystem services were calculated with simulation outputs. Habitat quality was measured using a habitat suitability index that integrated stand structural indicators. A multi-criteria decision analysis (MCDA) was performed in order to rank scenarios. We show that the most intensive management yielded greater timber volumes but resulted in the weakest carbon and habitat quality scores. The TRIAD scenarios in sugar maple–beech stands offered the best compromise in services compared to single management. In shade-intolerant deciduous stands, there was a loss of timber production with TRIAD scenarios, but greater carbon stock and habitat quality were observed. Our study contrasts alternative management scenarios for ecosystem services in woodlots of different forest types. It confirms that multiple harvest systems better achieve multiple services. The coupling of simulation modelling with MCDA offers a simple and flexible method to help stakeholders and managers make sound decisions.

Keywords: ecosystem services, forest dynamics modelling, forest management planning, multi-criteria decision analysis, TRIAD

INTRODUCTION

Forests are under increasing pressure to provide a multitude of ecosystem services (i.e. direct and indirect goods and benefits for humans), such as timber, carbon, recreation and biodiversity (Costanza *et al.* 1997), to a growing population. Tree carbon storage, for example, is now recognized as an important forest function that contributes to mitigating climate change (Canadell & Raupach 2008). Different forest management practices can either fix or release carbon (Dixon *et al.* 1994), making carbon accounting important (Moore *et al.* 2012) and furthermore necessary through carbon markets (Tavoni *et al.* 2007). Habitat quality – a well-used indicator of the potential of a habitat to harbour local biodiversity – reflects ecosystem integrity and is part of forest certification requirements (Brown *et al.* 2001). An ecosystem with high habitat quality contributes better to overall ecosystem function and service provision, including cultural services such as recreation (Balvanera *et al.* 2006). Strong trade-offs among supply, regulation and cultural ecosystem services have been identified (Bradford & D'Amato 2011), yet few tools and approaches exist to help private forest owners and managers integrate multiple management objectives in their forests.

One such tool – forest simulation modelling – is used to predict, within uncertainty boundaries, the dynamics and the possible outcomes of various management decisions on forests (Peng 2000; Messier *et al.* 2003). However, well-informed management decisions based on the interpretation of several simulation outputs can be overwhelming, particularly when comparing the success of various management scenarios in achieving different management objectives (Mendoza & Martins 2006). This is why multi-criteria decision analysis (MCDA) has been proposed to improve the structuring and understanding of complex management scenarios with several management objectives (Belton 2002).

Combining simulation modelling and MCDA, our study aimed to quantify the trade-offs between three important ecosystem services resulting from different forest management practices so as to provide decision-making tools for stakeholders. We compared the levels of timber production, carbon storage and habitat quality (henceforth

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referred to as a service) under various single- and combined-management scenarios, using forest stand characteristics produced by the growth simulation model Forest Vegetation Simulator (FVS). We used a simplified MCDA approach on model output by Schwenk *et al.* (2012). Habitat quality was measured with a habitat suitability index (HSI) that we developed in order to use the FVS outputs directly, thus simplifying the overall process for the potential users of this approach. Furthermore, we used five stands from three forest types in order to cover a realistic range of stands encountered in eastern North America. Sugar maple–beech (SM) stands, shade-intolerant deciduous (SID) stands and white spruce plantations (WSP) were each simulated under three alternative, increasing intensity, single-management scenarios. We extended the management possibilities seen in Schwenk *et al.* (2012) by calculating five functional zoning multiple-management scenarios, hereafter named TRIAD (i.e. three-zone) scenarios (*sensu* Messier *et al.* 2009). Similar to the compartment model described by Odum (1969), each TRIAD scenario combines all ecosystem service results with three different proportions of intensive, extensive and no-management zones.

The goals of our study were to: (1) simulate the effects of contrasting management scenario intensities applied in three different forest types on multiple services; (2) quantify trade-offs in ecosystem services; and (3) estimate whether TRIAD scenarios could better fulfil multiple services at a time. To our knowledge, this is the first analysis comparing multiple ecosystem services that combined even- and uneven-aged management prescriptions within different forest types and contrasting management scenarios.

METHODS

Study region and stands

Our modelling approach explores stands that one could encounter in a typical private hardwood forest of eastern North America. Stands of SM, SID and WSP were selected for the simulation of various forest management scenarios.

Stands from the Forest Inventory and Analysis (FIA) database of the state of New York (2012 survey) were used to make the simulation as realistic as possible. To simplify the number of simulations to be made and render all scenarios more easily comparable, we decided to select stands that were ready to harvest, resulting in a bank of suitable stands from which to draw five stands randomly. The criteria for stand selection are described in Appendix S1 (available online) and their silvicultural characteristics are shown in Table S1.

Forest simulation model

The Northeast Variant of FVS, a well-known growth model (Crookston & Dixon 2005), was used to simulate three management scenarios, with different harvest types and

cycles, applied on the stands described above. FVS simulates the dynamics of each tree in a stand in a non-spatially explicit context.

Management scenarios and simulation parameters

Management scenarios were simulated over a 70-year horizon using 10-year time steps. The first three scenarios were designed to replicate management that is typical of Northeast American forests. An ecosystem (Grumbine 1994) and intensive management scenario that differed depending on forest type was compared to a no-management scenario (where no timber is cut) for each of the three different forest types (scenarios hereafter named No-management, Ecosystem, and Intensive; see Table 1). The scenarios and the rotation lengths were developed in order to reflect the current thinking in terms of silvicultural practices for these kinds of stand in private woodlots.

Harvesting parameters for the individual tree selection (ITS) used for Ecosystem in SM stands were set in order to allow for initial basal area recovery in a 20-year harvest cycle. The merchantable volume of a tree was calculated from 15-cm stump height trees with a minimal diameter at breast height (DBH) of 9 cm. The maximum basal area was set at 35 m² ha⁻¹ in the SM stands, representative of forests dominated by sugar maple and beech (McCune & Menges 1986), at 40 m² ha⁻¹ for the denser SID stands and at 50 m² ha⁻¹ for the WSP. Setting a maximum basal area ensured that the stands would not grow to exceed what is sustainable for the site, which has been recommended for FVS (Dixon 2002).

TRIAD forest management scenarios consisted of simultaneously applying the three simulated management scenarios (shown in Table 1 for SM and SID) within one single stand of a particular forest type. The mean of the five stands under each single-management scenario was used for this single stand in order to simulate the various TRIAD scenarios. Spatial components were not considered. The ‘wood production’ zone corresponded to our Intensive, which was divided into two sub-zones: the original stand under Intensive and a WSP under Intensive. The latter was implemented following a clearcut in the SM and SID stands. Following Côté *et al.* (2010), we investigated five different zoning proportions (Table 2). The numbering in the names of the TRIAD scenarios reflects the percentage of the land set aside for conservation, increasing from T12 to T50. The zoning proportions of T12 and T20 have been tested by Côté *et al.* (2010) and T50 is currently demanded in boreal forests by some environmental groups (Badiou *et al.* 2013).

FVS simulation cycles and regeneration sub-model

There is a fixed processing sequence of operations in a FVS simulation (Dixon 2002): the model first reads and computes the initial stand characteristics, then processes the thinning if requested, grows trees, allows some mortality that generates

Table 1 Management scenarios for the 70-year simulations (2012–2082). Retention harvesting refers to 80% of the basal area being removed from below. Commercial thinning refers to 35% of the basal area being removed from above. Pre-commercial thinning refers to 10% of the basal area being removed from below. DBH = Diameter at breast height; ITS = Individual tree selection.

Management scenario	Sugar maple–beech stands	Shade-intolerant deciduous stands	White spruce plantations
No-management	No management	No management	No management
Ecosystem management	ITS every 20 years: q-factor: 1.4; min DBH class: 5 cm; max DBH class: 61 cm; DBH class width: 5 cm; residual basal area: 21.6 m ² ha ⁻¹	Retention harvesting: 2012, 2082; commercial thinning: 2052	
Intensive management	Clearcut: 2012, 2082; pre-commercial thinning 20 years after clearcut: 2032; commercial thinning 40 years after clearcut: 2052	Pre-commercial thinning: 20 years after seedling plantation; Commercial thinning 30 years before clearcut: 2052; Clearcut: 2082	

Table 2 Proportions (%) allocated to each TRIAD management scenario (modified from Côté *et al.* (2010)).

TRIAD scenario	No-management zone	Ecosystem management zone	Wood production zone	
			Intensive	Plantation-Intensive
T12	12	74	10	4
T20	20	40	36	4
T33	33	33	17	17
T50	50	25	25	0
T50I	50	25	13	12

Table 3 Measures of ecosystem services on 70-year simulation results. DBH = Diameter at breast height; FVS: Forest Vegetation Simulator.

Ecosystem service	FVS output measure
Timber	Total merchantable volume harvested over 70 years (m ³ ha ⁻¹)
Carbon storage	Mean carbon stocked in aboveground live trees, standing dead trees and down dead wood (tons ha ⁻¹)
Habitat quality	
Vertical structure	Mean Gini index
Large tree density	Mean number of trees of DBH >40 cm (trees ha ⁻¹)
Large snag density	Mean number of standing soft and hard snags of DBH >30.5 cm (trees ha ⁻¹)

snags and finally establishes new trees (regeneration). As mortality is density dependent, parameters of new seedling regeneration must be computed in order to ensure proper forest dynamics (see Table S2) (Nunery & Keeton 2010). The parameter selection and adjustment for the model are described in Appendix S1.

Ecosystem service measurements and utility analysis

We limited our analyses to three services that could be easily assessed using only the variables included in FVS. Timber, habitat quality and stored carbon were calculated based on the FVS outputs for the different stands (Table 3). Timber is a common source of revenue for forest owners, habitat quality is an expected requirement of many certification programmes and carbon is increasing in importance and value. All merchantable volumes that were removed were

summed over the 70-year simulation for the timber service. It was equal to zero in No-management, as no merchantable volume was extracted. We used the sub-model Fire and Fuels Extension of FVS in order to evaluate carbon storage. The default 10-year time step was used for all of the simulation outputs (Wykoff & Crookston 1982). We considered only the carbon stored in the aboveground live tree biomass and followed the carbon calculation of Jenkins *et al.* (2003).

Habitat quality was quantified with a HSI (Schamberger & Krohn 1982) based on measurable structural components of a forest stand (Ferris & Humphrey 1999). Three characteristics of old-growth forests were considered as optimal in the calculation of the HSI for each stand (Bauhus *et al.* 2009). The densities of large trees (DBH ≥ 40 cm) and large snags (DBH ≥ 30.5 cm) were averaged over the simulation. Furthermore, since tree diameter distribution is a good indicator of stand

biodiversity (Buongiorno *et al.* 1994), it was calculated using the Gini index (Gini 1921) on DBH classes of 2 inches (5.08 cm). This coefficient has been found to be particularly appropriate for discriminating diverse stand parameters, such as its vertical structure (e.g., Bílek *et al.* 2013).

The MCDA approach allows for the determination of which alternative scenario performs best considering multiple services, as well as for visualizing the trade-offs and benefits among them (Diaz-Balteiro & Romero 2008; Ananda & Herath 2009). Each service was designated as a partial utility scaled to 1, or 100%, to allow for comparison among them. Partial utilities can be weighted depending on the priorities and values of the manager. Among the many multiple-criteria decision-making techniques available (Tamiz *et al.* 1998; Romero 2001; Belton 2002), we used a simple methodology fit for a discrete-choice problem like ours. The overall performance of a scenario was quantified by the sum of the service levels transformed into partial utilities.

In this study, we gave services equal weights. For each of the three stand types, partial utilities were calculated as:

$$U_{P,i,j} = \frac{P_{i,j}}{P_{max}} \quad (1)$$

for all three services P , five stands i and three management scenarios j . To obtain the carbon stock utility, $U_{Cstock,i,j}$, every carbon stock annual mean for an i,j combination, $Cstock_{i,j}$, was divided by the maximum value of the annual mean carbon stock, $Cstock_{max}$, found among the five stands i , across all three management scenarios j . Likewise, for the timber utility $U_{T,i,j}$, the value of the total harvested volume after 70 years of every i,j combination, $T_{i,j}$, was divided by the maximum value showed by any combination i,j , T_{max} .

Habitat quality was measured with a HSI, $H_{i,j}$:

$$H_{i,j} = U_{LT,i,j} + U_{LS,i,j} + U_{G,i,j} \quad (2)$$

where sub-utilities (density of large trees $U_{LT,i,j}$, density of large snags $U_{LS,i,j}$ and Gini coefficient $U_{G,i,j}$) were obtained with eqn (1) using HSI components instead of P services. Following eqn (2), the partial utility of habitat quality, $U_{H,i,j}$, was then calculated with eqn (1).

Finally, for every management scenario j , the partial utilities of the five stands i of a specific type (SM, SID or WSP) for a service P were averaged, giving a mean utility $U_{P,j}$:

$$U_{P,j} = \frac{\sum_{i=1}^5 U_{P,i,j}}{5} \quad (3)$$

The TRIAD management scenarios were evaluated with eqn (3) in the SM and SID stands. The calculation of a total score $U_{P Tot}$ for a given service P was realized by using the proportions p found in Table 2 to weight each mean utility U_j :

$$U_{P Tot} = p_{NM}U_{P,j=NM} + p_{ECO}U_{P,j=ECO} + p_{INT}U_{P,j=INT} + p_{PI}U_{WSP,P,j=INT} \quad (4)$$

where p_{NM} , p_{ECO} and p_{INT} are the proportions of the utility value U for No-management, Ecosystem and Intensive, respectively. In eqn (4), p_{PI} refers to the proportion of the

partial utility found for the most timber-productive WSP stand under Intensive.

Simulation outputs were analysed by first computing utilities for single-management scenarios. All TRIAD scenarios and single-management scenarios were then compared with respect to every utility using MCDA. A non-parametric Kruskal–Wallis test ($\alpha = 0.05$) was used in order to test the differences between single-management scenarios within a forest type. *Post hoc* contrasts were performed when necessary with pairwise comparisons using a multiple comparison test after Kruskal–Wallis testing (R package ‘pgrimess’). All of the FVS output data analyses were conducted with R (R Development Core Team 2010).

RESULTS

Simulated stand characteristics over a rotation

Live tree basal area (Fig. 1), aboveground carbon and available merchantable volume (similar pattern as basal area; see Fig. S1) changed over the rotation according to the harvesting interventions that were planned. In all forest types, No-management maintained the highest values for all three stand characteristics. Ecosystem and Intensive were very similar except for the SM forest type, where Ecosystem tended to maintain higher values throughout the rotation (Table 1). The fluctuating values for the two management scenarios reflected the scheduled harvests and density-dependent mortality. In fact, after the first cutting event in 2012 in managed stands, the levels of carbon and available merchantable volume never reached those of unmanaged stands. In SM stands, stored aboveground carbon at the end of No-management was twice the highest value of carbon stored during the rotation under Intensive (Fig. S1(a1)).

Sharp increases in the basal area of SID stands under active scenarios after the first harvest were caused by a massive recruitment of seedlings, of which a large proportion died in the following time step due to density-dependent mortality (Fig. 1(b)). This heavy mortality explained the drop in 2032 for basal area and carbon values in Ecosystem, while the drop in Intensive also resulted from a pre-commercial thinning. Both scenarios in SID stands showed almost the same amounts of carbon throughout the rotation (Fig. S1(a2)).

MCDA for single-management scenarios

As expected, harvest volume increased with increasing management (Fig. 2, Table S3). The most timber for all forest types was harvested under Intensive, although the overall model was significant ($p < 0.001$) only in the SM forest type, in which more than 2.5-times the amount of timber was harvested compared with Ecosystem management. Timber utility in the latter scenario resulted in 25% of the maximum timber being produced (Fig. 2(a)) compared to 67% for Intensive.

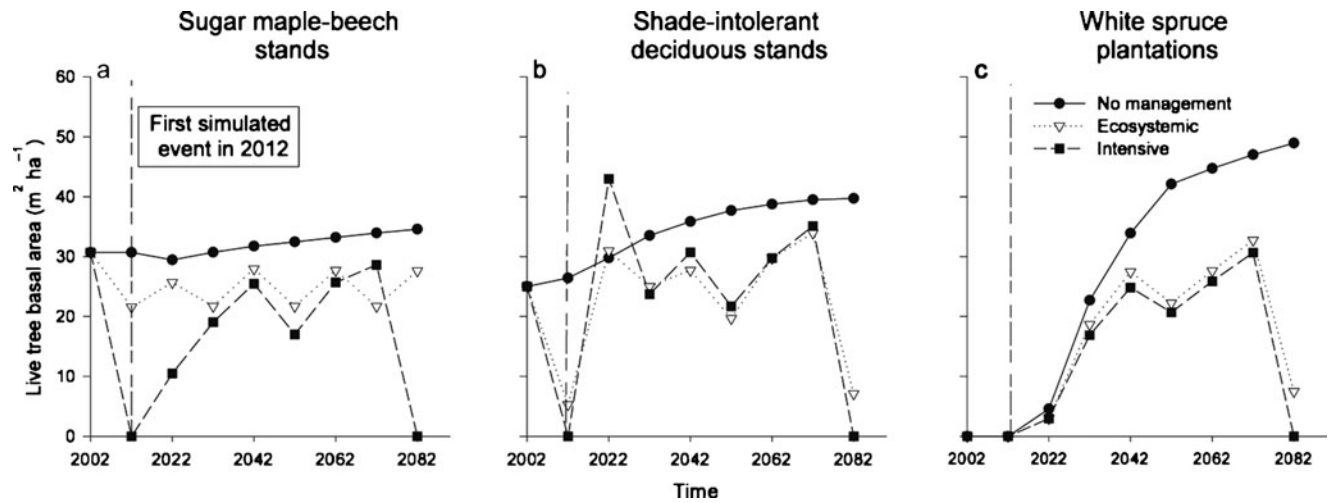


Figure 1 Results of the 70-year simulation (2012–2082) with 10-year time steps, averaged over (a) five sugar maple–beech stands, (b) five shade-intolerant deciduous stands and (c) five white spruce plantations for three management scenarios. Measurements shown are the mean live tree basal areas calculated after harvesting activities if scheduled. Values in 2002 for (a) and (b) were calculated using the predicted 70-year rate of change in the No-management scenario. The null values in 2002 for (c) represent the stand after a clearcut, at the beginning of the next rotation. These 2002 values are for visual purposes and are not used in subsequent analyses.

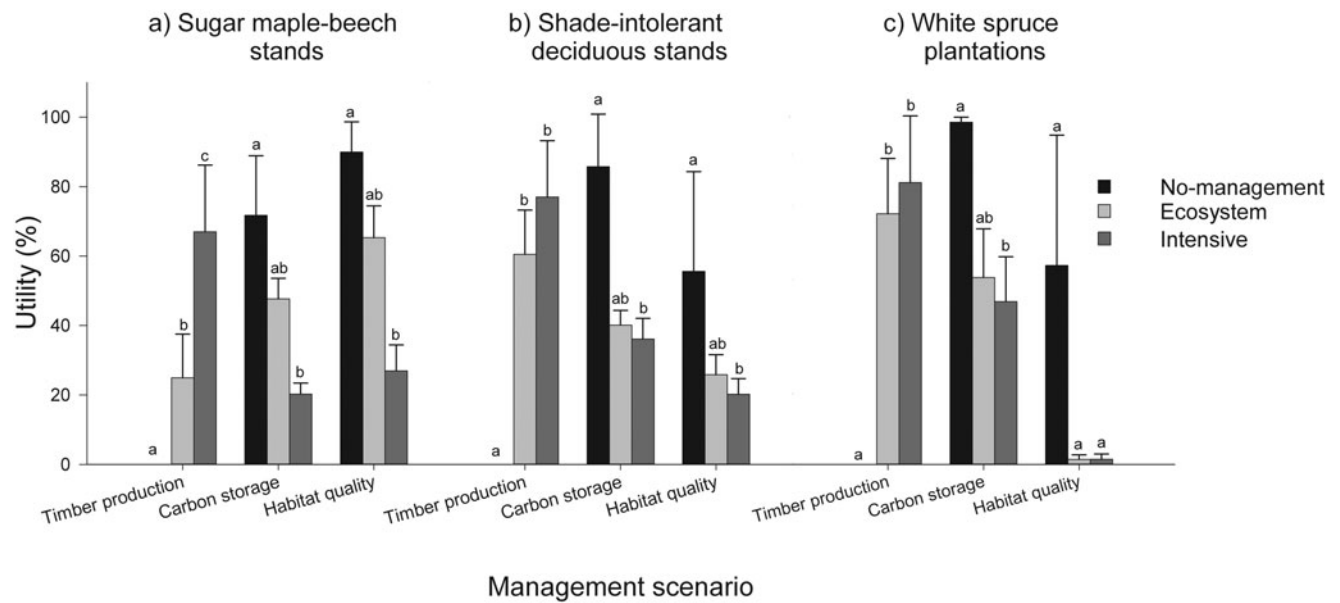


Figure 2 Expected mean utilities \pm SD for timber production, carbon storage and habitat quality over the 70-year rotation for the No-management, Ecosystem and Intensive management scenarios applied in (a) sugar maple–beech stands, (b) shade-intolerant deciduous stands and (c) white spruce plantations ($n = 5$ for each forest type). Utilities are service values relative to each other, where the maximum value reached by any combination of a single stand for any of the three management scenarios is given 100%. For each management scenario within each forest type, a different letter (a, b or c) above the bars indicates a significant difference between utility values.

For carbon storage, No-management resulted in higher utilities than the two other scenarios for all three forest types, though this was only significant when compared to Intensive ($p < 0.05$; Fig. 2, Table S3). In SM stands, the predicted mean carbon storage utility was of 72% for No-management, which is 50 and 300% higher than Ecosystem and Intensive, respectively (Fig. 2(a)). In turn, Ecosystem stored more aboveground live carbon than Intensive.

In the SID and WSP stands, No-management achieved a carbon utility of more than twice the utilities found under the active scenarios (Fig. 2(b) and (c)).

The utilities for habitat quality displayed similar patterns as for carbon storage in the SM and SID stands (Fig. 2(a) and (b)). In SM stands, while No-management produced a greater habitat quality utility score than Ecosystem, the difference was significant between No-management and

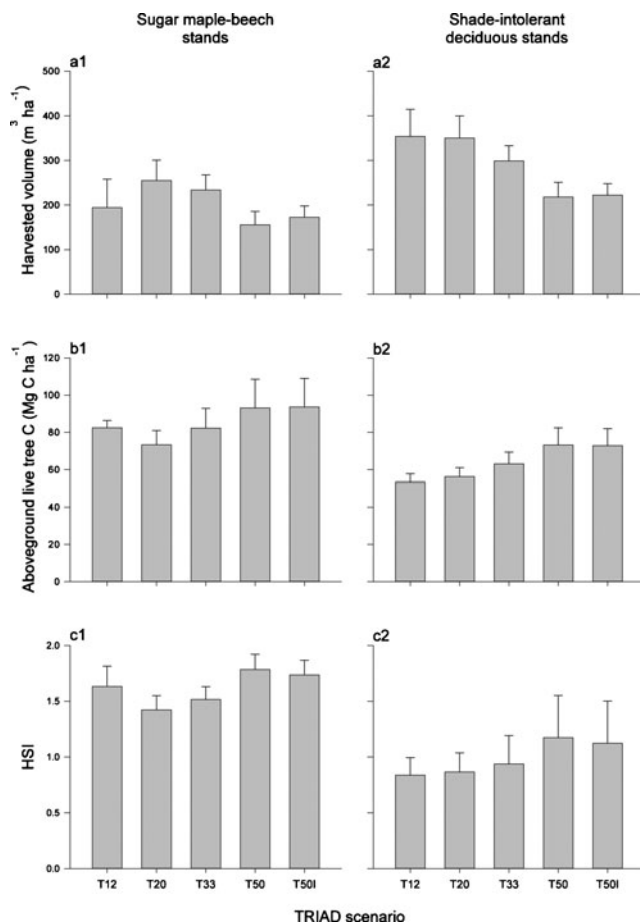


Figure 3 Comparison of (a) total harvested volume (mean \pm SD), (b) carbon (C) stored in aboveground live trees biomass and (c) habitat suitability index (HSI) among the five TRIAD scenarios in (1) sugar maple-beech and (2) shade-intolerant deciduous stands. The results are based on the 70-year means obtained from single-management scenarios (Table S3), multiplied by their assigned proportion within the multiple-management TRIAD scenarios. The results of all of the single-management scenarios are then summed within each TRIAD scenario.

Intensive only ($p < 0.05$; Fig. 2(a)). In SID stands, habitat quality was significantly greater under No-management than under Ecosystem or Intensive scenarios ($p < 0.05$; Fig. 2(b)). Unmanaged stands displayed large variability in habitat quality and their mean utility score reached 56%, which did not differ significantly from Ecosystem despite a lower utility score (26%), but was more than double that of the Intensive scenario (20%, $p < 0.05$; Fig. 3(b)). In WSP stands, while habitat quality had a higher utility score under No-management (57%; Fig. 2(c)), none of the scenarios resulted in significant differences. Like the available merchantable volume and carbon stocks, habitat quality (higher density of large trees and snags and greater Gini index) was greatest in No-management during the whole rotation in all stands (see Fig. S2 for the utility results of HSI components). The mean HSI was very low in unmanaged WSP stands and almost null in managed ones (Table S3) due to their poor vertical

structure. None of the WSP stands had large trees or snags throughout the rotation, so the HSI was based only on the Gini index (Fig. S2).

MCDA for single- and multiple-management TRIAD scenarios

The different TRIAD scenarios resulted in different values of ecosystem services for each forest type (Fig. 3). The highest timber production, carbon storage and habitat quality were found in the T20, T50I and T50 scenarios, respectively, for the SM forest type, and in the T12, T50I and T50 scenarios, respectively, for the SID forest type. Indeed, a decrease of timber production (Fig. 3(a1) and (a2)) echoed a reverse tendency in carbon storage (Fig. 3(b1) and (b2)) and habitat quality (Fig. 3(c1) and (c2)).

Finally, trade-offs were observed among the utility values for timber, carbon and habitat quality produced under the single management scenarios (No-management, Ecosystem and Intensive) and the five TRIAD scenarios (Fig. 4). Clearly, no scenario can be singled out for the optimized production of all three services. While the No-management scenario produced the highest habitat quality and carbon utilities, it did not produce any timber (Fig. 4). Conversely, while the Intensive management scenario had the highest timber utilities, it also had the lowest habitat quality and carbon utilities. Despite showing the highest total utility, No-management did not produce timber, hence it cannot be seen as the best compromise between the three services. The best compromise among ecosystem services was found with the TRIAD T50I scenario in SM stands and the T50 scenario in SID stands, which resulted in the highest scores for the provision of all three services. The lowest utility scores were observed in Intensive and Ecosystem single-management scenarios.

DISCUSSION

This study presents a straightforward approach to identifying and quantifying trade-offs among three important ecosystem services – timber, carbon and habitat quality – under commonly used management scenarios. The different harvesting schedules and intensities on three types of forest stands highlighted the variability of responses to management practices. The MCDA approach helped assess and compare the overall performances of different management scenarios for these three services and revealed the best, average and worst management options for each service individually; this is valuable information in the decision-making process of managers.

Evaluation of each ecosystem service

Timber production

The measure of timber volume is largely used by foresters and is the easiest to grasp by stakeholders. However, timber

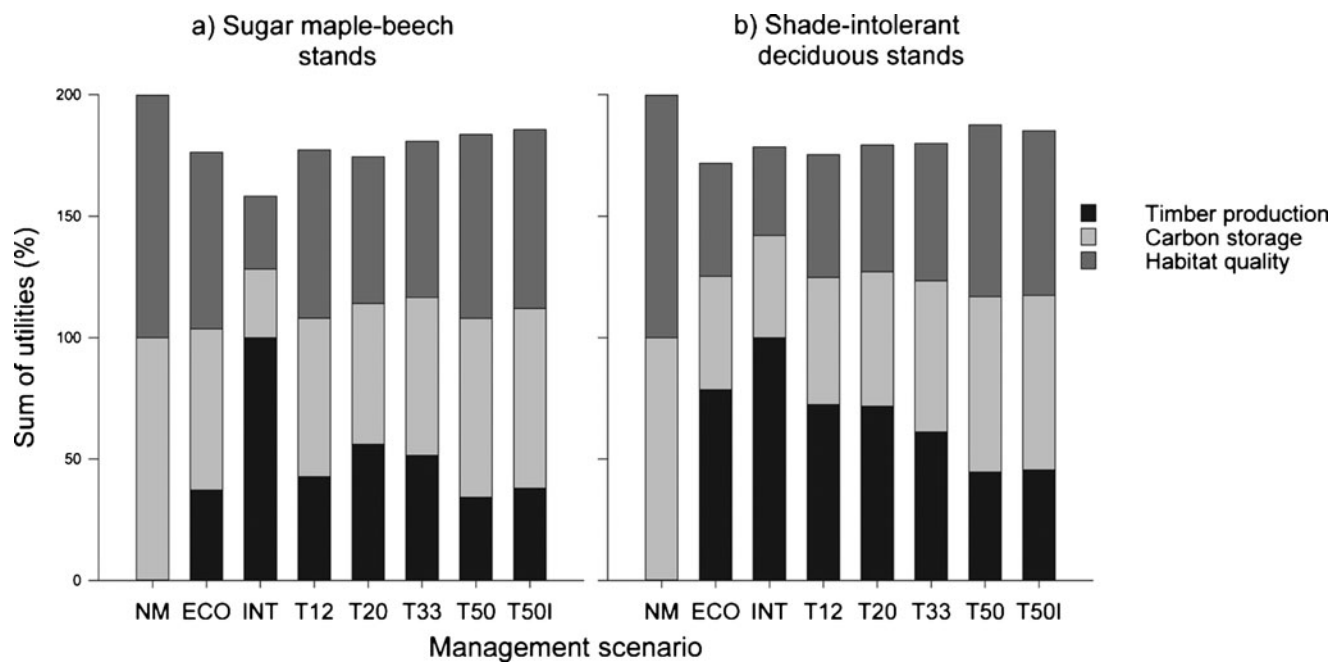


Figure 4 Comparison of the sum of expected utilities of timber, carbon and habitat quality among three single-management and the five multiple-management TRIAD scenarios. Forest types are (a) sugar maple–beech and (b) shade-intolerant deciduous. The utility for one service in a given scenario is the ratio expressed as a percentage between its value for that scenario and its highest value across all scenarios. Single-management scenarios are NM = No-management; ECO = Ecosystem; INT = Intensive.

was measured without regard to its quality and so our method is likely to underestimate the value of timber-performant scenarios, depending on the type of products the stakeholder is interested in. The harvested species are also differentially valued on the market, their values fluctuate over time and they are highly uncertain in the future (Brazee & Mendelsohn 1988). Measures of the quadratic mean diameter and sawlog volumes, which are available FVS outputs, could help differentiate harvesting scenarios based on the quality of timber. The integration of these additional measures and the identification of the tree species of the harvested stems would make future analyses of timber production more precise and facilitate the decision-making process.

Carbon stock

The calculation of carbon stocking as an ecosystem service was accomplished here for the purpose of comparing the performance of different management scenarios and should be seen as an estimate rather than a precise prediction. Nonetheless, our mean expected aboveground live carbon stock for SM stands reached $126.4 \pm 30.3 \text{ MgC ha}^{-1}$, which is consistent with reported means for old-growth northern hardwood stands (Hoover *et al.* 2012; MacLean *et al.* 2014). We recognize that contemporary carbon accounting calls for a closer tracking of carbon fate in timber products (Profft *et al.* 2009). Carbon pools situated underground or on the forest floor (live and dead organic matter, coarse woody debris and standing dead wood) not estimated here could improve estimates (Nunery & Keeton 2010). For example,

the root biomass of hardwood trees can be 1.5-times that of aboveground biomass (Li *et al.* 2003). However, the overall ranking of the best scenario for carbon storage is unlikely to differ if these pools were considered, since they are likely to be highly correlated with our estimate of aboveground carbon (Kurz *et al.* 1996). We also suggest caution in the interpretation of our carbon results since no local calibration was carried out after direct FVS computation of FIA data processed with the FIA2FVS software.

Habitat quality

Values of habitat quality, measured through our HSI, were always greater in No-management, regardless of forest type. As reported elsewhere, unmanaged stands had greater snag densities than managed ones (Vanderwel *et al.* 2006). Our HSI was intended to give high values to stands showing ‘old-growth’ characteristics (Bauhus *et al.* 2009). Thus, early-successional stands would not display a high HSI score, even if they had high species diversity. The attributes of the HSI favoured scenarios maintaining already-present species in old uneven-aged stands and increasing late-successional species in ageing stands. Consequently, the low average habitat quality utilities of managed SID and WSP stands were anticipated. While WSP stands may provide suitable habitats for some organisms, such as generalist carabid species (Brockerhoff *et al.* 2008), the quality of these stands is considered inferior to more mature stands (Lindenmayer & Hobbs 2004), which provide habitats for a wide range of species such as cavity-dependent birds. However, different results could be obtained

if emphasis was given to earlier-successional stands (Dessecker & McAuley 2001; Brooks 2003).

Managing for multiple ecosystem services

Clear trade-offs were evident when considering multiple ecosystem services. The TRIAD scenarios provided a good compromise in terms of the amount of each of the three ecosystem services investigated. Our findings demonstrated that TRIAD scenarios can indeed achieve multiple forest management goals. With only single-management scenarios at hand, one could select Ecosystem in SM stands as a compromise between producing timber, carbon and habitat quality closest to unmanaged levels, but all stands were then subject to some level of management. Adding the TRIAD scenarios to the portfolio of possibilities revealed that it is possible to harvest as much timber as for the Ecosystem scenarios while storing, on average, a greater quantity of carbon, and having a certain proportion of the forest under total protection. As ITS in SM stands is a harvest practice of predilection in northern hardwoods (O'Hara 2002; Bédard & Majcen 2003), this finding is most relevant and promising for future uneven-aged planning. Mean habitat quality in TRIAD may be poorer than in Ecosystem since zones under Intensive have lower HSIs. However, by limiting timber activities to a certain area and maintaining many areas totally unmanaged, the TRIAD approach may also be financially and ecologically appealing for forest owners in terms of reduction in road construction and the disturbance of some key habitats.

In our scenarios, all three ecosystem service objectives had the same weight. However, given that assigned weights should respond to stakeholder objectives, these could be modified at any point of the simulation to suit different values and interests attributed to each ecosystem service (Bengston 1994; Arnette *et al.* 2010). Moreover, ranking based on values that are not significantly different, or within a range of acceptability as determined by stakeholders, could be assigned a similar ranking in order to compare the variation in performance among different management scenarios (Saaty 1980; Greco *et al.* 2008). Alternative MCDA procedures that require *a priori* decision-maker preferences such as target values for each criterion in goal programming (Stewart 1992) are less user friendly. However, future modelling efforts that aim to determine optimal proportions of TRIAD zoning, for example, would benefit from the use of a continuous-optimization MCDA procedure (Estrella *et al.* 2014). This study focused on three important ecosystem services, but additional services of relevance to managers could also be investigated, such as the production of non-timber products (e.g. mushrooms, berries and fiddleheads) and specific recreational services. In addition, spatial configurations of TRIAD zones could be investigated in order to evaluate the effects of spatial heterogeneity, landscape fragmentation and connectivity on each service (Côté *et al.* 2010; Tittler *et al.* 2015). The parameters of forest dynamics within the FVS could be redefined according to the predicted effects of

climate change that may alter tree growth and disturbance risk (Crookston *et al.* 2010). Moreover, the weight associated with the carbon stock utility in the MCDA could be increased in order to reflect its rising value due to the implementation of a carbon market. All of these services could also be attributed economic factors that will realistically change (e.g. an annuitized net present value) throughout the simulation period. Simplicity was an important goal of this study in order to attract new users, but future users of the model could further refine their models with such adjustments in order to improve predictions and better inform management choices.

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Supplementary material

To view supplementary material for this article, please visit <http://dx.doi.org/10.1017/S0376892916000357>

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