WP-20-03

NCASI White Paper

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REVIEW OF LAND USE AND BIODIVERSITY APPROACHES IN LIFE CYCLE ASSESSMENTS FOR FOREST MANAGEMENT APPLICATIONS

NCASI WHITE PAPER
MAY 6, 2020

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Cite this report as:

NCASI. 2020. *Review of land use and biodiversity approaches in life cycle assessments for forest management applications*. White Paper (WP-20-03). Cary, NC: National Council for Air and Stream Improvement, Inc.

About this report:

This is a review of novel life cycle assessment approaches developed since 2015 that evaluate the potential effects of forest management on biodiversity.

About NCASI:

NCASI (National Council for Air and Stream Improvement, Inc.) is a non-profit environmental research organization that seeks to create credible scientific information required to address the environmental information needs of the forest products industry in North America. NCASI conducts surveys, performs field measurements, undertakes scientific research, and sponsors research by universities and others to document the environmental performance of industry facility operations and forest management, and to gain insight into opportunities for further improvement in meeting sustainability goals.

REVIEW OF LAND USE AND BIODIVERSITY APPROACHES IN LIFE CYCLE ASSESSMENTS FOR FOREST MANAGEMENT APPLICATIONS

SUMMARY

This White Paper reviews novel life cycle assessment (LCA) approaches developed since 2015 that evaluate the potential effects of forest management on biodiversity. This review builds upon NCASI Special Report No. 15-04, which expands upon the theory of land use and biodiversity in LCAs and is foundational to this review of seven pertinent LCA methods.

KEYWORDS

biodiversity, life cycle assessment (LCA), sustainable forest management

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1.0 BACKGROUND

Prescribed burn in a pine forest - photo: Darren Miller

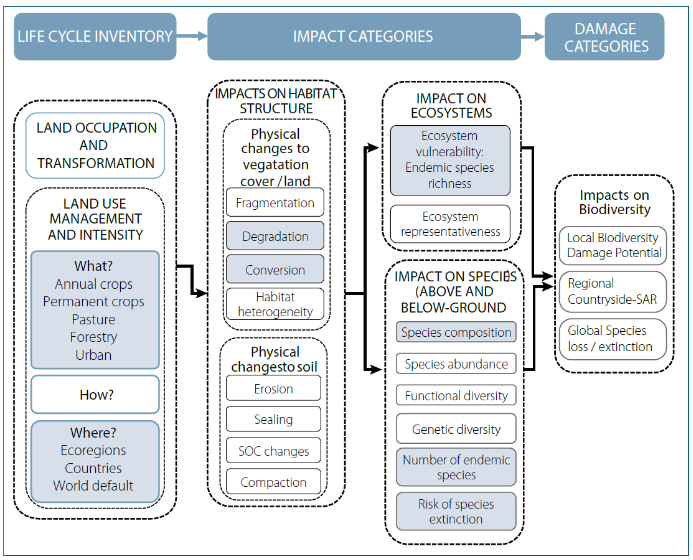
There is currently no globally accepted method for assessing biodiversity within life cycle assessment (LCA) frameworks. Modeling how biodiversity changes in relation to different forest management approaches is inherently difficult. Sustainably managed forests are dynamic systems that are affected by a host of factors that cannot be easily boiled down to a handful of cause and effect metrics. Forest biodiversity changes dynamically over time with responses to management actions often dictated by underlying abiotic factors that differ across regions (Verschuyl et al. 2008). Forest management can be optimized to achieve a wide range of biodiversity goals that can also increase habitat for target species (Demarais et al. 2017). Forest biodiversity can be enhanced through a range of options from prescribed burns to selective cutting, and can focus on management of riparian zones and wildlife connectivity. Having a discrete numerical value for the effect that forest management has on biodiversity is tempting, but current LCA methods come up short when trying to capture the important nuances of sustainable forest management. This review of recent methods shows that progress is being made at distilling complex aspects of forest management into LCA-ready values, and that there is still much work to be done before any of these models can be reliably used in LCAs.

2.0 UNEP/SETAC RECOMMENDATIONS

The joint Life Cycle Initiative between the United Nations Environment Program and the Society of Environmental Toxicology and Chemistry (UNEP/SETAC 2020) is deemed an authority on LCA methodologies (Verones et al. 2017). The organization initiated a global process in 2013 to reach consensus on recommended environmental indicators and characterization factors (CFs) for life cycle impact assessments (LCIA). UNEP/SETAC's objective is to provide guidance on quantitative and life cycle-based indicators that best quantify and monitor environmental impacts. The first volume of LCIA indicators included a section on land use impacts on biodiversity (UNEP 2016). Their conclusion, based in large part on the complexity of this task, was that, *"CFs representing global potential species loss from land use are proposed as an interim recommendation, suitable to assess impacts on biodiversity due to land use and land use change in hotspot analyses in LCA only (not for comparative assertions nor eco-labeling).*

Further testing of the CFs as well as the development of CFs for further land use types are required to provide a full recommendation." Because the second UNEP/SETAC LCIA indicators volume focused on indicators that did not expand upon biodiversity impacts (UNEP 2019), the interim recommendations in the first volume are the most relevant and up to date guidance.

While there is no consensus on what indicators should be used in an LCA to represent the effects that land use (and sustainable forestry regimes as a subset) has on biodiversity, UNEP/SETAC recommends a general approach for researchers to follow.



The UNEP/SETAC interim recommended impact pathway model is shown herein, with aspects covered by the interim recommended method (Chaudhary et al. 2015) in blue and those not covered in white. This model is also operational for application in LCA through the European Union's LC-IMPACT method (Verones et al. 2019). Note the multiple, critical, white boxes where impact categories are relevant to forestry and are not covered by the interim method, particularly those related to biodiversity and species composition categories.

UNEP/SETAC makes several recommendations that are needed to strengthen this interim model. The most pertinent to sustainable forestry is the recommendation to include different management regimes, "*(Include) management practices with scientific evidence proving their efficacy in protecting biodiversity to differentiate them from untested, unspecific, or average management practices*." NCASI agrees with this assessment and emphasizes that many different forest management regimes should be studied in different ecoregions, under unique local environmental and social characteristics, and over enough years to adequately model effects on biodiversity. Until this research is further along, UNEP/SETAC will probably recommend following the interim model, but only for specialized hotspot LCA modeling. NCASI tested the UNEP/SETAC recommendations in a forest product LCA case study and showed that their application was at risk of producing counterproductive forest management decisions.

If the UNEP/SETAC interim recommended model is used, the following points should be considered:

- Only 6 of the 16 total impact categories are addressed in this model for forests, while none of the damage categories are adequately modeled according to UNEP/SETAC.

- The limited number of forest management practices available in this model limit its utility for widespread use.
- The model has been tested on a limited number of forest ecoregions, which narrows the geographic scope of where the model can be reliably used.

3.0 HEMEROBY LEVEL

This method develops LCA indicators from estimates of remaining fractions of species in a forest and levels of deviation from 'naturalness' of an ecosystem calculated for different forest management practices.

The method described in Capturing the Potential Biodiversity Effects of Forestry Practices in Life Cycle Assessments (Rossi et al. 2018) is based on the notion of hemeroby, which is used to express the deviation from 'naturalness' of an ecosystem. The method attempts to augment the UNEP/SETAC recommended model by adding localized information for habitat heterogeneity to the "impacts on habitat structure" category, as well as for local biodiversity damage potential for impacts on biodiversity. This hemeroby model is a simplified linear approach that relies on four biodiversity states, or indicators, and does not require collecting field data. These indicators are native tree species composition, deadwood volume and quality, protected vulnerable habitats, and forest structure. This study applies the four indicators to 16 forest management practices commonly used in boreal forests. Hemeroby estimates are used to derive partial biodiversity scores, which are then combined into a single value intended for LCA use. This method does not incorporate specific types of habitat change, relationships between managed forests and adjacent lands, effects of fragmentation, connectivity, climate, pests, or threatened species in deriving an LCA-ready value. The underlying theory that biodiversity can be modeled in terms of distance to naturalness, in other words on how 'un-natural' a forest is, associates forest management with a negative action to be avoided. In reality, sustainably managed forests provide ecological and societal benefits while providing habitat and functional biodiversity (Janowiak and Webster 2010; Swanson et al. 2014). In addition, the starting point of an undisturbed 'natural' forest, in terms of biodiversity composition and baseline timeframe, is a debatable comparator because predicting how an ecosystem would have evolved in the absence of human intervention is almost impossible given the many factors that can influence it over time, for instance climatic conditions, fires, hurricanes, and other naturally occurring factors and events beyond a forest manager's control (Gaudreault et al. 2016).

Underlying the hemeroby concept is the notion that it captures "the biodiversity of the exploited forest." This value decision, that managed forests are "exploited," is expressed multiple times by the authors and should be considered when evaluating the results of this or similar methods. A conclusion made by the authors that, "*This method can be implemented based on declared practices; hence, it can be applied in LCA by a practitioner in possession of information on forestry practices, without the need for measuring field biodiversity data*" is supported neither by the results of this method nor by field data.

Certain aspects of the study's methods limit its utility:

- The model uses a linear approach based on only four biodiversity indicators, which is overly simplistic in both its method and in the input data it uses.
- The model does not require collecting field data, which calls into question how to calibrate the model though ground truthing and validating its results.
- Value decisions made by the authors that equate managed forests with exploitation should be considered and weighed.

This concept of hemeroby is expanded upon in the 'naturalness' method discussed herein, which adds additional facets to this conceptual model.

4.0 'NATURALNESS' METHOD

> This method estimates levels of 'naturalness' for different forest management practices over time to compare historic, current, and future states of naturalness for a forest.

A proposed approach, A Conceptual Model for Forest Naturalness Assessment and Application in Quebec's Boreal Forest (Côté et al. 2019), attempts to establish a numerical value for 'naturalness' to be used in LCAs. The method attempts to augment the UNEP/SETAC recommended model by adding a measure of ecosystem representativeness to the "impact on ecosystems" category. The model is designed to be primarily applicable in Canadian forest systems and was tested and tuned on a reference area of three forest management units (FMUs) in Quebec's boreal forest, which limits the current model's geographic applicability. The authors note that the generalized model could be modified for use in other forest types outside of Canada and in LCAs using additional data and modifications to account for specific regional characteristics.

3 FMU test area in Quebec

This method uses five characteristics to establish a measure of naturalness: landscape context, forest composition, structure, dead wood, and regeneration processes. The baseline comparator for naturalness is always historic data, either gathered or modeled, for a forested area prior to forest operations commencing. These five measures have both condition (current state) and pressure (action) indicators that are assigned ranges within the model to generate a naturalness time series index to estimate effects over 70 years. The model has eight forest management scenarios ranging from 100% careful logging to 100% planting of exotic species. All scenarios start with a reduction from a natural condition and estimate a continual degradation in the naturalness index for all types of forest management. Careful logging results in the smallest decrease in naturalness (most desirable), while planting exotic species results in the largest decrease (least desirable). This method implies that no managed forest can increase environmental attributes to achieve an original level of naturalness on the land. Because the original naturalness of a forest is the maximum and optimum state in this method, it is impossible for a managed forest assessed using it to ever achieve a level that would be better than an original natural level. These results are echoed by the authors stating, *"Our model indicates a trend toward a slow erosion of the ecosystem quality over time during the sustainable production phase."* However, sustainably managed forests have been shown to support high levels of biodiversity that can exceed levels in adjacent, unmanaged forests (Miller et al. 2009).

Conceptual models such as this often rely on sparse data from a limited geographic area. Decisions that compensate for lack of data in this model introduce potential errors. For example, the ranges of classes of naturalness, the amount of habitat loss that adversely affects other species, and the amount of exotic species planted that creates high degradation to the forest matrix are all rough estimates that have large effects on the model's results. Data are not available to validate the model beyond a 40-year range. However, results are projected out to 70 years with a conclusion that if forestry completely stops on the land and a relaxation period where external pressures cease, *"Theoretically the ecosystem should never recover completely."* Some of the data and applicability to the method are unclear, such as stating that the case study area of 1.3 million hectares is larger than the home range of the boreal caribou, which it is not (Environment Canada 2012, p.72), or that the caribou is an umbrella species for the boreal forest, which is currently a debated topic in the scientific literature (Murray et al. 2015).

This approach has significant methodology and data limitations for its intended purpose of evaluating ecosystem quality in relation to forest management. Value decisions made by the authors cast all managed forests as sub-optimal. For example, naturalness is modeled on data "*prior to commercial forest exploitation*" and the "*lower class, most altered state, corresponds to artificial forests created by humans*."

The following aspects of the study's methods make it unusable:

- Establishing a baseline comparator that is prior to forest operations commencing disregards societal needs for forest products and disregards changes and trends in surrounding lands.
- The model is designed such that land can never achieve the highest level of 'naturalness' once it is used for forestry, even with active biodiversity management or cessation of forest operations.
- Model results extend decades beyond data availability, which assures that the extent of the model's projections cannot be validated.

The authors' conclusion that this method could be integrated into LCA models and used to inform building and construction designers is unsupported by the results of the model.

5.0 POTENTIALLY DISAPPEARED SPECIES

This method estimates biodiversity loss in forests and agricultural lands based on different bioenergy policy decisions in the EU.

Another research method, Spatially Explicit LCA Analysis of Biodiversity Losses Due to Different Bioenergy Policies in the European Union (Di Fulvio et al. 2019), models relationships between biodiversity loss and changes in land uses, changes in land use intensity and forestry, and indirect effects on species resulting from bioenergy policies in the European Union (EU) and in countries exporting bioenergy products to the EU. The method augments the UNEP/SETAC recommended model by adding a prospective measure of potential global species loss to the "impacts on biodiversity" category.

The primary measure of biodiversity impact in this method is Potentially Disappeared Fraction of Global Species (PDF), which denotes an estimate of the fraction of global species that this model projects to go extinct. The study incorporates three different policy scenarios for bioenergy consumption in the EU:

Baseline	Constant Demand	EU Emissions Reduction Scenario
Models policies to reduce EU greenhouse gas (GHG) emissions 20% by 2020, and demand is allowed to change afterward	Models EU GHG reductions similar to the Baseline scenario, then demand is held constant after 2020	Models GHG reductions of 80% by 2050

This method is based on various well-established tools and methodologies, including GLOBIOM (a global economic model that analyzes agriculture, forestry, and bioenergy land use change) and procedures outlined by UNEP/SETAC. The results of this study shed light on potential biodiversity loss of future, potential land use scenarios that may occur under different policy decisions.

Each model projects changes in land use and PDF for the EU and for countries exporting biomass to the EU, such as the US and Canada for wood pellet exports. In all scenarios land is actively converted to producing biomass in the EU at varying percentages. Overall, this model shows that producing bioenergy products from wood has less impact on PDF than does growing perennials for bioenergy. It also shows that higher GHG reduction targets in the EU translate into higher wood pellet imports from Canada, the US, and the former USSR.

This study acknowledges that additional research is necessary in order to use PDF methodology robustly in LCAs. Whether ultimately usable in an LCA or not, some results are worth noting:

- Species will be negatively affected (higher PDF) under policies that target GHG reductions in the EU.
- Most of the biodiversity damage occurs on food producing croplands within and outside the EU, and less than 1% is caused by importing pulp logs and pellets.

- Converting land to grow perennial energy crops, such as miscanthus, has the largest overall effect in the EU.

The study concludes that, "*biodiversity damage created by wood pellet imports has only marginal relevance compared to the import of agricultural products*" and "*biodiversity damage per unit of wood pellet is 4 to 24 (times) smaller than the damage in the EU resulting from perennial cultivation*." These conclusions reinforce EU policies focused on reducing GHG emissions by burning biofuels for energy production. Thus, the results suggest that importing pellets instead of cultivating perennial crops can help reduce impacts on biodiversity globally compared with growing the needed biomass within the EU.

This method puts biodiversity loss in the context of different land use change futures to compare potential effects on biodiversity. This is a useful approach for modeling different policies and may have benefits over other approaches that are retrospective in nature and rely purely on counterfactual baselines.

While there is useful information for policy and decisionmakers contained within this study, certain aspects of the study's methods limit its widespread utility.

- They are reliant on external models and methods that have their own limitations and data gaps.
- Large-scale results are not applicable at smaller FMU scales for forest managers or forest landowners.
- The year 2000 is set as the baseline year, which is debatable, and changing it will alter results.

6.0 BIOIMPACT METRIC

Another approach, Accounting for Biodiversity Impact in Life Cycle Assessments of Forestry and Agricultural Systems – The BioImpact Metric (Turner et al. 2019), focuses on literature meta-analysis and expert opinion to develop a single value for the effect of land use change on biodiversity. The method augments the UNEP/SETAC interim recommended model by adding information about fragmentation for the "impacts on habitat structure" category and the functional diversity and genetic diversity subcategories for the "impact on species" category. The analysis incorporates extensive and intensive forestry as two land use change types and looks at 12 species groups. The methodology relies on 26 semi-quantitative questions that are answered through literature reviews, expert opinion, or a combination of both. Based on scores derived from these questions, a weighted final BioImpact score is calculated and integrated into an LCA.

> This method estimates the effect land use decisions have on biodiversity through literature meta-analysis and expert opinion.

This methodology and its associated research attempt to generate a generic value for biodiversity impact that can be linked to a functional unit (forestry product) that is free from interactions between impact pathways. This task is exceedingly difficult and may never be possible in current LCA frameworks. The proposed methodology has multiple hurdles to surmount before it can be reliably applied to forest land use LCAs. The authors have identified some areas requiring further research and improvement:

- Literature review is the preferred data source for generating a BioImpact score, but not all literature will provide the same score for a given question. This negatively effects the reproducibility and robustness of the score.
- Scores cannot be calculated for multiple species groups from literature analysis alone.
- A small cross section of experts was involved in key aspects of this methodology.

Certain aspects of this method limit its utility and impartiality:

- As noted by the authors, there is no means of calibrating derived scores and the scores cannot be verified by field studies to measure biodiversity response.
- Reliance on expert evaluation can incorporate human biases into the results.
- The weighting process undertaken by the researchers was inconclusive, and weights were added by the researchers in an attempt to ensure that all ecological concepts were adequately represented. This process would need to be properly vetted, documented, and tested for reproducibility.
- Industry and non-government organizations (NGOs) should be involved in the survey and weighting procedures.

This method is unlikely to become a common approach for incorporating biodiversity changes from forest management into LCAs because it requires a comprehensive set of literature across various geographies for many species, and a large set of experts to review and score the literature in a consistent and reproducible manner. However, the overall approach may be built upon and improved by others, which may warrant industry attention at these early stages to ensure adequate input from foresters and NGOs alike if this methodology gains traction with researchers.

7.0 SPECIES RICHNESS

> This meta-analysis expands on recommended UNEP/SETAC methods to estimate effects from forestry practices at smaller spatial scales.

The global analysis, Impact of Forest Management on Species Richness: Global Meta-Analysis and Economic Trade-Offs (Chaudhary et al. 2016), is an extension of the UNEP/SETAC recommendations. As such, this is not a new LCA methodology for forest land use change and its effect on biodiversity. This study is, however, pertinent because it expands upon the original approach by Chaudhary et al. (2015) that included only intensive and extensive CFs by adding more management intensities related to forest management approaches. It also uses a modified measure of species richness loss that is intended to be focused more locally, as opposed to the original study based on ecoregions. This study uses hypothetical FMUs based on results of reviewing 287 studies containing 1008 comparisons of species richness in managed and unmanaged forests. The analysis shows that, in general, lower intensity logging results in higher species richness for ten forest management types. The authors also performed a biodiversity-economic trade-off analysis for ten hypothetical FMUs in ten countries.

It is unfortunate that the hypothetical comparisons in this study were all performed on natural forests and no plantations were used in the model. Plantations, being highly productive forested areas, not only support a wide range of biodiversity within their borders, but enable intact and relatively unfragmented landscapes to exist and retain high levels of biodiversity within their borders. Current spatial research exploring the point at which land use change affects biodiversity points to abrupt biodiversity declines occurring rapidly and at high rates when such intact landscapes are modified (Betts et al. 2017). NCASI can only assume that the inclusion of plantations in this analysis would expand on the relationships the authors identified between biodiversity impacts and net present value (NPV) per hectare of forests in different regions that result from different harvesting approaches. It is of some interest that this research showed that Canada had a high NPV to species lost ratio, indicating that single-tree and group-tree selection management provides high value per hectare while producing negligible species loss. However, this analysis again shows the pitfalls of using a small number of factors to represent a large and diverse area. No matter how well weighted an average value is, it can never fully describe large geographic regions. With these caveats in mind, it is interesting that the study generally found that worldwide, forest management regimes focusing on timber production were less harmful to biodiversity than those not primarily optimizing for timber, such as slash-and-burn land clearing for agricultural purposes. It also identified highest species loss in Malaysia and Indonesia for nearly all types of forest management.

The applicability of this analysis is limited, as identified by the authors in stating, "*our case studies cannot be used to generalize outcomes for the selected timber producing management regimes and countries*," largely because "*data for timber prices, yield, rotation cycle, and production costs are highly site-specific*," as are effects on local biodiversity within FMUs and surrounding areas not engaged in forest management. However, Chaudhary et al.'s work in the area of quantifying biodiversity change from land use is routinely referenced and built upon by other researchers. Therefore, the areas the authors identify for additional research may be viewed as important and warranted in the research community:

- Indicators that compare compositional changes in the affected species community;
- Analyses on appropriate payments for biodiversity schemes;
- Forest management effects on surrounding habitat types;
- Analysis of relative importance of species affected rather than a total fraction of all species affected;
- Effects of forest management regimes on mammals, amphibians, fungi, and lichens.

In addition to the areas identified for improvement by the researchers, if this method is used certain points should be considered:

- While additional forest management practices are modeled compared to the UNEP/SETAC interim method that this model extends, more management practices should be analyzed in a variety of real-world applications.
- Basing the model on hypothetical FMUs may be an early step in model development, but sufficient validation through ground truthing will be needed before the model can be reliably used in real-world situations.

This research is well regarded in the scientific community. While this specific research thread has limited applicability to forest management, it is reasonable to expect more cutting-edge research from this team in the future.

8.0 FRAGMENTED-AREA RELATIONSHIP

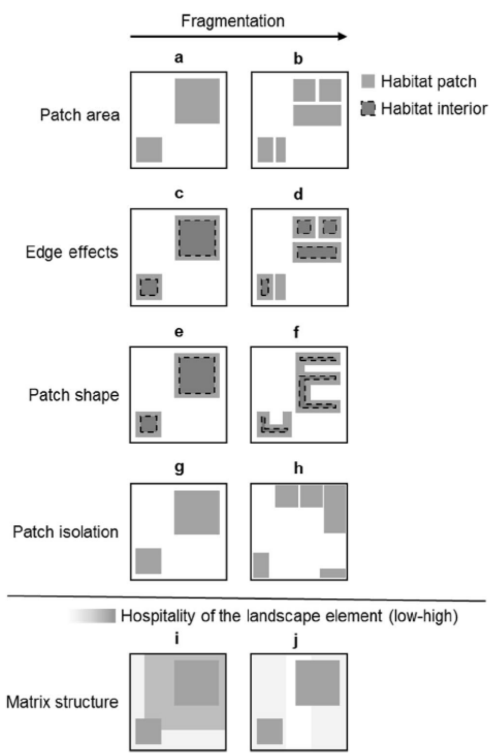


Fig. 1 Patch area, edge effects, patch shape, patch isolation and matrix structure. The total amount of habitat is identical in every figure; the total amount of habitat edge and interior varies; the hospitality of the landscape elements displays the contrast between the elements and the permeability of the landscape

Patch-based fragmentation, Kuipers et al. 2019

This analysis expands on SAR models to include aspects of habitat fragmentation into biodiversity changes from land use changes.

A recent augmentation to species at risk (SAR) models, such as the meta-analysis by Chaudhary et al. (2016), is to attempt to characterize potential impacts on biodiversity from land fragmentation in LCAs. Pioneering work in developing a species fragmented-area relationship (SFAR) by Larrey-Lassalle et al. (2018) has led to a method for calculating CFs for use in LCIAs. This method augments the UNEP/SETAC recommended model by attempting to incorporate fragmentation into the "impacts on habitat structure" category. This is an important first step in bringing necessary spatial-scale nuance to land use and biodiversity effects in LCAs. While this method is only applicable for biodiversity hotspots and only for bird species, it may be expanded upon by additional research in the future. Work by Kuipers et al. (2019) evaluated the feasibility of including habitat fragmentation effects on biodiversity in LCAs and the implications of not doing so. The researchers identified limitations in much of the current landscape-level research on biodiversity that creates a binary category of hospitable forests vs inhospitable. Their more nuanced approach recognizes that, "*landscape consists of a gradient from hospitable to inhospitable areas that are conceived differently per species, obscuring a clear* *distinction between habitat and matrix elements*." As shown in the figure herein from their paper, modeling and categorizing fragmentation is complicated. Adding in the potential effects of different types of fragmentation on biodiversity, by species, is a daunting task. This complexity is identified by the authors when they state that, "*Fragmented landscapes involve several fragmentation effects simultaneously. Furthermore, responses to the various fragmentation effects differ per species. It is therefore difficult to determine the relative importance of each fragmentation effect for biodiversity in general terms*."

The authors identify issues supporting the need for cautious use of this method in LCAs, and question whether their general use is warranted by the current availability of information, "*Scant species and region-specific data availability complicates the generation of parameters specifying the species' response to various fragmentation effects*". However, the field of landscape ecology has started to move away from measuring fragmentation based on habitat patches and patch metrics, including those used in this model, and has started to view landscapes in terms of continuous variables (Costanza et al. 2019). Advances in related fields expose the vulnerability of these types of multifaceted modeling approaches where an entire branch of research may shift in a new direction and render the methodology obsolete. In addition to the caveats expressed by the researchers regarding use of this method's outcomes in LCAs, these points should also be considered:

- Habitat fragmentation is an important aspect of biodiversity but using continuous landscape variables instead of patch-based landscape approximations such as those used in this model may be more representative of real-world forest conditions.
- Adding in complexity, such as habitat fragmentation, to models whose underlying methods are not fully mature, rigorously tested, and broadly accepted by the scientific community increases the possibility of cascading errors in the modeling framework and the model's results.

9.0 DISCUSSION

Stakeholders are interested in the interconnections between forest management, land use, and effects on biodiversity. Researchers continue to find novel ways to assimilate these effects and distill results into a form applicable to LCAs. However, the framework of LCAs, which work exceptionally well for tracking the environmental impacts of disaggregated material flows for specific products and materials, is unlikely to work well for modeling biodiversity change. The multi-directional effects that forestry practices have on biodiversity over space, time, and successional stages make characterization in LCAs even more difficult. Once the sheer complexity of biodiversity and unique aspects of each FMU are included, the task of developing these types of CFs is a monumental one that is constrained not only by current LCA framework limitations, but also by the state of knowledge of biodiversity, including the many ways to define biodiversity itself (Casetta et al. 2019, 167-193). Efforts to advance research in this field will benefit from addressing the major limitations in current approaches, including:

1. Setting the baseline for analysis as ideal conditions prior to any forest land use change.
    - Not only is it debatable to identify what ideal conditions used to be or should be, but this baseline also provides little incentive for improving the current state of biodiversity on any given piece of land. This type of baseline all but mandates that biodiversity change is unidirectional and negative. In reality, biodiversity change occurs irrespective of human interference, and sustainable forest management can increase biodiversity or improve conditions for species at risk.
2. Penalizing land use decisions that prepare forests for future needs.
    - Evidence is mounting that forests will need to adapt to future climates that lack modern analogs (Williams and Jackson 2007). Designing healthy and productive forest ecosystems for the future, rather than merely mimicking forests of the past, is critical to society and the environment. Using the best technology and tools available to allow adaptation to projected future situations should be recognized as positive steps.
3. Generalizing biodiversity responses to forest management across large geographic and spatial areas.
    - Biodiversity responses to disturbance are highly specific to characteristics of resident species, forest type, abiotic conditions, and intensity of disturbance. Assessments of biodiversity change over time should incorporate such complex interconnections with the environment. Any generalization will necessarily lose nuance that may be critically important to the intended outcomes and uses of the LCA.
4. Disregarding the effects managed forests have on biodiversity in a global context.
    - Sustainably managed forests provide society with renewable fiber, fuel, and building materials. These highly productive forests reduce demand for these products to be generated by largely intact and unaltered forest landscapes. Only one study reviewed here attempts to put managed forests into a global context and account for their beneficial effects well beyond their own FMU boundary (Di Fulvio et al. 2019). Future studies should attempt to put managed forests into a broader biodiversity context to more fully capture the broader, noncontiguous effects that managed forests have on biodiversity.
5. Deriving LCA-ready values representing assemblages of total biodiversity in an area.
    - Biodiversity itself may be a poor measure of what is meaningful and important to try to optimize in a sustainably managed forest. For example, in some cases it is not the overall biodiversity that is important, but a single species or group of species that might be the target for protection, such as an imperiled species or a keystone species that has an outsized effect on the entire ecosystem.
6. Using results of an LCA to prescribe alternative forest management regimes.
    - While LCA results may be instructive in some cases, sustainable forest management and the benefits it provides to society and the environment do not necessarily need, and may not benefit from, LCA results.

10.0 CONCLUSION

Condensing biodiversity potential in different forest types, how biodiversity changes based on forest management practices over time, and which alternative land uses may provide greater biodiversity into a set of factors is tempting. Given the limitations of the methods reviewed and the high complexity of forest ecosystems, more research and ground truthing of results in multiple, disparate situations will be necessary. These shortcomings of current methods and models are known to researchers in this field and some are actively being addressed. Models will never be able to perfectly emulate real-world processes, but that is not a reason to dismiss all forest land-use/biodiversity/LCA outcomes. Rather, LCA results must be provided with the necessary background, caveats, estimate ranges, and acknowledged sources of error so policy designers and decision makers can thoughtfully weigh their options.

LITERATURE CITED

Betts, M.G., Wolf, C., Ripple, W.J., Phalan, B., Millers, K.A., Duarte, A., Butchart, S.H.M., and Levi, T. 2017. Global Forest loss disproportionately erodes biodiversity in intact landscapes. *Nature* 547(7664):441-444. https://doi.org/10.1038/nature23285.

Casetta, E., Marques da Silva, J., and Vecchi, D. (eds.). 2019. *From Assessing to Conserving Biodiversity*. Cham Switzerland: Springer. https://doi.org/https://doi.org/10.1007/978-3-030-10991-2.

Chaudhary, A., Burivalova, Z., Koh, L.P., and Hellweg, S. 2016. Impact of forest management on species richness: global meta-analysis and economic trade-offs. *Scientific Reports* 6:1-10. https://doi.org/10.1038/srep23954.

Chaudhary, A., Verones, F., De Baan, L., and Hellweg, S. 2015. Quantifying Land use impacts on biodiversity: combining species-area models and vulnerability indicators. *Environmental Science and Technology* 49(16):9987-9995. https://doi.org/10.1021/acs.est.5b02507.

Costanza, J.K., Riitters, K., Vogt, P., and Wickham, J. 2019. Describing and analyzing landscape patterns: where are we now, and where are we going? *Landscape Ecology* 34(9):2049-2055. https://doi.org/10.1007/s10980-019-00889-6.

Côté, S., Bélanger, L., Beauregard, R., Thiffault, É., and Margni, M. 2019. A Conceptual model for forest naturalness assessment and application in Quebec's boreal forest. *Forests* 10(4):325. https://doi.org/10.3390/f10040325.

Demarais, S., Verschuyl, J.P., Roloff, G.J., Miller, D.A., and Wigley, T.B. 2017. Tamm review: terrestrial vertebrate biodiversity and intensive forest management in the U.S. *Forest Ecology and Management* 385:308-330. https://doi.org/10.1016/j.foreco.2016.10.006.

Di Fulvio, F., Forsell, N., Korosuo, A., Obersteiner, M., and Hellweg, S. 2019. Spatially explicit LCA analysis of biodiversity losses due to different bioenergy policies in the European Union. *Science of the Total Environment* 651:1505-1516. https://doi.org/10.1016/j.scitotenv.2018.08.419.

Environment Canada. 2012. *Recovery Strategy for the Woodland Caribou (*Rangifer tarandus caribou*), Boreal Population, in Canada. Species at Risk Act Recovery Strategy Series*. Gatineau QC: Environment Canada. https://doi.org/10.2307/3796292.

Gaudreault, C., Wigley, T.B., Margni, M., Verschuyl, J., Vice, K., and Titus, B. 2016. Addressing biodiversity impacts of land use in life cycle assessment of forest biomass harvesting. *Wiley Interdisciplinary Reviews: Energy and Environment* 5(6):670-683. https://doi.org/10.1002/wene.211.

Janowiak, M.K., and Webster, C.R. 2010. Promoting Ecological sustainability in woody biomass harvesting. *Journal of Forestry* 108(1):16-23.

Kuipers, K.J.J., May, R.F., Graae, B.J., and Verones, F. 2019. Reviewing the potential for including habitat fragmentation to improve life cycle impact assessments for land use impacts on biodiversity. *International Journal of Life Cycle Assessment* 24(12):2206-2219. https://doi.org/10.1007/s11367-019-01647-1.

Larrey-Lassalle, P., Loiseau, E., Roux, P., Lopez-Ferber, M., and Rosenbaum, R.K. 2018. Developing characterisation factors for land fragmentation impacts on biodiversity in LCA: key learnings from a sugarcane case study. *International Journal of Life Cycle Assessment* 23(11):2126-2136. https://doi.org/10.1007/s11367-018-1449-5.

Miller, D.A., Wigley, T.B., and Miller, K.V. 2009. Managed forests and conservation of terrestrial biodiversity in the southern United States. *Journal of Forestry* 107(4):197-203. https://doi.org/10.1093/jof/107.4.197.

Murray, D.L., Majchrzak, Y.N., Peers, M.J.L., Wehtje, M., Ferreira, C., Pickles, R.S.A., Row, J.R., and Thornton, D.H. 2015. Potential Pitfalls of private initiatives in conservation planning: a case study from Canada's boreal forest. *Biological Conservation* 192:174-180. https://doi.org/10.1016/j.biocon.2015.09.017.

Rossi, V., Lehesvirta, T., Schenker, U., Lundquist, L., Koski, O., Gueye, S., Taylor, R., and Humbert, S. 2018. Capturing the potential biodiversity effects of forestry practices in life cycle assessment. *International Journal of Life Cycle Assessment* 23(6):1192-1200. https://doi.org/10.1007/s11367-017-1352-5.

Swanson, M.E., Studevant, N.M., Campbell, J.L., and Donato, D.C. 2014. Biological associates of early-seral pre-forest in the Pacific Northwest. *Forest Ecology and Management* 324:160-171. https://doi.org/10.1016/j.foreco.2014.03.046.

Turner, P.A.M., F Ximenes, F.A., Penman, T.D., Law, B.S., Waters, C.M., Grant, T., Mo, M., and Brock, PM. 2019. Accounting for Biodiversity in life cycle impact assessments of forestry and agricultural systems–the BioImpact Metric. *International Journal of Life Cycle Assessment* 24(June):23. https://doi.org/10.1007/s11367-019-01627-5.

UNEP. 2016. *Global Guidance for Life Cycle Impact Assessment Indicators, Vol. 1*. Frischknecht, R., and Jolliet, O (eds.). Nairobi Kenya: United Nations Environment Program. https://www.lifecycleinitiative.org/training-resources/global-guidance-lcia-indicators-v-1.

———. 2019. *Global Guidance on Environmental Life Cycle Impact Assessment Indicators, Vol. 2*. Frischknecht, R., and Jolliet, O (eds.). Nairobi Kenya: United Nations Environment Program. https://www.lifecycleinitiative.org/training-resources/global-guidance-lcia-indicators-v-2.

UNEP/SETAC. 2020. Life Cycle Initiative. Paris France: Life Cycle Initiative. https://www.lifecycleinitiative.org.

Verones, F., Bare, J., Bulle, C., Frischknecht, R., Hauschild, M., Hellweg, S., Henderson, A., Olivier, J., Laurente, A., Liao, X., Lindner, J.P., de Souza, D.M., Michelsen, O., Patouillard, L., Pfister, S., Posthumano, L., Prado, V., Ridoutt, B., Rosenbaum, R.K., Salat, S., Ugaya, C., Vieira, M., and Fantke, P. 2017. LCIA Framework and cross-cutting issues guidance within the UNEP-SETAC Life Cycle Initiative. *Journal of Cleaner Production* 161:957-967. https://doi.org/10.1016/j.jclepro.2017.05.206.

Verones, F., Huijbregts, M.A.J., Azevedo, L.B., Chaudhary, A., De Baan, L., Fantke, P., Hauschild, M., et al. 2019. LC-IMPACT: a spatially differentiated life cycle impact assessment approach. https://lc-impact.eu.

Verschuyl, J.P., Hansen, A.H., McWethy, D.B., Sallabanks, R., and Hutto, R.L. 2008. Is the effect of forest structure on bird diversity modified by forest productivity? *Ecological Applications* 18(5):1155-1170. https://doi.org/10.1890/07-0839.1.

Williams, J.W., and Jackson, S.T. 2007. Novel climates, no-analog communities, and ecological surprises. *Frontiers in Ecology and the Environment* 5(9):475-482. https://doi.org/10.1890/070037.