frontiers | Frontiers in Forests and Global Change

TYPE Perspective
PUBLISHED 13 September 2024
DOI 10.3389/ffgc.2024.1459045

OPEN ACCESS

EDITED BY
Renzo Motta,
University of Torino, Italy

REVIEWED BY
Valeriu-Norocel Nicolescu,
Transilvania University of Braşov, Romania
Ana Cristina Gonçalves,
University of Evora, Portugal

*CORRESPONDENCE
Philippe Nolet
philippe.nolet@uqo.ca

RECEIVED 03 July 2024
ACCEPTED 28 August 2024
PUBLISHED 13 September 2024

CITATION
Nolet P, Béland M and Messier C (2024) Adapting the patch-cut system to implement forest assisted migration. *Front. For. Glob. Change* 7:1459045.
doi: 10.3389/ffgc.2024.1459045

Adapting the patch-cut system to implement forest assisted migration

Philippe Nolet[1]*, Martin Béland[2] and Christian Messier[1,3]

[1]Institut de Recherche sur la Forêt Tempérée, Département des Sciences Naturelles, Université du Québec en Outaouais, Ripon, QC, Canada, [2]École de Foresterie, Université de Moncton, Campus d'Edmundston, Edmundston, NB, Canada, [3]Département des Sciences Biologiques, Université du Québec à Montréal, Montréal, QC, Canada

As the Anthropocene tightens its grip on the world, forests are facing escalating disturbance rates, tree mortality, degradation and risks of catastrophic collapses. A popular and controversial proposition is to enhance forests' response diversity by adding novel tree species with missing functional traits through forest assisted migration (FAM). Beyond tests of the survival and growth of southern species or provenances in colder regions and studies of the socio-ecological challenges facing FAM, little interest has been paid to the silvicultural system for FAM implementation. Yet, the topic could influence its biological success, social acceptability, and economic feasibility. For example, southern light-intolerant tree species introduced into northern uneven-aged forests may experience a lack of light availability. Likewise, implementing FAM in clearcuts raises social acceptability issues. The patch-cut system combines advantages of even- and uneven-aged systems useful for FAM; however, perhaps due to the difficulty of its operationalization, it is rarely used. We propose a new way to implement the patch-cut system, enabling from the get-go to plan the location and timing of treatment of each patch in a stand. We discuss the advantages that this revisited patch-cut system presents for FAM: (i) the testing of various planting environments, (ii) easy monitoring in an adaptative management context where each patch is a replicate of a repeated-measure experiment and (iii) low intensity planting for efficient future dispersion of species adapted to a changing climate. We end with a call for the development of an international network of FAM trials within the revised patch-cut system.

KEYWORDS

assisted colonization, assisted migration, global change, adaptation, silviculture, gap, forest management, regeneration method

1 Introduction

As the Anthropocene tightens its grip on the world, our natural ecosystems are facing escalating disturbance rates (Ellis, 2011; Worm and Paine, 2016; Nyström et al., 2019; Folke et al., 2021; Anderegg et al., 2022). Forest health and functioning are particularly affected by the rapidly mounting direct and indirect impacts of climate change along with invasive pests, diseases, and exotic species. Numerous scientific papers indicate rising levels of tree mortality, forest degradation and forest disturbances around the world (Trumbore et al., 2015; Seidl et al., 2017; Hartmann et al., 2022; Patacca et al., 2023). Others report increasing risks of catastrophic collapses of forest ecosystems and functions (Lindenmayer et al., 2016; Silva Junior et al., 2020; Canadell and Jackson, 2021; Forzieri et al., 2022; Parisien et al., 2023).

An increasingly popular and controversial proposition is to enhance the overall response diversity of natural ecosystems such as forests (Mori et al., 2013; Walker et al., 2023) by adding novel tree species with specific key missing functional traits (Mouillot et al., 2013; Messier et al., 2019) to the ecosystem to bolster the forest's resilience and adaptation to future novel climates and other biotic threats. Forest assisted migration (FAM) is such a tool and has emerged as a burgeoning field of study. FAM consists of favoring the establishment of new species in forests within or at varying distance from their current range (Williams and Dumroese, 2013).

While the concept of FAM has been scrutinized (Neff and Larson, 2014; Michalet et al., 2023; Refsland et al., 2023; Argüelles-Moyao and Galicia, 2024), Xu and Prescott (2024) found that 60% of recent papers on FAM express a positive stance toward FAM. They advocate for a holistic approach to its implementation.

Examples of FAM implementation are relatively scarce (Palik et al., 2022). For example, Messier et al. (2019) proposed using functional complex networks as an approach to favor connectivity among stands in a landscape in which FAM was suggested as a tool to increase functional diversity, but without silvicultural strategies ensuring FAM success. Similarly, (Royer-Tardif et al., 2021) suggested a new zoning strategy using FAM in stands with high vulnerability to global change. Royo et al. (2023) present the Desired REgeneration through Assisted Migration (DREAM) network where they focus more on species provenance and physiology than on silvicultural systems. While considerations for connectivity, vulnerability, and species provenance are important, we believe that it is equally important to develop/adapt silvicultural systems that favor FAM success; silvicultural systems could significantly impact the biological success, social acceptability, and economic feasibility of FAM. For instance, introducing temperate light-intolerant tree species into uneven-aged forests managed under the single-tree selection system presents limited chances of success due to lack of light availability. Although the use of even-aged treatments (e.g., clearcuts) could be used to implement FAM, it is likely to raise social acceptability issues (Arnberger et al., 2022).

We believe that there is a silvicultural system which combines the best of both even- and uneven-aged systems — the patch-cut system (Box 1). We believe its advantages of promoting the regeneration of forest tree species that are moderately to highly shade tolerant (Schnake et al., 2023) and maintaining old-growth attributes (Bauhus et al., 2009) would both be very useful when implementing FAM.

While the patch cut system concept relies on solid bases (e.g., improving structural and tree species diversity) (Runkle, 1992; Coates and Burton, 1997), its operational implementation remains underdeveloped. Much of the literature on patch cuts focuses on tree species regeneration (Béland and Chicoine, 2013; Gauthier et al., 2016) and determining the optimal size and positioning of the patches during the initial harvest to promote this regeneration (Coates and Burton, 1997; Parish and Antos, 2005; Bolibok and Szeligowski, 2011; Kern et al., 2017). However, even when patches or gaps have been implemented in a FAM context (Palik et al., 2022), there is a lack of long-term planning regarding how and where subsequent patches (in subsequent entries or harvests) should be located without disrupting the regeneration established in earlier patches.

> BOX 1 The patch-cut system in the silvicultural literature.
> While the concept of patch cutting, involving selective cutting of parts of a stand larger than a tree or small groups of trees, is not new, it is often not formally classified as a distinct regeneration method but rather considered a variant of selection cutting (Leak and Filip, 1975; Nyland et al., 2016; Ashton and Kelty, 2018), irregular shelterwood (Raymond et al., 2009) or clearcutting (Ministry of Natural Resources and Forestry, 2008). Many silvicultural textbooks do not explicitly mention the patch-cut system (Daniel et al., 1979; Schütz, 1990, 2002; Matthews, 1991; Lanier, 1994; Bailey et al., 2015; Savill, 2019). The definitions of the silvicultural systems are highly variable among jurisdictions and authors, and the way the patch-cut system fits in theses definitions reflects this variability. Despite the patch-cut system's potential benefit in integrating aspects of both even- and uneven-aged approaches, its practical application remains limited. This is revealed by its disproportionately low occurrence in the scientific literature; a search in Google Scholar using the phrases "forest and patch cut," "forest and single-tree selection," and "forest and clear-cut," yielded 261,000, 1,300,000, and 1,610,000 results, respectively. It is even possible that the patch-cut approach is over-represented in scientific studies compared to forest practices used in real-world forest management.

In this paper, we propose a new way to implement the patch-cut system, enabling forest practitioners to plan from the very beginning the location and timing of treatment of each patch and corresponding forwarding trails in a stand for the whole rotation. We hereafter refer to this new implementation as the STEP (Spatially and Temporally Explicit Patch-cut) system. After describing the basics of the STEP system, we delve into the numerous advantages as well as some disadvantages and limitations that this revisited patch-cut system presents for FAM. Afterward we discuss its flexibility and the contexts most suitable to its application. We end with a call for the development of an international network of assisted migration trials using the STEP system.

2 Basics of the STEP system

When planning the STEP system, a stand is subdivided into multiple patches. I. The subdivisions are based on a planned permanent network of forwarding trails adapted to the terrain; these trails are designed in such way that they allow a continued and direct access to each patch (Figure 1A). This is essential to enable the implementation of treatments beyond the primary harvesting operation, such as commercial thinning or a cleaning treatment to release regeneration. Direct access ensures that movement between patches does not disturb regeneration within them. Otherwise, moving through the second patch could harm the regeneration. This planned permanent network of trails is a fundamental distinction between the STEP system and the irregular shelterwood approach proposed by Saunders et al. (2014). II. Each subdivision is large enough (e.g., 0.1 ha) to ensure that most trees will have competition from trees of the same cohort during their whole lifespan, as in even-aged silviculture, thus limiting treatments on a given subdivision to a single development stage. In a FAM context, the patch size is particularly important so as not to restrict our species choice to only light-tolerant species. III.

Each subdivision is small enough (e.g., no more than 0.2 ha) to avoid leading to some negative impacts of clear-cutting. e.g., social acceptance or soil erosion (see Nolet et al., 2018). IV. No more than 1/4 of the subdivisions are harvested successively over the whole rotation, providing at least 4 cohort of patches in the stand and a constant area harvested each time. For example, a stand with 100 subdivisions (of similar sizes) and an 80-year rotation could experience a harvest in 20% of its subdivisions (no adjacent subdivisions) every 16 years (Figure 1A). The relationship between number of cohorts of patches (NCP), age at maturity or rotation age (RA) and cutting cycle (CC) is NCP = RA/CC (Nyland et al., 2016). Of course, productivity could vary among patches and the forest practitioner may choose to modify the harvest schedule during the course of the rotation.

In the stand example presented in Figure 1, the network of trails and mosaic of patches have been sketched manually using a GIS software. This process was time-consuming and would not be efficient on an operational basis. Hence, the implementation of the STEP system on a large scale would require the development of a GIS-based tool to locate the trail network and the patches. Such a tool could first use LiDAR-based elevation model to identify potential trails that avoid terrain obstacles (e.g., steep slopes) for forest operations. Second, the patches could be located and delineated through an optimization algorithm that would consider the potential trails, and the number, size and shape of gaps. Afterward during forest operations, high-accuracy GPS would allow the implementation of both trails and patches that accurately reflects their localisation planned through the GIS based-tool.

3 Advantages of the STEP system for forest assisted migration

In a FAM context, the goal is to utilize as many species as possible to adapt to future climates. In regions where forests are primarily managed through uneven-aged or irregular silviculture, such as single-tree selection cutting or continuous-cover irregular shelterwood, the light-tolerance of dominant species and social pressures often limit the introduction of light-intolerant or mid-tolerant species for FAM. The STEP system enables the use of more light-intolerant species in an environment resembling uneven-aged or irregular structure. This is achieved through larger canopy openings that allow for higher light levels compared to single-tree selection, group selection, or continuous cover irregular shelterwood. Additionally, it involves enhanced care for seedlings and saplings, which can be accessed via a permanent trail network and permanent patch locations. This approach contrasts with current suggestions for group selection or expanding-gap irregular shelterwood. In essence, the STEP system facilitates more efficient implementation of FAM in uneven-aged stands.

Another advantage of the STEP system is that it allows for a gradual introduction of new species into an ecosystem. First, the patches are not harvested and regenerated all at the same time; while FAM is implemented in a patch, there are other patches in which regeneration is naturally established. Second, even within a patch, it is possible to promote both natural regeneration and assisted migration. Hence, if one method fails, the other can step in. In other words, natural regeneration and FAM can co-habit; it is not one or the other. The gradual aspect of FAM implementation in the STEP system is also in line with the gradualness of the effects of global warming. For example, a given southern species may not yet be suitable for a northern site and regenerating a patch with this species may fail. However, the climate may eventually become suitable for that species, and regenerating a patch with this species 10 or 20 years later might have greater chances of success (Nabel et al., 2013). The gradual introduction of species through assisted migration in patches contributes to maximize the dispersion of assisted migrants where patches can act as nuclei for dispersion (Corbin and Holl, 2012). This approach could potentially achieve FAM more efficiently compared to area-wide planting in clearcuts, irregular shelterwood or selection systems.

We argue that the STEP system is inherently a suitable silvicultural approach for implementing forest assisted migration. When implementing FAM, foresters must acknowledge that they are venturing into the unknown underscoring the importance of learning from both successes and failures (Achim et al., 2022). Each patch within a stand managed using the STEP system can be viewed as a replicate of an experiment at the stand level. Implementing the STEP system in a stand aligns with principles of active adaptative management (Walters and Hilborn, 1978), since it can be designed explicitly for continuous learning. For example, if a stand is managed through the STEP system, patches could be planted using various species potentially interesting in a FAM context and compared to patches where indigenous species (natural and/or artificial) are favored (Figure 1B). Enough patches of species (or species assemblies) should be replicated to obtain valuable scientific results. As the knowledge improves with the monitoring of the results from the first cohort of patches, more sound management decisions can be made for the following cohorts of patches. Afterward, the following cohorts should be utilized with the same learning and replication principles in mind. Moreover, as there should be several stands managed through the STEP system in a landscape, the experience could be repeated in time and space in other stands or other questions could be tested in other stands (e.g., the effect of the size of the gaps). When applied within the framework of active adaptive management, the STEP system facilitates the evaluation of concerns related to FAM and influences its associated regulations. This ensures that management practices are based on rigorous scientific knowledge.

Numerous studies have shown that there are segments of society that are reluctant to implement FAM for various reasons including, risks of displacement of indigenous species, potential maladaptation of planted species and risks of pest introduction (Neff and Larson, 2014). Of course, the use of the STEP system cannot completely alleviate these concerns. However, if the STEP system is used in the context of an active adaptive management framework (as it should be), these risks will be monitored, and modifications can be made, if needed. Also, to some extent the STEP system can be considered as an uneven-aged system. As such, the residual trees surrounding a patch can (i) provide propagules for regeneration into the patches and (ii) act as a barrier to potential invading species. Finally, uneven-aged silviculture is generally much more accepted socially than even-aged management. Even though the patches represent small clear-cuts, they are unlikely to raise major esthetics concerns with the public as their visual effects are limited, as illustrated through this landscape visual simulation (Figure 2).

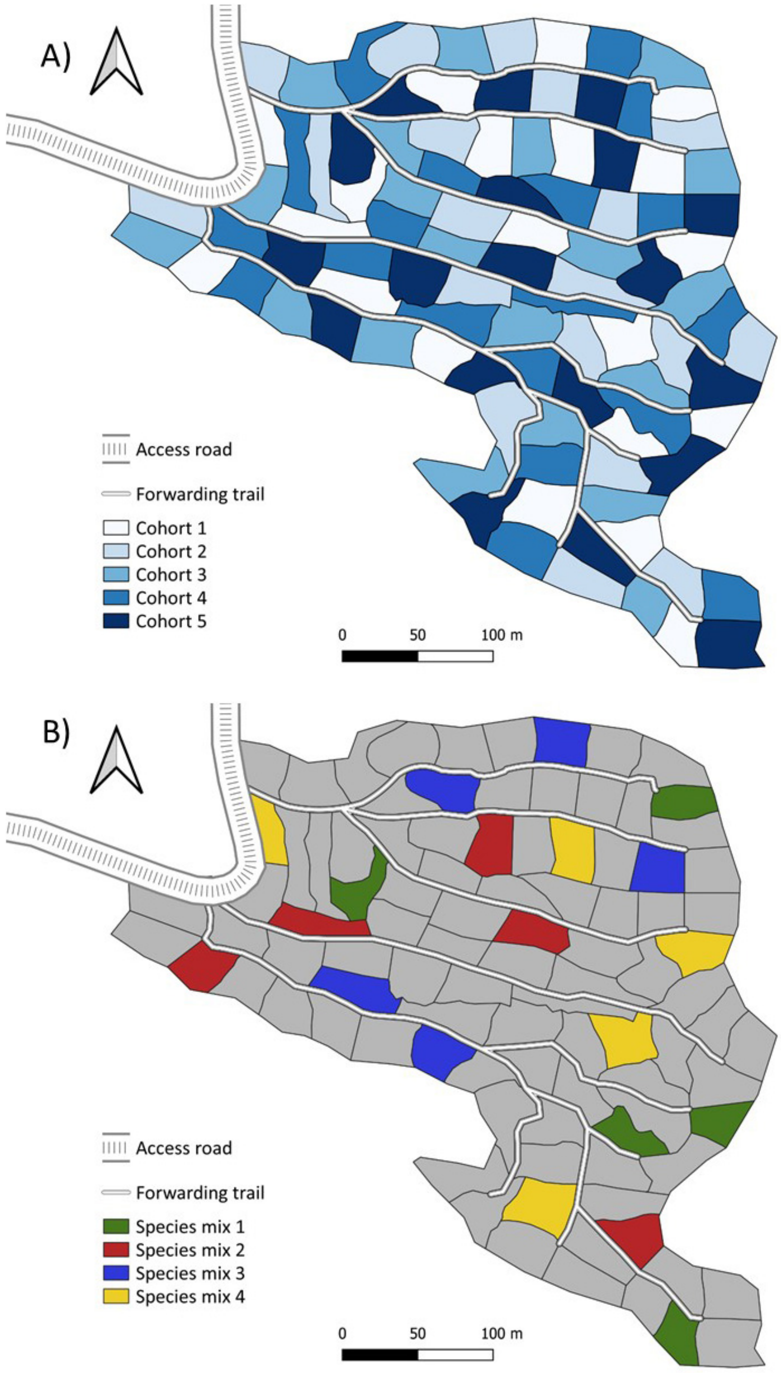

FIGURE 1
To-scale 2D rendering of the layout of trails and 97 patches for the spatially and temporally explicit patch-cut (STEP) system applied to a shade-tolerant hardwood stand with five cohorts. In this example, the average patch size is 0.097 ha and the total area of the stand is 9.43 ha. **(A)** Patches of the same color belong to the same cohort, **(B)** Test of different forest assisted migration species mixtures in one of the cohorts of patches within the spatially and temporally explicit patch-cut (STEP) system.

4 Flexibility of the STEP system

The patch-cut system offers inherent flexibility and variability, as heterogeneity in light conditions within patches favors a diversity of species (Lu et al., 2021). The STEP system allows this flexibility to be more efficiently implement. While a number of examples are provided here, we recognize that foresters would use their knowledge, experience, and imagination to adapt the STEP system to their specific needs. For example, when harvesting the patches, residual trees could be left behind for regeneration, ecological (variable retention) or societal reasons. These trees could either be harvested later when other patches are harvested or could be left permanently. A patch that is to be harvested in a defined year could benefit from a commercial thinning treatment or seedcut 10

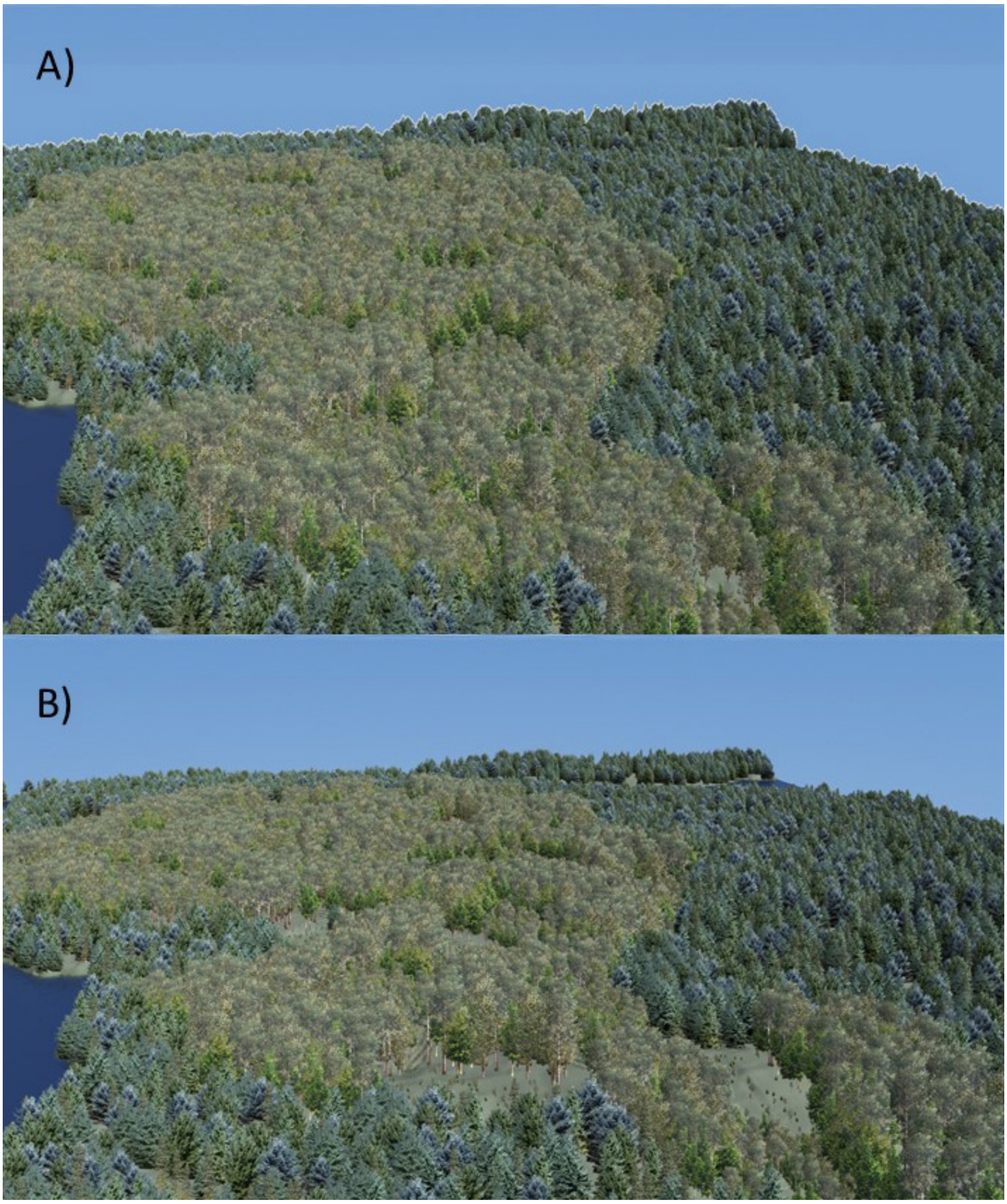

FIGURE 2
Visual effect of implementing the spatially and temporally explicit patch-cut (STEP) system simulated with Visual Nature Studio 3, **(A)** before cutting; **(B)** after cutting the first cohort of patches. The appearance of patches will vary depending on colors of the soil in patches, view angle and distance. All these factors can be modeled according to local conditions.

to 20 years before the harvest. This commercial thinning could be synchronized with the harvesting of other patches, using the permanent trails to provide access to the patches. Likewise, a patch that had been harvested 10–20 years previously could benefit from a non-commercial treatment (e.g., removal of competing vegetation) to promote the growth of seedlings/saplings of desired species. While we usually consider a stand as homogeneous, there is often small-scale heterogeneity within a stand. Hence, patches within the same stand may show abiotic variability especially for soil thickness, slope, moisture regime and aspect. Hence with the STEP system, tree species adapted to the specific conditions of the patches or tree species already present as advanced growth can be favored in given patches. In order to favor the establishment of natural regeneration, the creation of patches can be synchronized with seed years. The size of the patches can also be adjusted to local tree height and to shade tolerance of the desired species. Also, patch size can be adjusted as a function of biodiversity (Schall et al., 2018) or social acceptability concerns. Finally, some patches (clustered or not) could even remain free of harvesting to develop old-growth forest legacies structures (Ezquerro et al., 2019).

5 Contexts appropriate for the application of the STEP system

Minimally, as for any partial harvest silvicultural system, stands appropriate for the application of the STEP system should meet a number of criteria: (i) have a sufficient level of maturity to sustain a financially viable harvest, (ii) not be overmature with short-lived species unable to remain standing until the entire stand is harvested, (iii) be in areas accessible by a regularly maintained road network to facilitate frequent entries, and (iv) present few obstacles hindering the configuration of regularly spaced skidding trails leading to each patch.

More specific to the STEP system, cutting a stand using patches implies either adapting to the current spatial configuration of age classes or imposing a regular configuration. The STEP system advocates for the latter, which implies transforming the natural horizontal structure of the stand and acknowledging that the current state of an untreated stand will never naturally align with this configuration. Consequently, patches where interventions are needed may contain trees that are either younger or older than optimal maturity, potentially leading to sacrifices in wood production during the conversion to the STEP system.

Opting to implement the STEP system in stands of long-lived species could reduce the production sacrifices mentioned earlier, given that these species encompass a wide range of ages suitable for commercial wood volume extraction. Likewise, stands with an irregular or uneven age structure and shade-tolerant species are ideal candidates for the STEP system. These stands typically have enough volume to justify cutting operations, along with advanced growth ready to be promoted into the canopy within newly cut patches.

Despite the above limitations mainly pertaining to the conversion period of the stand into the STEP system, assuming acceptance of production sacrifices, and implementation of artificial regeneration, the STEP system could in theory be applied in stands of any species composition, shade tolerance, longevity or stand structure. Success is however not guaranteed and may vary depending on herbivory, the presence of advanced growth or microsite quality (Kern et al., 2017).

Other considerations, specific to the context of adaptation to climate change, include a strategy promoted by Royer-Tardif et al. (2021) which suggests focusing the effort devoted to assisted migration in portions of the forest that are highly vulnerable to forest ecosystem loss and where wood production is a priority. Similarly, Aquilué et al. (2021) suggested planting novel tree species with specific functional traits that were missing in the forest in centrally located and highly vulnerable stands having low functional diversity. One may assume that in these areas, the current horizontal structure would also be very vulnerable so there would be less wood production sacrifices from converting to the STEP system.

Moreover, in the context of using the STEP system for assisted migration, choosing stands that have many species which are at the northern limit of their distribution could be a good opportunity for introducing these species or provenances or increasing their abundance. Assisted migration of the kind that extends natural distribution has higher social acceptability than assisted migration of species far outside of their current range.

6 The STEP system and forest assisted migration: a call for the development of an international network of experiments

As the interest and number of FAM experiments are increasing worldwide, it is becoming important to start implementing them using appropriate silvicultural systems. We have argued in this paper that the STEP system is one of them, given its advantages for FAM, especially its flexibility and capacity to be designed for continuous learning. This is especially important because we have to keep in mind that using FAM may produce profound changes in ecosystem functioning. Forest scientists thus have the burden of proof to show that they do not play the “sorcerer’s apprentice.” Therefore, we are calling for the establishment of an international network of STEP system assisted migration experiments in different forest biomes and forest types in close collaboration with both researchers and forest managers. We also suggest pairing this network with other FAM experiments and networks already established using other silvicultural systems for comparison (DREAM: Palik et al., 2022; ASCC: Royo et al., 2023).

The main objectives of this paired network should be the following. First, to undertake a world inventory of experimental and commercial FAM tests set up in various biomes to determine which tree species could be tested using different silvicultural approaches. Second, to coordinate the establishment of different silvicultural experiments, ideally but no exclusively based on the STEP system, to address a set of important socio-ecological questions that are directly relevant to policy makers, stakeholders, and the public regarding FAM. Third, to encourage the writing of scientific papers and technical reports to help establish the silvicultural basis on which FAM could successfully be established in various forest biomes, forest types, silvicultural systems and socio-political conditions. The successful implementation of such a novel silvicultural system as STEP could be crucial in transitioning forest management into the integral role of adapting our world forests to global change.

We invite researchers and practitioners to contact us to report on any assisted migration silvicultural experiments or to express their interest in establishing STEP-based trials. Both old and new assisted migration silvicultural experiments will be registered within DIVERSE[1] as a new global research initiative.

Data availability statement

The original contributions presented in this study are included in this article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

PN: Conceptualization, Visualization, Writing – original draft, Writing – review & editing. MB: Writing – original draft, Writing –

1 https://diverseproject.uqo.ca/

review & editing. CM: Writing – original draft, Writing – review & editing.

Funding

The authors declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

We thank Pascal Rochon for the preparation of figures and Lana Ruddick for language editing.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Achim, A., Moreau, G., Coops, N. C., Axelson, J. N., Barrette, J., Bédard, S., et al. (2022). The changing culture of silviculture. *Forestry* 95, 143–152. doi: 10.1093/forestry/cpab047

Anderegg, W. R. L., Wu, C., Acil, N., Carvalhais, N., Pugh, T. A. M., Sadler, J. P., et al. (2022). A climate risk analysis of Earth's forests in the 21st century. *Science* 377, 1099–1103. doi: 10.1126/science.abp9723

Aquilué, N., Messier, C., Martins, K. T., Dumais-Lalonde, V., and Mina, M. (2021). A simple-to-use management approach to boost adaptive capacity of forests to global uncertainty. *For. Ecol. Manage*. 481:118692. doi: 10.1016/j.foreco.2020.118692

Argüelles-Moyao, A., and Galicia, L. (2024). Assisted migration and plant invasion: Importance of belowground ecology in conifer forest tree ecosystems. *Can. J. For. Res*. 54, 110–121. doi: 10.1139/cjfr-2023-0016

Arnberger, A., Gobster, P. H., Schneider, I. E., Floress, K. M., Haines, A. L., and Eder, R. (2022). Landowner acceptability of silvicultural treatments to restore an open forest landscape. *Forests* 13:770. doi: 10.3390/f13050770

Ashton, M. S., and Kelty, M. J. (2018). *The practice of silviculture: Applied forest ecology*, 10th Edn. Hoboken, NJ: Wiley.

Bailey, J. D., Harrington, T. B., Maguire, D. A., and Tappeainer, I. (2015). *Silviculture and ecology of western U.S. forests*. Corvallis, OR: Oregon State University Press.

Bauhus, J., Puettmann, K., and Messier, C. (2009). Silviculture for old-growth attributes. *For. Ecol. Manag.* 258, 525–537. doi: 10.1016/j.foreco.2009.01.053

Béland, M., and Chicoine, B. (2013). Tolerant hardwood natural regeneration 15 years after various silvicultural treatments on an industrial freehold of northwestern New Brunswick. *For. Chron.* 89, 512–524. doi: 10.5558/tfc2013-092

Bolibok, L., and Szeligowski, H. (2011). The influence of site conditions, opening size and location within a gap on height of 6-and 10-year-old pedunculate oaks (*Quercus robur* L.). *Sylwan* 155, 84–95.

Canadell, J. G., and Jackson, R. B. (2021). *Ecosystem collapse and climate change*. Cham: Springer International Publishing, doi: 10.1007/978-3-030-71330-0

Coates, K. D., and Burton, P. J. (1997). A gap-based approach for development of silvicultural systems to address ecosystem management objectives. *For. Ecol. Manag.* 99, 337–354.

Corbin, J. D., and Holl, K. D. (2012). Applied nucleation as a forest restoration strategy. *For. Ecol. Manag.* 265, 37–46. doi: 10.1016/j.foreco.2011.10.013

Daniel, T. W., Helms, J. A., and Baker, F. S. (1979). *Principles of silviculture*, 2nd Edn. Victoria, BC: AbeBooks.

Ellis, E. C. (2011). Anthropogenic transformation of the terrestrial biosphere. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* 369, 1010–1035. doi: 10.1098/rsta.2010.0331

Ezquerro, M., Pardos, M., and Diaz-Balteiro, L. (2019). Integrating variable retention systems into strategic forest management to deal with conservation biodiversity objectives. *For. Ecol. Manag.* 433, 585–593. doi: 10.1016/j.foreco.2018.11.003

Folke, C., Polasky, S., Rockström, J., Galaz, V., Westley, F., Lamont, M., et al. (2021). Our future in the Anthropocene biosphere. *Ambio* 50, 834–869. doi: 10.1007/s13280-021-01544-8

Forzieri, G., Dakos, V., McDowell, N. G., Ramdane, A., and Cescatti, A. (2022). Emerging signals of declining forest resilience under climate change. *Nature* 608, 534–539. doi: 10.1038/s41586-022-04959-9

Gauthier, M.-M., Lambert, M.-C., and Bédard, S. (2016). Effects of harvest gap size, soil scarification, and vegetation control on regeneration dynamics in sugar maple-yellow birch stands. *For. Sci.* 62, 237–246. doi: 10.5849/forsci.15-058

Hartmann, H., Bastos, A., Das, A. J., Esquivel-Muelbert, A., Hammond, W. M., Martínez-Vilalta, J., et al. (2022). Climate change risks to global forest health: Emergence of unexpected events of elevated tree mortality worldwide. *Annu. Rev. Plant Biol.* 73, 673–702. doi: 10.1146/annurev-arplant-102820-012804

Kern, C. C., Burton, J. I., Raymond, P., D'Amato, A. W., Keeton, W. S., Royo, A. A., et al. (2017). Challenges facing gap-based silviculture and possible solutions for mesic northern forests in North America. *Forestry* 90, 4–17. doi: 10.1093/forestry/cpw024

Lanier, L. (1994). *Précis de sylviculture*, 2nd édition Edn. Nancy: Engref.

Leak, W. B., and Filip, S. M. (1975). *Uneven-aged management of northern hardwoods in New England. Res. Pap. NE-332.* Upper Darby, PA: US Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, 332.

Lindenmayer, D., Messier, C., and Sato, C. (2016). Avoiding ecosystem collapse in managed forest ecosystems. *Front. Ecol. Environ.* 14:561–568. doi: 10.1002/fee.1434

Lu, D., Zhu, J., Wang, X., Hao, G., and Wang, G. G. (2021). A systematic evaluation of gap size and within-gap position effects on seedling regeneration in a temperate secondary forest, Northeast China. *For. Ecol. Manag.* 490:119140. doi: 10.1016/j.foreco.2021.119140

Matthews, J. D. (1991). *Silvicultural systems*. Oxford, NY: Oxford University Press.

Messier, C., Bauhus, J., Doyon, F., Maure, F., Sousa-Silva, R., Nolet, P., et al. (2019). The functional complex network approach to foster forest resilience to global changes. *For. Ecosyst.* 6:21. doi: 10.1186/s40663-019-0166-2

Michalet, R., Carcaillet, C., Delerue, F., Domec, J.-C., and Lenoir, J. (2023). Assisted migration in a warmer and drier climate: Less climate buffering capacity, less facilitation and more fires at temperate latitudes? *Oikos* e10248. doi: 10.1111/oik.10248

Ministry of Natural Resources and Forestry (2008). *A silvicultural guide to managing southern Ontario forests*. Peterborough, ON: Ministry of Natural Resources and Forestry.

Mori, A. S., Furukawa, T., and Sasaki, T. (2013). Response diversity determines the resilience of ecosystems to environmental change. *Biol. Rev. Camb. Philos. Soc.* 88, 349–364. doi: 10.1111/brv.12004

Mouillot, D., Graham, N. A. J., Villéger, S., Mason, N. W. H., and Bellwood, D. R. (2013). A functional approach reveals community responses to disturbances. *Trends Ecol. Evol.* 28, 167–177. doi: 10.1016/j.tree.2012.10.004

Nabel, J. E. M. S., Zurbriggen, N., and Lischke, H. (2013). Interannual climate variability and population density thresholds can have a substantial impact on simulated tree species' migration. *Ecol. Model.* 257, 88–100. doi: 10.1016/j.ecolmodel.2013.02.015

Neff, M. W., and Larson, B. M. H. (2014). Scientists, managers, and assisted colonization: Four contrasting perspectives entangle science and policy. *Biol. Conserv.* 172, 1–7. doi: 10.1016/j.biocon.2014.02.001

Nolet, P., Kneeshaw, D., Messier, C., and Béland, M. (2018). Comparing the effects of even- and uneven-aged silviculture on ecological diversity and processes: A review. *Ecol. Evol.* 8, 1217–1226. doi: 10.1002/ece3.3737

Nyland, R. D., Kenefic, L. S., Bohn, K. K., and Stout, S. L. (2016). *Silviculture: Concepts and applications*, 3rd Edn. Waveland Press, Inc.

Nyström, M., Jouffray, J.-B., Norström, A. V., Crona, B., Jørgensen, P., Carpenter, S. R., et al. (2019). Anatomy and resilience of the global production ecosystem. *Nature* 575, 98–108. doi: 10.1038/s41586-019-1712-3

Palik, B. J., Clark, P. W., D'Amato, A. W., Swanston, C., and Nagel, L. (2022). Operationalizing forest-assisted migration in the context of climate change adaptation: Examples from the eastern USA. *Ecosphere* 13:e4260. doi: 10.1002/ecs2.4260

Parish, R., and Antos, J. A. (2005). Advanced regeneration and seedling establishment in small cutblocks in high-elevation sprucefir forest at Sicamous Creek, southern British Columbia. *Can. J. For. Res.* 35, 1877–1888. doi: 10.1139/x05-108

Parisien, M.-A., Barber, Q. E., Bourbonnais, M. L., Daniels, L. D., Flannigan, M. D., Gray, R. W., et al. (2023). Abrupt, climate-induced increase in wildfires in British Columbia since the mid-2000s. *Commun. Earth Environ.* 4, 1–11. doi: 10.1038/s43247-023-00977-1

Patacca, M., Lindner, M., Lucas-Borja, M. E., Cordonnier, T., Fidej, G., Gardiner, B., et al. (2023). Significant increase in natural disturbance impacts on European forests since 1950. *Glob. Change Biol.* 29, 1359–1376. doi: 10.1111/gcb.16531

Raymond, P., Bedard, S., Roy, V., Larouche, C., and Tremblay, S. (2009). The irregular shelterwood system: Review, classification, and potential application to forests affected by partial disturbances. *J. For.* 107:405.

Refsland, T. K., Adams, B., Bronson, D., Kern, C. C., Marquardt, P., McGraw, A. M., et al. (2023). Synthesis of plant-soil feedback effects on eastern North American tree species: Implications for climate-adaptive forestry. *Front. Ecol. Evol.* 11:1073724 doi: 10.3389/fevo.2023.1073724

Royer-Tardif, S., Bauhus, J., Doyon, F., Nolet, P., Thiffault, N., and Aubin, I. (2021). Revisiting the functional zoning concept under climate change to expand the portfolio of adaptation options. *Forests* 12:273. doi: 10.3390/f12030273

Royo, A. A., Raymond, P., Kern, C. C., Adams, B. T., Bronson, D., Champagne, E., et al. (2023). Desired REgeneration through assisted migration (DREAM): Implementing a research framework for climate-adaptive silviculture. *For. Ecol. Manag.* 546:121298. doi: 10.1016/j.foreco.2023.121298

Runkle, J. R. (1992). *Guidelines and sample protocol for sampling forest gaps. Gen. Tech. Rep. PNW-GTR-283*. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 283. doi: 10.2737/PNW-GTR-283

Saunders, M. R., Seymour, R. S., and Wagner, R. G. (2014). "The acadian forest ecosystem research program: An example of natural disturbance-based silviculture in the Northeast," in *Penobscot experimental forest: 60 years of research and demonstration in Maine, 1950-2010. Gen. Tech. Rep. NRS-P-123*, eds L. S. Kenefic and J. C. Brissette (Newtown Square, PA: US Department of Agriculture, Forest Service, Northern Research Station), 71–80.

Savill, P. (2019). *The silviculture of trees used in british forestry 3rd edition from summerfield books*, 3rd Edn. Wallingford: CABI Publishing.

Schall, P., Gossner, M. M., Heinrichs, S., Fischer, M., Boch, S., Prati, D., et al. (2018). The impact of even-aged and uneven-aged forest management on regional biodiversity of multiple taxa in European beech forests. *J. Appl. Ecol.* 55, 267–278. doi: 10.1111/1365-2664.12950

Schnake, D. K., Forrester, J. A., Sánchez Meador, A. J., Mladenoff, D. J., and Lorimer, C. G. (2023). Tree regeneration and spatial patterning among midtolerant tree species following gap-based harvesting in a temperate hardwood forest. *Front. For. Glob. Change* 6:1144091. doi: 10.3389/ffgc.2023.1144091

Schütz, J.-P. (1990). *Sylviculture 1: Principes d'éducation des forêts [Principles of forest tending]*. Lausanne: Presses polytechniques et universitaires romandes.

Schütz, J.-P. (2002). Uneven-aged silviculture: Tradition and practices. *Forestry* 75, 327–328. doi: 10.1093/forestry/75.4.327

Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., et al. (2017). Forest disturbances under climate change. *Nat. Clim. Change* 7, 395–402. doi: 10.1038/nclimate3303

Silva Junior, C. H. L., Aragão, L. E. O. C., Anderson, L. O., Fonseca, M. G., Shimabukuro, Y. E., Vancutsem, C., et al. (2020). Persistent collapse of biomass in Amazonian forest edges following deforestation leads to unaccounted carbon losses. *Sci. Adv.* 6:eaaz8360. doi: 10.1126/sciadv.aaz8360

Trumbore, S., Brando, P., and Hartmann, H. (2015). Forest health and global change. *Science* 349, 814–818. doi: 10.1126/science.aac6759

Walker, B., Crépin, A.-S., Nyström, M., Anderies, J. M., Andersson, E., Elmqvist, T., et al. (2023). Response diversity as a sustainability strategy. *Nat. Sustain.* 6, 621–629. doi: 10.1038/s41893-022-01048-7

Walters, C. J., and Hilborn, R. (1978). Ecological optimization and adaptive management. *Annu. Rev. Ecol. Evol. Syst.* 9, 157–188. doi: 10.1146/annurev.es.09.110178.001105

Williams, M. I., and Dumroese, R. K. (2013). Preparing for climate change: Forestry and assisted migration. *J. For.* 111, 287–297. doi: 10.5849/jof.13-016

Worm, B., and Paine, R. T. (2016). Humans as a Hyperkeystone species. *Trends Ecol. Evol.* 31, 600–607. doi: 10.1016/j.tree.2016.05.008

Xu, W., and Prescott, C. E. (2024). Can assisted migration mitigate climate-change impacts on forests? *For. Ecol. Manag.* 556:121738. doi: 10.1016/j.foreco.2024.121738