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Envisioning a global forest transition: Status, role, and implications

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ABSTRACT

Satellite data-driven discoveries are fuelling the literature on forest transitions, particularly in quantifying slow, large-scale trends. Mather's forest transition concept depicts the inflection point marking a change from decreasing to increasing forest area. This theory is being elucidated using satellite images of global forest cover from the National Aeronautics and Space Administration of the United States (NASA), the European Space Agency (ESA), and now from the FAO's recently introduced geospatial monitoring platform SEPAL 2.1. Recently, a series of high profile papers have illuminated the concept of the forest transition using analysis of remote sensing-based forest cover images. Defined as an increase in global forest cover, analysis of satellite images over the past thirty years suggests that a global forest transition has occurred. However, satellite data provide less information about biodiversity and carbon sequestration outcomes in new forests. Incorporating other data sources on the quality of forest transitions offers the potential to develop better reforestation programs, address climate change goals and enhance other ecological and human benefits. This article presents a view on remote sensing, biodiversity, and carbon science that has changed the study of forest transitions, and an outline of anticipated and suggested science and policy directions.

1. Introduction

British geographer Alexander Mather introduced the term "forest transition" in 1992 (Mather, 1992) to describe a pattern observed in a number of European countries, namely, a shift from shrinking to expanding forest areas. Mather observed a pattern where seemingly poor agricultural land abandoned by humans regenerated and contributed to a rebound in forest cover. This inflection point, from declining to expanded forest cover, was termed by Mather a "forest transition." Mather's later work in Asia also documented the important role of state policy and enforcement in contributing to forest transitions (2007).

Subsequent to Mather's work, researchers documented numerous forest transitions in locations around the world (e.g., Ashraf et al., 2017; Walters, 2017; Youn et al., 2017; Leblond, 2019). These studies confirmed that marginal agricultural land was being abandoned and regenerated, and also that state intervention was at times a significant factor in forest recovery, such as tree planting in China's interior (Zhang et al., 2017). Syntheses also indicate that countries have supported tree planting to reduce droughts, floods, and land degradation (Rudel et al., 2019). Multiple pathways to forest transition have been observed reflecting a myriad of social and cultural contexts in which FTs take place.

More recently, researchers have been exploiting remote sensing (RS) data to answer the question of whether the Earth as a whole has experienced a forest transition, defined in a spatial context as a gain in total forest area. Data from the National Aeronautics and Space Administration of the United States (NASA), the European Space Agency (ESA), and now from the FAO's recently introduced geospatial monitoring platform SEPAL 2.1, powered by some 190 satellites, are being used to track forest cover changes (FAO, 2019). For instance, a 2018 Nature article by Song, Hansen, Stehman, Potapov and other colleagues (2018) concluded that global tree cover expanded between 1982 and 2016 based on analysis of satellite data. While this study confirmed tropical deforestation (noted in Nowosad et al., 2019; Li et al., 2016; Hansen et al., 2013; FAO, 2015; Intergovernmental Panel on Climate Change (IPCC), 2019), it also highlighted tree canopy increases in locations such as Russia and China. The study identified expansion of tree cover in mountainous areas, reflecting trees growing at higher altitudes.

The possibility of a global forest transition has tremendous consequences for climate change. Song et al. (2018) hypothesize that the change in forest area might constitute the missing global carbon sink identified by Le Quéré et al. (2017). Pugh et al. (2019) estimate that

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forests re-growing after past disturbances account for 1.30 Pg per year of the terrestrial carbon sink compared to a carbon sink of 0.85 Pg per year in intact old-growth forest, although they do note that the contribution of regrowth forest may be transient.

Our purpose here is to briefly present research about the status of a global forest transition as measured by remote sensing technology. Thereafter, we explore the role of a possible forest transition in mitigating climate change. As well, we consider implications of research evaluating the *quality* of documented forest transitions in terms of biodiversity. We finish with science policy and program recommendations/interpretations.

2. Methods

This environmental scan briefly summarizes research trends regarding forest transitions as reported in six databases: Scopus; Web of Science Core Collection; Environment Complete; Business Source Premier; BIOSIS; and Material Science and Engineering. We searched scholarly and peer reviewed journal articles concerning "forest transition" and either a) "carbon", b) "biodiversity" or c) "remote sensing".

Using these search criteria, from April 2000 to April 2020, we identified 3290 articles with the term "forest transition." Of these articles, there were 1814 articles on "forest transition" and "biodiversity", 1613 articles about "forest transition" and "carbon", and 1020 articles concerning "forest transition" and "remote sensing". The number of articles by journal subject area is illustrated in Table 1. Journals can be classified into multiple subject areas; as a result, the count of subject categories in Table 1 is greater than the total articles. The most common journal disciplines for these articles included ecology (1215) and environmental sciences (1063). Other common subject categories are listed in Table 1.

Nearly one in three forest transition papers also concerned remote sensing (1020 of 3290 articles from 2000 to 2020). The opening of the Landsat archive was credited in a number of articles as generating substantial advances in research about forest cover (e.g., Arévalo et al., 2020; Wulder et al., 2012). Articles concerning both forest transitions and remote sensing were more common post-2008, increasing from 147 articles (2000–2008), compared to 873 articles published between 2008 and 2020.

Of note, one short-coming with the approach is the emphasis on natural sciences and engineering fields. Scopus and Web of Science under-represent articles from the social sciences compared to the natural sciences, medicine and engineering (Mongeon and Paul-Hus, 2016). While there are multiple databases contributing to our results, there is certainly a natural science and engineering focus to the database.

Table 1
Number of Journal Articles Produced by a Search of "Forest Transition" and selected terms from 2000 to 2020.

Journal Subject	All Results	Biodiversity	Carbon	Remote Sensing
Ecology	1215	857	654	369
Environmental Sciences	1063	709	624	407
Biology	650	446	375	192
Forestry	577	349	291	143
Agriculture	543	339	292	164
Economics	416	233	179	136
Geography	455	259	227	227
Total, 2000 – 2020	3290	1814	1613	1020
Total, 2015 – 2020	1601	957	850	507

3. Results

3.1. Status of a global forest transition

The UN Strategic Plan for Forests 2017–2030 targeted an increase in global forest area by 3 % by 2030 (United Nations, 2017). This plan was brought into question when Song et al. (2018) released an analysis of data from multiple satellite sensors showing a net gain of forest cover of more than two million km^2 globally over thirty-four years (+7.1 %). Even though the study contradicted the "current understanding of long-term forest area change" (p. 1), the estimate of gross forest loss was similar to that reported by the FAO (2015). Table 2 summarizes remote sensing studies estimating global forest cover.

Song et al. (2018) integrated lower resolution (300 m) with 30 m resolution Landsat Enhanced Thematic Mapper Plus data (the rationale for using multiple sources is provided in Hansen and DeFries, 2004), supplemented with qualitative interpretation of a probabilistic sample of Google Earth images.

Using these data sources, Song et al. (2018) estimated a net global loss of bare ground and greening of mountainous areas, consistent with other studies that documented greening (Forkel et al., 2015; Zhu et al., 2016). However, forest cover expansion was uneven by biome, with the largest area of net tree canopy gain recorded in the temperate continental forest. In contrast, the largest area of net tree canopy *loss* occurred in tropical dry forest and tropical moist deciduous forests.

3.2. Role of a global forest transition in combatting climate change

The size of the forest expansion noted by Song et al. (2018) and the length of time over which the change occurred suggests that such a transition could play a role in mitigating climate change. Song et al. (2018) hypothesize that the global expansion of forest cover observed may constitute the missing carbon sink (Le Quéré et al., 2017). Tracking of carbon fluxes is still very challenging, motivating the launch of the European Space Agency's BIOMASS mission (Quegan et al., 2019). Research to date, however, indicates that forest regrowth has a strong effect on biomass turnover and carbon sinks, including "reestablishment of forest stands on previously nonforested land, such as on abandoned agricultural land" (Pugh et al., 2019, p. 4382). The largest sink was found to be mid-latitude rather than tropical. However, Pugh et al. (2019) suggest that the contributions from re-growing forests will be temporary.

Instead, protection of carbon-rich "older forests that are often multiaged and multilayered and have experienced minimal human disturbance" (Keith et al., 2009, p. 11,635) will be critical to address climate change (Mackey et al., 2013). Even where forest expansion has occurred, research suggests that ecological and carbon sequestration impacts will be greatest when existing intact forests are expanded or restored (Wilson et al., 2017). Specifically, mitigation effects will be greatest if efforts are concentrated on achieving the full ecological potential of existing intact forests, termed "profestation" (Moomaw et al., 2019).

However, in expanded forests, even those adjoining intact landscapes, increased tree growth may not always result in greater carbon sequestration (Strandberg and Kjellström, 2019). The effect of land use change on climate varies regionally. Studies have indicated that in some regions, afforestation has a warming effect due to albedo, or changes to reflection of solar radiation (Shen et al., 2019). In Europe, for instance, earlier studies had concluded that new forests were significant contributors to carbon sequestration (Vilà-Cabrera et al., 2017). However, more recent work suggests that in in this region, faster growing trees do not always translate into increased carbon sequestration due to earlier mortality of trees observed (Büntgen et al., 2019). Post-transition forests will continue to evolve in response to changing climate. Continued attention to the changing characteristics of forests is essential to clarify the role of post-transition forests in carbon sequestration.

Table 2
Articles Analysing Global Forest Cover Data.

Author	Time Period Measured	Primary Data Source	Spatial Resolution	Forest Cover +/-
Song et al., 2018	1982 – 2016	NASA	30 m and 300 m	+2.24 million km^2
Nowosad et al., 2019	1992 – 2015	ESA	300 m	−436,079 km^2
Li et al., 2016	2000 – 2012	ESA	300 m	−172,171 km^2
Hansen et al., 2013	2000 – 2012	NASA	30 m	−2.3 million km^2

3.3. Post-transition biodiversity

While the amount of tree canopy globally has garnered much attention internationally, the quality of forest transitions in terms of sheltering biodiversity has come under increasing scrutiny, as evidenced by almost 1000 forest transitions articles in the past five years that also address various aspects of biodiversity. The forest transitions literature has been challenged as ignoring “ecologically important characteristics such as forest age, species composition, vertical structure, or all but the most severe levels of degradation” (Wilson et al., 2017, p. 4). Studies have criticized observed forest transitions, particularly industrial plantations, as adversely affecting biodiversity (Heilmayr et al., 2016; Wilson et al., 2017; Mang and Brodie, 2015; Bergeron and Fenton, 2012; Rodríguez-Caro et al., 2017; Holt et al., 2012). Secondary forests and plantations in the tropics were found to be similarly impoverished in terms of biodiversity compared to primary forest (Alroy, 2017). Other research linked forest transitions observed in some regions to deforestation to other, even more vulnerable locations (Meyfroidt et al., 2013; Ingalls et al., 2018).

More important than a net global forest gain is that "diversity of forest structure and composition need to be maintained at landscape and regional scales" (Brockerhoff et al., 2017, p. 3015). Recent research has estimated that one-third of the Earth’s land surface would need to be protected in order to preserve niche habitats of 19,937 vertebrate species (Hanson et al., 2020). While new forests may play a role, particularly in connecting strands of mature forest (e.g., Wilson et al., 2017), research has indicated that gains in forest cover over 14 years, while of benefit to amphibians, showed no significant response from mammals (Betts et al., 2017).

Foundational research by Potapov et al. (2012) identified size and intactness of natural landscapes as linked to biodiversity. In addition, a recent study identified initial forest loss is an indicator of threats to biodiversity, based on analysis of 19,432 species ranges, historical forest cover loss from 2000 to 2014, and IUCN Red List categories for extinction risk and population trends (Betts et al., 2017; International Union for Conservation of Nature (IUCN), 2017). However, protection of intact landscapes does not guarantee that biodiversity will not be eroded (Naughton-Treves and Holland, 2019). Globally, significant disturbance has been observed in protected areas (Jones et al., 2018). Further, defining intact forest landscapes has complexities in disturbance driven forests such as boreal systems (Venier et al., 2018).

In response to a growing need for better spatial data on biodiversity, the Group on Earth Observations Biodiversity Observation Network (GEO BON) was established in 2008 (Navarro et al., 2017). Using the Essential Biodiversity Variables framework, data from remote sensors are combined with field observations to produce spatial and temporal illustrations of ecosystem and species extent (Navarro et al., 2017). For instance, Light Detection and Ranging (LiDAR), which is used to quantify forest canopy height and complexity, and understorey density, has had some success at predicting vertebrate and invertebrate species (Bush et al., 2017). Despite these useful contributions, the scientific literature suggests that lack of spatial data on biodiversity still impedes conservation efforts (Betts et al., 2017; Erb et al., 2018, van der Sande et al., 2017, Navarro et al., 2017), in part because of the need to ground-truth models with in situ data.

Our environmental scan raised research questions that would be fruitfully investigated pertaining to the new forests observed by Song et al. (2018), such as whether planted forests can eventually host biodiversity similar to mature natural landscapes, particularly for countries that historically lost a large percentage of primary forest (Onyekwelu and Olabiwonnu, 2016; Wilson et al., 2017). Because change is rapidly occurring in the global forest stock (Pugh et al., 2019), monitoring of how forest cover expansion can best support ongoing efforts to preserve existing habitats is critical.

4. Conclusions and recommendations

While remote sensing-based studies have contributed greatly to the literature on forest cover, the impact of land use and forest dynamics on biodiversity, carbon sequestration, and other benefits add critical challenges to interpretations. RS data will undoubtedly continue increase in relevance for validating and cross-referencing of metrics of global forest transitions. RS has been used in the research reviewed to provide interpretations and understanding of forest transitions at larger spatial scales. However more subtle satellite data-based interpretations must be augmented and validated with ground-truthed data. The extent and quality of FTs in terms of biodiversity and carbon will undoubtedly continue to be cast against the economic and social descriptions provided in foundational research of Mather, Rudel, and other scholars.

Our environmental scan suggests the following conclusions:

1 Remote sensing data, integrated with sophisticated analytic and sample-based validation, have provided a new lens by which to consider the forest transition concept, as evidenced by our finding that one in three forest transitions articles also addressed remote sensing over the past 20 years.
2 Forest transitions may be defined simply as a net increase in forest cover, but the *quality* of transitions has drawn significant scientific attention in terms of carbon sequestration and biodiversity. Simultaneous consideration of changes in forest cover, biodiversity, carbon, and climate adds complex but much needed layers of interpretation to observed FTs.

There are a multiplicity of forest transitions all over the globe with a wide range of ecological characteristics. Our review indicates that forest cover expansion is often likely to have the most positive ecological/biodiversity benefits when attached to existing intact landscapes.

- **Establish validated forest transition timelines.** Song et al (2018) provide annual data between 1982 and 2016. These data will no doubt be used to create a timeline which needs to be further augmented and interpreted against FTs documented by Mather and other scholars.
- **Identify regional variations in response mechanisms.** Forests exhibit different responses to climate and land use change. Consequently, forest cover data should ideally support policy action for individual jurisdictions. Further, a multiplicity of regionally-based goals and mitigation strategies are essential.
- **Assessments of forest carbon stocks and flows.** Trees’ effects on climate depends on where they are planted. Better understanding these effects will produce better estimates of the effects of tree planting and landscape restoration projects on climate change.

- **Plan for better biodiversity outcomes.** Expanding or restoring forests that adjoin already existing larger natural forests will promote better biodiversity outcomes. Restoring and enhancing existing forested areas is an "effective, immediate, and low-cost" strategy to support both carbon sequestration and biodiversity (Moomaw et al., 2019, p. 1).
- **Promote common gardens for experimentation.** We are continuing to learn about how climate change affects forests globally. Ecological restoration projects should incorporate demonstration sites, test plots and long-term monitoring to add scientific knowledge about how changing climate affects tree species survival, growth, biodiversity and carbon sequestration among other attributes.

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Declaration of Competing Interest

The authors are both employed by the Canadian Forest Service. Notwithstanding, the authors have no competing interests to declare.

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