

Seeing the trees in the world's forests: an extension of the forest transition concept

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Abstract

The *forest transition* – or *forest-area transition* – has been put forward as a land-use concept by A.S. Mather in 1992 (The forest transition. *Area* 24, 367-379), to describe the historical trend generally observed in the forest area of developed countries, embodied in a V-shaped curve of the forest area over time, and that may serve as a paradigm to understand and anticipate deforestation in the developing world. Well in line with a geographical approach to forests, forest transition has thus been defined as one-dimensional, forest area being the reference state variable.

From a forestry perspective, the analysis appears to be reductive, as forests are described by many other state variables than area, including forest growing stock, composition in tree species, or stand structure. Whether the drivers of forest transition (population dynamics, economic modes of production and consciousness, as classified by Mather) also impact these other forest state variables in a general way thus comes forth as a logical issue.

From a deductive analysis of forest transition drivers, and from forest trends brought to light in Europe, France, and at other places in the world, we here argue that the forest transition concept can be extended to a multi-dimensional space of forest attributes, characterized by typical ideal dynamics. Cumulative impacts onto forests and irreversible losses in forest biodiversity over a forest transition are hence highlighted. Global change, as a parallel consequence of countries' developing process, further appears as one additional albeit less coupled dimension of forest transition, as it modifies forest productivity and vitality over time.

Since forest ecosystem services and forest profitability primarily depend on such attributes, we argue that the extension of the forest transition concept has significance for land-use change and forest protection issues. A prospect on future changes in the forests of developed countries with the European space as a benchmark is finally proposed that leads to extend the temporal significance of forest transition. Though poorly described, returning forests on abandoned agricultural lands are significant, and deserve greater attention.

Keywords: forest transition, land-use change, returning forests, global change, growing stock, stand structure, composition, diversity, forest policy

Introduction

The forest(-area) transition framework, and the omission of trees

The concept of forest transition (Mather, 1992) refers to the observed inversion in the long-term – often pluri-secular – trend of the forest area of a country that shifts from negative to positive (a typical V-shaped curve) over time, as an integrative consequence of the many drivers that come along with country's development (see also Grainger et al., 1995). In spite of the difficulty to dispose of relevant and compatible forest areal data over the longer term (e.g. Audinot et al., 2020), this phenomenon and its variations have been initially exemplified from the forest histories of several developed European countries, including Denmark, France, Scotland, Hungary (Mather et al, 1998, 1999, Mather, 1992, 2004) and other places in Europe (Mather, 2001). For most countries, the forest (-area) minimum is attested to have been reached in the 19th and 20th centuries (Meyfroidt and Lambin, 2011), a period time where national forest inventory programs were nonexistent or in emergence (first inventories in Nordic European countries; Tomppo et al., 2010) and associated forest maps or area statistics hardly available. Taking countries as initial reference support units for forest transition analysis has been justified by the major historical role of national policies and markets in land-use change dynamic, despite some drivers may be common to a continent (Mather, 2001). While the concept and evidences of forest transition are of global significance for land-use change and have inspired a profuse literature, the issue has gained wide recognition only recently (e.g. Foley et al., 2005; Rudel et al., 2005; Kauppi et al., 2006; Meyfroidt et al., 2010).

Socio-economic drivers of the forest transition have been identified that provide a generic and mechanistic understanding of the phenomenon (Mather and Needle, 1998; Mather, 2001). These have been classified into three categories, each typical of distinct phases of the forest transition (Mather et al., 1999; their Figure 2), including *population*, *mode of production* and *consciousness*. These drivers demonstrate tremendous variations across countries, amplified by the irreversibility of the energetic substitution from wood to fossil fuels, the growing urbanization of populations (Rudel et al., 2005) or economic globalization (Lambin et al., 2001) and deforestation exportation (Meyfroidt and Lambin, 2009). Yet, both already draw attention onto the dual need for land area and wood resources. *Population* refers to the demographic dynamics of a country and the associated impacts onto forests induced by the needs for both agricultural surfaces, and for energy or construction wood at its early stages.

The negative relationship between rural population and forest cover changes has hence been evidenced on a global scale (Mather and Needle, 2000). *Mode of production* refers to the economic organization of agricultural and industrial production, and the general reduction of pressures exerted i) on forest area following technological development in agriculture (agricultural, or ‘green revolution’; van Zanden, 1991) and facilitation of regional economic exchanges, and ii) on forest resources, owing to energetic transitions (Gales et al., 2007). *Consciousness* refers to either strategic perceptions of wood resources, leading to forest protection and productive policies enforced by law, and to perception of the protective role of forests on threatened lands (against erosion or landslide; Mather, 2001), or more recently their support as recreational spaces to urban populations (Konijnendijk, 2003). Obviously, forests deliver wood, and not only space resources (Kauppi et al., 2006). While the forest transition concept has arisen from a geographic perspective on forests and has as such placed focus on the primary dynamics of forest area and its interplay with land-use change, this initial view has therefore remained reductive.

Forestry sciences moreover envision forests through many other attributes than forest area (McElhinny et al., 2005), most likely to be modified by the drivers of a forest transition, including volume of the growing stock, tree species composition and richness (Grainger, 2005), or forest structure. Last, managing forests in a sustainable way also increasingly calls for embracing its provision for species habitats, and interplay with associated wildlife and plant communities (Bremer and Farley, 2010). Adopting a forestry perspective on the forest transition concept hence comes forth as more inclusive approach of forest changes, and leads to ask whether and which forest attributes may undergo generic and concomitant changes in addition to forest area, and what their implications for forest and environmental policies may be.

Synthesis objectives and outline

The aims of this synthesis contribution were therefore threefold. First, we review the evidences for extending the forest transition concept to an enlarged set of forest attributes, including forest growing stock, diversity in forest trees and accompanying species, and forest structure, as new dimensions of the forest transition. The analysis was based on forest inventory statistics and historical perspectives in Europe, in France (that served as an initial support for Mather’s theory), and in different regions in the world, and was used to infer generic forest transition trajectories. Anthropogenic environmental changes and their

impact onto forest vitality are also discussed. **Second, we show that this multidimensional perspective on the forest transition not only has a cognitive interest, but also provides a renewed framework in analyses of forest value and land-use change.** **Third, we attempt to infer and discuss possible future generic post-transitional forest changes** with the European continent as a benchmark, by highlighting current and future trends in forest dynamic and management, in conservation ecology policies, and in land-use change.

Section 1. We show that forests primarily provide not only space, but also wood and timber resources that both vary in a qualitatively similar way over a forest transition. **Section 2.** The mechanisms of forest exploitation or restoration are shown to modify tree species composition and forest structure, through preferential species exploitation or selection for afforestation, and implementation of efficient silvicultural approaches. Some of these processes have irreversible impact on species diversity. **Section 3.** We emphasize that global change, like forest transition, is an outstanding consequence of countries' economic development, and also has impact on forests, as it has modified several abiotic resources of forest growth. **Section 4.** Implications of this multi-dimensional perspective on forest transition, with cumulative and irreversible forest alterations, are discussed as regards the valuation of forest lands in land-use change perspective. **Section 5.** We draw a prospect on future possible changes in the forests of developed countries, based on the current situation of forests in Europe, and we suggest that 'forest transition' may gain achieved temporal significance for attributes other than area over the longer term.

1. Resources provided by forests: area, and wood

1.1 Acknowledgement in international forest reporting

Current forest inventory reporting, performed at different levels (national forest inventories at country scale; Tomppo et al., 2010, or international reporting at continental or global scale, e.g. the *Forest Europe* reporting process; MCPFE, 2002, or the FAO global *Forest Resource Assessment*; FAO, 1948), places a primary emphasis on both forest area and volume of the growing stock (either total volume, or average volume per unit of area for which total forest area matters). These variables have definitions that may vary across countries and/or that have been harmonized internationally. Hence, the international definition of a forest is inclusive and assumes a minimum area of 0.5 ha, with a minimum width of 20 m, a minimum ground vegetation cover of 10%, and a vegetation potential to reach a 5 m height (FAO, 2000). The

definitions for growing stock are more variable, but always refer to part of aerial volume of the living trees (timber wood in the tree stem up to a given diameter limit, e. g. of 7 cm), and beyond a minimum individual diameter threshold at conventional “breast height”, e. g. 10 cm at 1.30 m (Gschwantner et al., 2019), that makes these definitions much more restrictive.

1.2. Shifting to a 2-dimensional representation of forest transitions

From a forestry perspective, the acknowledgement that forests actually represent both space and wood resources suggests a two-dimensional description of forest transition (total forest area and total growing stock of a given territory). In a global analysis of the recent evolution of countries’ forests, Kauppi et al. (2006) introduced the concept of ‘forest identity’ that separates four nested variables describing forests, including forest area (ha), density of growing stock (m^3/ha), biomass ratio (tons of biomass/ m^3) and carbon concentration (tons/ton). Country’s forests evolution was hence analysed in a two-dimensional plane defined by rates of change in forest area and density of growing stock, therefore highlighting the relevance of such analytic approach. Nevertheless, a forest transition analysis based on the average growing stock per hectare may be less intuitive than by considering total growing stock (Rautiainen et al., 2011). Among obvious process examples, deforestation for newer agricultural lands lets the density of growing stock unchanged, but not the total growing stock. Also, active afforestation generates early-stage and low-stocked forest stands, leading to a transient decline in the density of the average growing stock (example of Viet-Nam, Kauppi et al., 2006). Second, the forest transition concept focuses on temporal changes in the forests, and thus on trajectories of forest attributes over time, more easily captured in a state space than in a momentum space (the space being defined by the rates of change of the different forest variables under consideration; Kauppi et al., 2006). We thus adopt the former convention in the following.

1.3. Area and growing-stock trajectories along the forest transition

In the initial reduction phase of the forest transition, a double need for both newer agricultural areas and energy/construction wood has been stressed. The need for agricultural surfaces implies clear-cutting forests, and thus a sudden change in the forested area. Deforestation of these new surfaces certainly comes along with a joint satisfaction of wood demand, so that the area and growing stock dynamics may be qualitatively similar. However, the need for

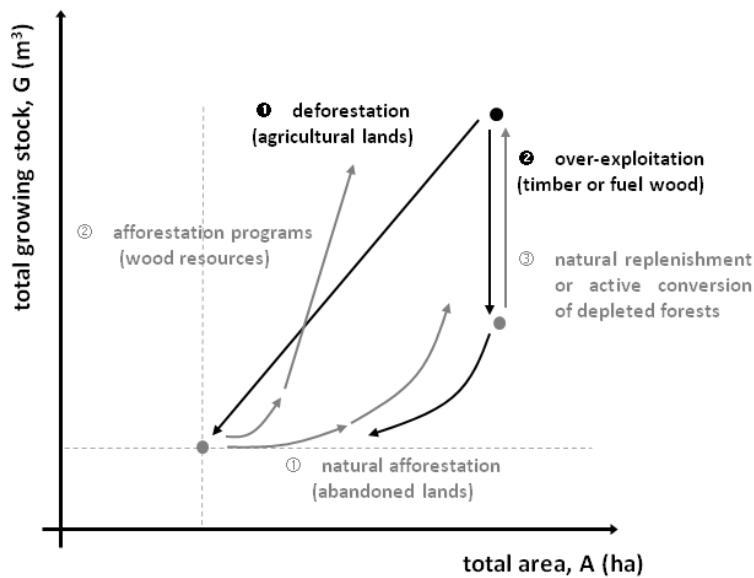
energy/construction wood for domestic or industrial purposes may rather imply a progressive depletion in the forest growing stock of the concerned forest territories, resulting – or not – in deforestation. Severe depletions of the growing stock are hence attested in forests that have persisted, e.g. in France, including the *Tronçais* forest to provision forges for energy wood in the 18th century (Roy, 1969), in the *Chaux* forest to fuel neighbour forges, saltworks of *Salins* and *Arc-et-Senans*, and glass factories from the 16th to the 18th century (Plaisance, 1966). A scarcity in fuelwood was also reported in forests of *Lorraine* region that provisioned tin and glass factories and saltworks, some of which even ceasing their activities by the end of the 18th century (Badré, 1992). Growing stock depletion in areas still afforested remains therefore ignored in the forest transition analysis, despite being strongly associated to the developing processes of a country. The pattern has been general in Europe at the pre-industrial era (Mather et al., 2001).

The same distinction remains operative in the forest expansion phase, where forests can expand: i) either naturally on abandoned agricultural or grazing lands following rural depopulation (Rudel, 1998; Mather and Needle, 1998), or ii) artificially when resulting from active plantation programs aimed to restore and secure wood resources (Rudel, 1998), with an attested global success along the 20th century (Sedjo, 1999). In the first case, a returning forest state will be reached following the progressive development of transient vegetation forms (lands with shrub-type vegetation) that will meet the forest definition far before they represent a non-zero growing stock. In this case, the growing stock expansion will be strongly delayed, currently over several decades. In the second case, planting for developing new forest resources will quite simultaneously add growing stock to these new forest areas, as technical options will be implemented to favour rapid forest development (soil preparation, use of nursery trees, and of fast-growing often coniferous tree species; Savill et al., 1997), despite these options may depend on socio-economic factors at a country level. In addition to these afforestation processes, non-deforested areas that were depleted or managed at a low density of growing stock (typical coppice forests to produce fuelwood) will also contribute to increase the total growing stock (e.g. Bontemps et al., 2020, in France), either through active conversion policies, or by natural development (section 2.2).

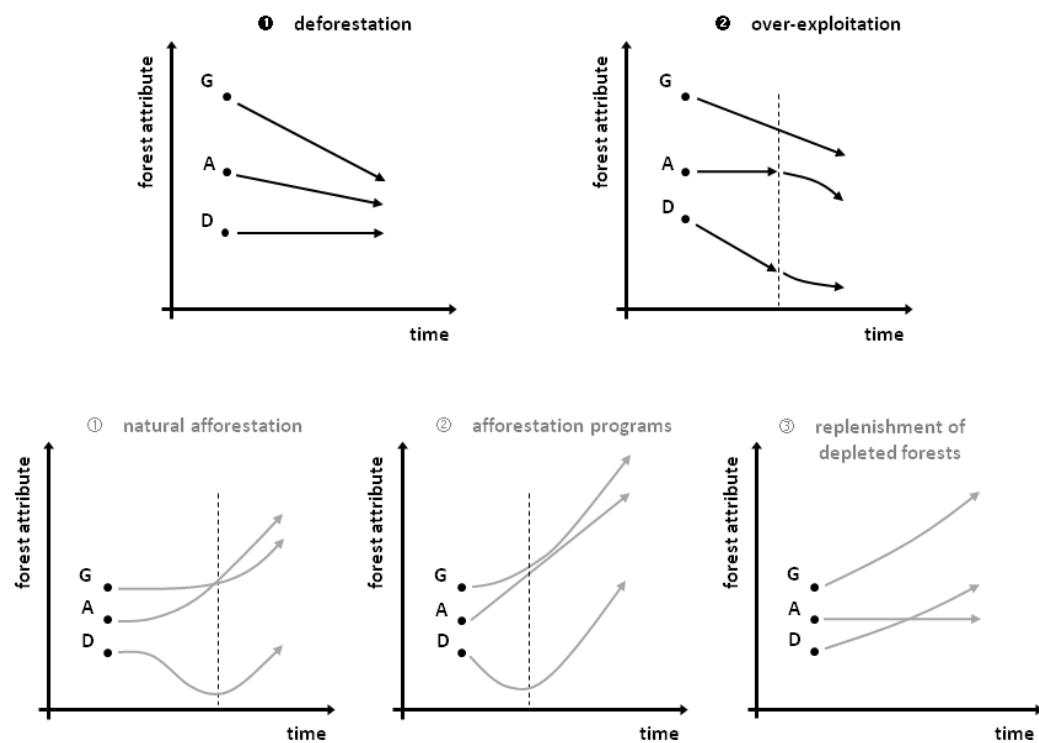
Theoretical trajectories featuring these different dynamics are summarized in **Figure 1**, both over time and in the two-dimensional forest state-space defined by area and growing stock. These illustrate the relevance of this two-dimensional perspective on forest transition. These dynamics are also illustrated in **Figure 2**.

Figure 1. Two-dimensional analysis of forest trajectories underpinning the forest transition based on total forest area (A) and total growing stock (G) of a given territory as state variables. The dotted vertical line figures the forest area minimum.

a-



a. Representation in the state space defined by A and G: ① forest depletion caused by a deforestation process leads to a decrease in both A and G. This decrease is linear as soon as the forest is assumed to be homogeneous in the density of growing stock (growing stock per unit area, or D), ② forest depletion caused by over-exploitation for timber or fuelwood exhibits a different footprint in this state space, where only G decreases. In situations of exacerbated depletion tending to zero G, gaps in the forest area may appear and cause a further decrease in A, ③ forest expansion caused by natural afforestation on abandoned agricultural lands. G will progress slowly as ground vegetation will precede a forest state, while definitions for G most often require a minimum countable threshold on tree diameter at 1.30 m height, ④ forest expansion due to active plantation programs aimed at securing a future timber and/or fuelwood energy resource. In this case, G will increase sooner than for natural afforestation as plantation engineering facilitates the quick establishment of forest stands, and it will also increase faster as the productivity of introduced species will a higher density of growing stock, ⑤ forest replenishment in G in areas where the growing stock was initially depleted, but that kept their 'forest' state (A does not change). Replenishment can occur naturally when forests turn under-exploited, or can result from active management, e.g. conversion of coppice forests into high forests. Under the hypothesis of homogenous forests, D increases proportionally. Progression in G under this process should be more regular than in forest expansion situations, because of a pre-existing forest state.

Figure 1. (continued)**b-**

b. Representation of the associated temporal dynamics in A and G. The same five situations are represented, and the density of growing stock (D, Kauppi et al., 2006) is added for the sake of comparison to the dynamics of total growing stock G. Vertical positions are arbitrary. ① Under deforestation process, A and G decrease proportionally when the forest is assumed homogeneous in D. D however remains constant, which forms the footprint of pure deforestation. ② Under an over-exploitation process, A remains constant and the decrease in D causes the decrease in G. Over-exploitation ultimately causes a decrease in A when forest gaps appear, which may slow the rate of decrease in D. ① Under a natural afforestation process, the increase in A will be delayed as the definition of a forest requires a minimum size, ground cover, and vegetation able to reach a height of 5 m. The increase in G will take a longer time as the definition for growing stock requires a minimum tree diameter. Accordingly, D will initially remain stable, and will then decrease as a consequence of increasing A with a zero G. Only after G is expanding, D will meet a minimum and will expand again with forest reconstitution. ② Under an active plantation policy, A will increase immediately, causing an immediate decline in D. G will increase sooner than under natural afforestation and will maintain a higher rate of progression. Note that under both processes of forest expansion, D will decrease. This early variation may seem counter-intuitive at first glance and it is further qualitatively similar to that of an over-exploitation, leading to discard D to evaluate growing stock. ③ the replenishment of forests with a continuous forest state leads to a fast increase in G, as the initial growing stock has a higher level than in previous situations to satisfy a forest state. In these forests, A is unchanged. Consequently, the dynamics of D and G are parallel.

Figure 2. Forest extension from artificial plantations (left) and natural afforestation (right). Artificial plantations contribute to the forest growing stock faster than natural afforestation. While of fragmented cover, patches of natural afforestation can nevertheless meet all criteria of the international forest definition. These two processes of forest extension also have compositional implications, with conifer plantations (left) contrasting with natural afforestation (right) by broadleaves as illustrated on the picture (see section 2).



Photograph taken at *Pierre-sur-Haute* site (1600 m asl) in the *Forez* mountain range of central France, at the border of *Puy-De-Dôme/Loire* (63/42) NUTS-3 units of the EU administrative classification. Credit: Jean-Daniel Bontemps, 2006.

2. No forest without trees: changes in forest composition and structure along forest transitions

While changes in these attributes remain more subtle than those related to forest area or growing stock, they also exhibit general trends that affect forest resources and the provision of ecosystem services (Wilson et al., 2017). Also, both composition and structure changes play a fundamental role in the definition of secondary forests (Chokkalingam and De Jong, 2001), stressing the relevance of their inclusion as patterns of the forest transition. The contribution of natural forest expansion on abandoned agricultural lands to these trends, however, remains undocumented to date and forms a matter of research (EU BeonNAT project, <https://www.bbi-europe.eu/projects/BeonNAT>).

2.1 Changes in forest composition

Forest composition in tree species present in the forests is prone to change during both the reduction and expansion phases of a forest transition. While the selective exploitation of forests before transition certainly has such impact, it remains far less documented than that of afforestation programs or natural regrowth (Cramer et al., 2008; Prévosto et al., 2011 in Europe) in the forest expansion phase.

In ancient forests that outlasted the forest area minimum, local selective exploitation of tree species is a likely first driver of compositional changes, the occurrence of native tree species showing main economic/technical advantages being reduced, especially those less successful in natural regeneration. In depleted forests, the expansion of pioneer light-demanding species of lower material value (King et al., 2006; Aiba & Nakashizuka 2009) and the ability of some species to regenerate fast by coppicing (Kammesheidt, 1998) has also certainly contributed to such compositional changes. These changes remain far less documented in the temperate zone, where forest transition has been experienced for long, than in the tropics (Chokkalingam and De Jong, 2001). They are further strongly context-dependent, as they involve complex ecological interactions (e.g. Barbero et al., 1990 in a Mediterranean context), and depend on both the frequency and spatial extension of human-induced disturbances on forests (e.g. Turner et al., 1993). The process is well exemplified by *sessile oak* species in France, whose wood has been praised for construction or domestic purposes, to the point of often forming a depleted resource. Oak plantation programs were launched under the Colbertism as soon as in the 17th century (Hüffel, 1926; Mather et al., 1999) to provide marine wood, with specific regeneration and silvicultural programs implemented in *sessile oak* forests to cope for the invasion of pioneer species across Northern France (selective or total successive coppicing method of Dralet, 1812; Hüffel, 1926). Such compositional changes in the forest vegetation during the forest transition are also attested in New England (USA), following European population settlements since the mid 17th century (Foster et al., 1998). There, human activities and accompanying land-use change have homogenized forest vegetation, and have favoured light-demanding species genera (e.g. *Birch*, *Oak* or *Pine*) over shade-tolerant ones (*Hemlock* or *Beech*).

The most obvious driver of species compositional changes however prevails in the forest expansion phase, when the emergence of a forest productivism (Mather et al., 1999) has resulted in active forest plantations (Sedjo, 1999) on either formerly non-forested areas, or to convert ancient forests, over typically several decades. Over the past century, economic and

industry-driven considerations have most often led to favour monocultures of exotic or native fast-growing coniferous tree species including pine and spruce genus, or *Douglas fir* (*Pseudotsuga menziesii*) species (Kuusela, 1994 in Europe), causing a shift in species composition in areas where broadleaved species prevailed (see illustration in **Figure 2**). This shift in species composition in favour of coniferous species has been a general trend in Europe (Savill et al., 1997; Spiecker, 2003). Among indications, coniferous forests extend over 50% of the European forest area, including the boreal zone and mountains where conifers are native species. Following the European forest type classification (Barbati et al., 2007), the 'Plantations and self-sown exotic forests' type ranks third with 7.1% of the ICP level I plots of the European monitoring program, behind the boreal and hemi-boreal forest types. Conifer forests also exceed 40% in Central-west and Central-east Europe regions (and >50% of the growing stock) where broadleaved species grow naturally. Even-aged forests finally form 80% of the forest area (MCPFE, 2011). As a more specific example, the forested area in France has increased by 4.5 million hectares (hereafter noted Mha) since 1945, for a total current area of 16.2 Mha (IFN, 2005) of which 2.0 Mha are planted coniferous forests (Cinotti, 1996). The National Forest Fund (FFN) incentive established in 1947 to renew and develop forest resources is estimated to have contributed by 75% to this increase in the coniferous forest area. The main planted tree species have essentially been coniferous species including pine (*Pinus sylvestris*, *Pinus nigra*), European larch (*Larix decidua*), Norway spruce (*Picea Abies*) and Douglas fir, Grand and Silver fir species (*Pseudotsuga menziesii*, *Abies grandis* and *Abies alba*, Pardé, 1966, Dodane et al., 2012). Yet, natural afforestation by broadleaved species on abandoned lands has finally led to a remarkable constant proportion of conifer and broadleaved species over one century, resulting in a notable increase in tree species diversity on a country scale (Audinot et al., 2020). A more recent and significant example is that of China, where unprecedented afforestation has been conducted since the 1960s (Bull and Nilsson, 2004). Plantation forests represented 47.0 Mha in 1999 (Haiqing and Takashi, 2006), i.e. 20% of the world's total plantations, and 54.6 Mha in 2005 (FAO, 2005). Since the 1990s, the annual rhythm of plantation has reached +4 Mha per year (Xu, 2011), with Masson pine (*Pinus massoniana*) and other exotic pine species, Chinese fir (*Cunninghamia lanceolata*), poplar (*Populus canadensis*) and eucalyptus species (Chen and Chen, 2002; Bull and Nilsson, 2004; Haiqing and Takashi, 2006; Turnbull, 2007) as main planted species. Despite statistics at species level remain hard to find, it is estimated that the plantations of *Masson pine*, *Chinese fir*, and *poplar* amount to 58.8% of the total plantation cover (Haiqing and Takashi, 2006), the two first ones having substantially replaced natural

evergreen forests of China (Chen and Chen, 2002). The focus on eucalypt species is more recent (Bull and Nilsson, 2004) and would amount to 1.5 Mha, thus forming a minor fraction of the planted forest area.

Shifts from primary or little managed forests to secondary forests, some of them being intensively managed, not only lead to quasi-irreversible changes in species composition and losses in tree species diversity (Chokkalingam and De Jong, 2001; Chazdon, 2003), but also in the accompanying diversity in plant and animal species (Hermy and Verheyen, 2007; Paillet et al., 2010), despite there is ongoing recognition that plantation forests form newer suitable habitats for diversity (Lugo, 1997; Brockerhoff et al., 2008) and also contribute to restore diversity on degraded lands (Bremer and Farley, 2010). These changes in forest composition therefore have important implications for forest functioning and value (Pearce, 2001), despite they remain ignored in the usual descriptions of forest transitions. Set in a current framework, they concern forest ability to provide goods and services and to satisfy the different criteria of sustainable forest management, including economic, ecologic and societal aspects (UN, 1992, section 4). Wilson et al. (2017) advocation of the ecological dimensions of the forest transition is a first noticeable attempt in this respect.

2.2 Changes in forest structure

Forest structure refers to “*the physical and temporal distribution of trees in a forest stand*” (Oliver and Larsson, 1990), and it includes the horizontal and vertical distribution of trees, their size and age, and species, implying a geometrical description of forest stands (Stone and Porter, 1998). Heterogeneity in forest structure is generally greater in natural or semi-natural forests than in managed ones, as natural disturbance regimes favour spatial heterogeneity in tree size, stand density or species composition (Huston, 1994; Franklin et al., 2002; Huang et al., 2003). Conversely, forest structure tends to be homogenized for the practical purpose of forest management. Therefore, changes in forest structure are a key aspect of secondary forest definition (Chokkalingam and De Jong, 2001).

In managed forests, forest structure results from management systems that can be discretized in ideal types. *Coppices* correspond to trees growing on stumps (of tree species able to regenerate by sprouting) and coppiced over short rotations (one to two decades) in order to produce fuelwood with rapid regeneration. *High forests* are formed of adult trees developing over decades in order to produce timber wood. Such forests can be regular or irregular depending on the homogeneity of tree size/age, and therefore on the mode of regeneration of

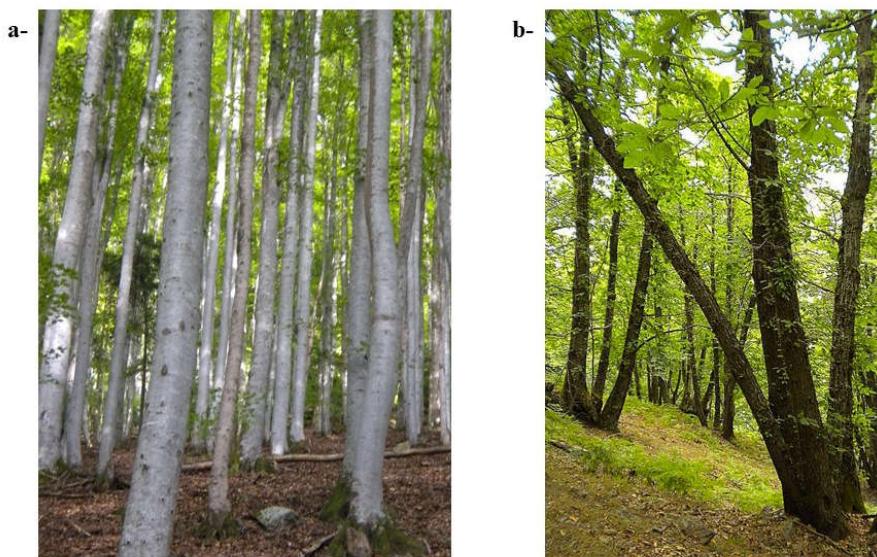
stands (clearcut with spatio-temporal rotation against selective cutting and gap regeneration). They can also be homogeneous or mixed in tree species. The practice of setting aside high forests in reserve in feudal or royal forests (“*defensa*”), to secure timber wood production, originates in the early middle age in Europe (Hüffel, 1926). In France, it was generalized with the “Quart en réserve” (one fourth of the forest area in high forest) in the Water and Forest law of 1669 inspired by Minister of Finance Colbert. *Coppice-with-standards* correspond to two-horizontal layered forest stands where adult trees are maintained over several coppice rotations to further secure provision of timber wood, and hence form an alternative management option to that of separating coppice and high forest systems over space.

All over non-deforested plains of Europe (see regional references in Baeten et al., 2009), coppices of the main oak species have formed a prevailing forest system since the Roman and medieval periods (Haneca et al., 2005) for a fast and regular renewal of fuelwood resource (Peterken, 1993, chapter 3). In European mountain ranges including the Pyrénées, the Alps, the Appennine ranges (Ciancio et al., 2006; Coppini et al., 2007), *common beech* coppices were also widespread (*common beech* is able to grow from stump beyond a minimum altitudinal level; Boppe, 1886) that currently served to provide renewable fuelwood to rural populations living from cattle breeding.

The energetic transition (Ben Gales et al., 2007) from fuelwood to fossil fuels in the 18th and 19th centuries in Europe (*mode of production* of Mather, 1992) and the progressive abandonment of agricultural land in mountainous contexts has contributed to lower the pressure on the forest growing stock. Obviously, it has also impacted forest structure over large areas, with coppices either freely developing as, or being actively converted to, high forests, a process known as ‘coppice conversion’ (Peterken, 1993 chapter 4, Coppini et al., 2007). According to Baeten et al. (2009) the abandonment or conversion of coppice forest stands hence form “*one significant, though largely overlooked, environmental change in European forests*” (p. 188). Both modes of coppice conversion are illustrated in **Figure 3**. This change may be one major driver of growing stock accumulation in Europe, as evidenced by Bontemps et al. (2020). In France, a large conversion momentum of oak coppices was initiated by Lorentz in the mid 19th century (Lorentz, 1837, cited by Hüffel, 1926), following the enactment of the forest code in 1827 and the conviction that “*the role of State forests was to product timber of large dimension, not fuelwood nor money income*”. Conversion started in North-eastern France and then propagated to the whole country. It formed a major challenge, as an estimated 64% of the French forest area was managed as coppice or coppice-with-standard forests (Degron, 1998). Conversion also met some resistance as the predominating

and so-called ‘immediate conversion’ method required the evolution from coppices to high forest on stumps, able to produce a natural regeneration, and implied transient profitability losses. The major conversion effort was paid during the period 1860-1888 after introduction of fossil fuels, with a rate of ongoing conversion of 74% by 1876 (Degron, 1998). Nevertheless, achieving conversion has taken long and sometimes failed (Lafouge, 1964; Vannières, 1983). Ancient forest statistics as compared with modern forest inventory statistics over one century have shown this shift from coppice to high forests being lasting up to recently (Audinot et al., 2020). Accordingly, current estimates (Dubourdieu, 1991) still indicate a current forest area of 1.3 Mha of coppice stands, i.e. 8% of the total forest cover.

Figure 3. Changes in forest structure resulting from active or natural conversion of forest coppices. (a) Active coppice conversion based on sprout selection to form high forests of regular structure. *Fagus sylvatica* (L.) stand in a mountain range, where winding stems attest of regrowth on stumps, (b) Spontaneous evolution of coppice can also lead to clear stands of high trees growing on stumps (multi-stemmed trees), here in a *Castanea sativa* (Mill.) stand.



Photographs taken at (a) *Fuchselsen* mount (> 1000 m asl) in the *Vosges* mountain range of Eastern France, Haut-Rhin (68), NUTS-3 unit of the EU administrative classification, (b) *Can de l'Hospitalet* plateau (1000 m asl) in the *Cévennes* mountain range of south-central France, Lozère (48). Credit: Jean-Daniel Bontemps, 2012/2010.

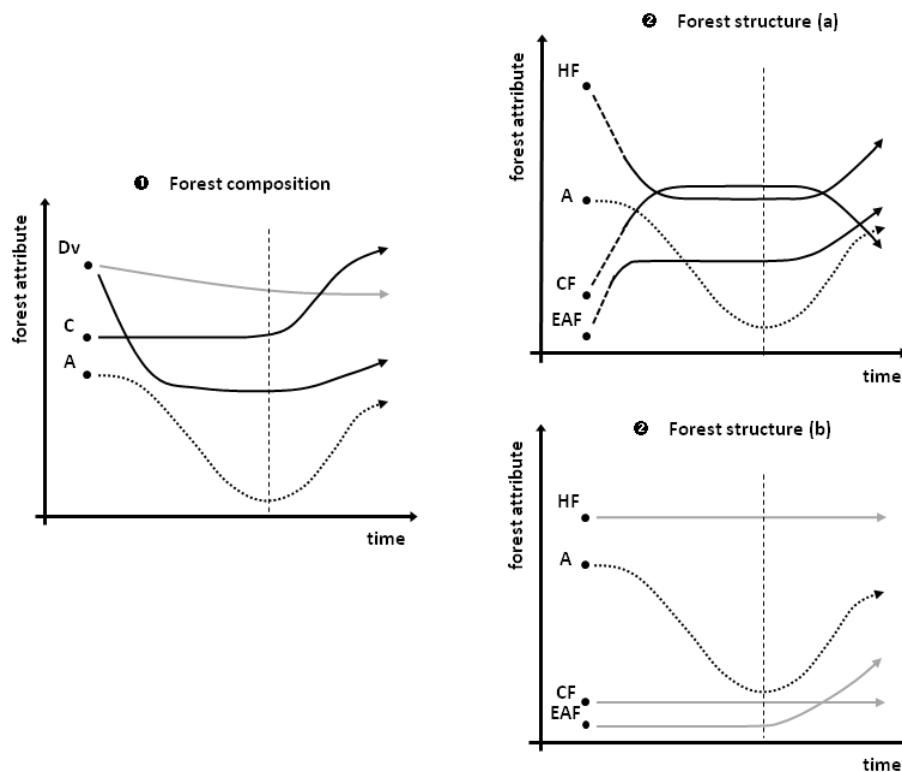
2.3 Forest transition trajectories of these state variables

Forest transition thus comes along with important changes in forest composition and structure. Forest composition in tree species strongly changes through favouring specific silvicultural systems, either in the depletion (e.g. coppices of sessile oak) or the expansion (e.g. plantations of coniferous species) phases. Tree species diversity is also likely to decrease, as a general pattern in transition from primary to secondary forests, despite the issue is of much more concern in the tropics (Chokkalingam and De Jong, 2001). An essay at idealizing theoretical trajectories for state variables describing forest composition (proportion of coniferous forests and tree species diversity) and structure (high forests, coppice forests, and even-aged forests) is provided in **Figure 4**.

2.4 Returning forests on abandoned agricultural lands: significant, but unknown

For 100 to 150 years in developed countries, agriculture intensification and rural exodus have caused physical land abandonment in marginal agricultural areas (Mather and Needle, 1998 for the theory, McDonald et al., 2000 in Europe, Brown et al., 2005 in the USA). Land abandonment in Europe primarily concerns Scandinavia, North-western Spain and Portugal, the Pyrénées, the Massif Central (France, see illustration in **Figure 5**), the Appenines (Italy), the Alps and the Carpathian mountain (Keenleyside and Tucker, 2010). Accurate pan-European statistics of land abandonment remain uneasy to draw (Keenleyside and Tucker, 2010). The annual rate of decrease in the agricultural area would reach e.g. 0.2% in France, and 0.8% in Spain. In the Eastern USA, it would range between 0.1 to 0.4% since 1950 (Brown et al., 2005). This abandonment is a primary cause of spontaneous vegetation dynamics able to reach a forest state (Cramer et al., 2008), and thus to significantly contribute to forest expansion. The latter is considered to be an important driver of the +17 Mha increase in the European forest area over 1990-2010, despite statistics for the European forest do not allow separate between afforestation and natural forest expansion in forest development (MCPFE, 2011, Fig. 42). In France, areas afforested naturally would range between 2.5 and 3.3 Mha between 1945 and 2010, *i.e.* much more than the forest expansion resulting from afforestation programs (between 1.2 and 2.0 Mha, Dodane, 2010). These figures are consistent with the suggested estimate of >50000 ha/yr of natural afforestation over the recent years (Denardou et al., 2017).

Figure 4. Temporal dynamics of state variables describing forest composition and structure during the forest transition. Dotted lines: the dynamics of forest area (A) is represented as a temporal reference. Black lines correspond to forest areas where both deforestation/exploitation of forests and natural/plantation afforestation may play a role in the dynamics of forest area (see Figure 1). Grey lines correspond to a theoretical forest transition where only deforestation (need for area) plays a role in the dynamics of forest area, the maintained forest area remaining untouched. Vertical positions remain arbitrary.



① Forest composition described by two state variables including the proportion of coniferous species occupying the forest area (C) and the diversity in tree species (Dv). In the temperate and tropical forest zones, the need to secure timber resources lead to implement afforestation programs and develop intensive forestry that will both contribute to increase A and C (see section 2.1). This evolution does not apply in the boreal zone where coniferous species prevail. Following human occupation and exploitation of forests, Dv should decrease and stabilize early in the forest transition process. The introduction of non-native tree species for afforestation, as well as natural afforestation following agricultural land abandonment should contribute to increase in Dv over the area, though at a much lower level than in the primary forests. In the deforestation-driven forest transition (light grey), Dv actually decreases, though at a much slower rate, due to variations in the distribution of species and habitats (Rosenzweig, 1995).

② Forest structure described by three state variables including the proportion of high forests (HF), coppice forests (CF), and even-aged forests (EAF) in the forest area. **(a)** Following early human occupation and exploitation of forests, high forests should be altered by initial removal of timber wood and evolve toward fast-regenerating coppice forest systems, leading to an early increase in CF and equivalent decrease in HF in the forest area, that should then stabilize before the end of the forest area reduction phase. Along with coppice extension and exploitation of forests, initially low EAF, not common in primary forests, should also increase and stabilize. In the forest expansion phase, active afforestation and conversion of coppice forests into high forests should reverse the trends in HF and CF, as well as contributing to a newer progress of EAF over the forest area. **(b)** Theoretical forest transition only driven by deforestation. Non deforested areas remained unmodified, with high forest as an exclusive and permanent forest structure. Initially low EAF will remain unchanged, unless active afforestation contributes to forest expansion and favours even-aged plantations.

Figure 5. Natural afforestation on marginal agricultural lands. Constraints of the physical environment influence the location of forest regrowth. In this marginal agricultural area, cereal crops remain cultivated in flat lands while forest is extending on peripheral slopes.



Photograph taken at *Causse Méjan* plateau (between 800 and 1200 m asl) in the *Cévennes* region, Lozère (68) NUTS-3 unit of the EU administrative classification. Credit: Jean-Daniel Bontemps, 2010.

Especially since they extend on physically abandoned lands, these naturally returning forests remain poorly described. They further hardly fit inventory classification categories of national forest inventory (NFI) programs or inventory thresholds (census diameter of a few centimetres, or measurable canopy cover rate), and have drawn restricted attention from the forest and ecology research communities to date. For instance, 1.2 million hectares of forest out of 17 million hectares remain of undocumented composition in France. Their exact contribution to shifts in forest composition or structure therefore remains largely unknown, despite it may lead to substantial inflection in the afore derived forest trajectories. In absence of historical analogues, the future dynamics of these forests, developing on pasture or agricultural lands, is highly uncertain (Schnitzler, 2014). Unexpected pathways in vegetation regeneration and succession, highly variable temporal dynamics in forest development, and original combinations of species may be observed (Proença et al., 2012; Schnitzler et al., 2014). At least in the temperate and Mediterranean areas, early-successional broadleaved species may form significant components of such forests (Foster et al., 1998), and may lessen

or thwart increase in the proportion of coniferous species resulting from active afforestation programs (**Figure 2**). Substantial research efforts remain needed to document these new forests and their dynamics, and assess their originality in a context where they are also envisioned as a support to new biomass extraction (<https://www.bbi-europe.eu/projects/pdf/BeonNAT>).

3. A quick glance at the atmosphere above forests: global environmental changes as an additional impact of forest transition drivers onto forest vitality

Previous sections explored direct changes in forest growing stock, composition or structure over the course of a forest transition. In a broader perspective, the energetic transition based on fossil energy that has accompanied the economic development in Northern countries has also strongly influenced the terrestrial and atmospheric environment of forests, through modifications known as global change (Vitousek et al., 1997). Human-induced net emissions of CO₂, shown to have started thousands of years ago with ongoing agricultural emergence, also find root in forest deforestation (Ruddiman and Ellis, 2009). Despite recurrent and increasing concern for forest vitality with ongoing climatic disturbances (Cornwall, 2016), global change has, to a large extent, benefited to forest ecosystems' productivity over the past centuries and more recent decades.

Modifications of the forest environment include the increase of atmospheric CO₂ since the mid 19th century (Machta et al., 1972; IPCC, 2013), the emission of nitrous oxides from industrial or transport sources and from agricultural areas with intensive nitrogen fertilizer use, leading to spatially variable sulfuric and nitrogen deposition onto terrestrial ecosystems (Holland et al., 2005; Dentener et al., 2006; Fagerli and Aas, 2008) with a strong increase after the second World War (Preunkert et al., 2003; Hastings et al., 2009), and climate warming that has turned obvious in the 1980s (Jones et al., 1982; Jones and Moberg, 2003). All such factors are prone to affect forest development: (i) CO₂ is the carbon source of photosynthesis, (ii) nitrogen deposition forms a supplementary source of nitrogen for forest ecosystems, often located on soils poorly suited to agriculture and actually nitrogen-limited (Tamm, 2011; Quinn Thomas et al., 2010) with however possible adverse effects in acid contexts (Aber et al., 1998; MacDonald et al., 2002), and (iii) temperature elevation increases the length of the growing season (Fabian and Menzel, 1999) and metabolic rates (Gillooly et al., 2001), despite considerable variations between species and biomes (Way and Oren, 2010).

These environment-driven impacts on forests have been demonstrated. Early acknowledgement of large-scale forest-environment interactions originates in the years 1980s, with the issue of acid rains (sulfur and nitrogen pollution), the threat they were assumed to pose on European and north-American forests, and symptoms known as forest dieback or decline (Krause et al., 1986; Skelly and Innes, 1994). It was however soon discovered that forests had experienced long-term growth increases (Hari and Arovaara, 1984; Becker et al., 1987; Kenk and Spiecker, 1988), simultaneously detected in the USA (Lamarche et al., 1984), in the more optimistic context of atmospheric CO₂ fertilisation of forests (Lovelock, 2000). In the following decades, further investigations have been conducted in Europe and all over the Northern hemisphere, using tree-rings as forest growth records (Spiecker et al., 1996 in Europe; Esper et al., 2002 over the boreal zone; Badeau et al., 1995; and Bontemps et al., 2012 in France). A salient aspect of these studies has been the careful control for the effect of non-environmental factors of forest development (tree species, silvicultural system, forest age, permanent site fertility conditions; Bontemps et al., 2009). Forest research has hence progressively reached consensus regarding the existence of environment-driven and overwhelmingly positive forest growth changes, of an average magnitude of +50% over the 20th century (Spiecker et al., 1996; Bontemps et al., 2009). More recent research on the causes of such productivity increases has pointed out the prominent role of fertilization by nitrogen deposition over the past century (with therefore a dual role of acidifier and fertilizer, depending on the forest context; MacGill et al., 1997; Cannell et al., 1998; Nelleman et al., 2001; Kahle et al., 2008; Quinn Thomas et al., 2010; Bontemps et al., 2011). Over the more recent decades the impact of temperature elevation onto forest growth has also been highlighted (Boisvenue and Running, 2006; Kahle et al., 2008; Charru et al., 2014), with early signs of adverse effects of climate warming onto forests in drier/warmer areas (Charru et al. 2017; Ols et al. 2020). The fertilizing effect of CO₂ has also been attested in short-term whole-ecosystem experiments (DeLucia et al., 1999; Norby et al., 2005), but has been under debate (Körner et al., 2005) and may act in synergy with nitrogen or water limitations (Huang et al., 2007).

It has therefore turned a reality that anthropogenic environmental changes resulting from industrial development affect forest growth and vitality worldwide. While their effect has been predominantly profitable to forest development to date (Kauppi et al., 1992; Spiecker et al., 1996, Boisvenue et al., 2006), the future may be less certain in a still warmer world (Ciais et al., 2005 and the pan-European heat wave of 2003) with potentially more severe droughts (IPCC, 2013). Thus, the direct drivers of the forest-area transition also form indirect drivers of

forest growth changes. And forest growth as a biological flux, not a state variable, subsequently forms an additional forest attribute impacted by countries' development. Since the latter has a global temporal significance, it however transcends local forest transition dynamics, as figured out in **Figure 1** and **Figure 4**.

4. The value of forest land in a land-use change perspective: forest attributes matter!

4.1 Economic valuation, ecosystem services and existence value of forests

Economic analyses of the forest transition have been produced that connect land-use change to land price or profitability (Angelsen, 2007; Barbier et al., 2010). Forest profitability depends on many socio-economic factors, and of intrinsic ecological attributes of forest stands. Hedonic pricing and optimization approaches have hence highlighted the role of the forest land area, land quality, growing stock, species composition, or forest structure in valuing forests and their profitability (Roos, 1996; Parks et al., 1998; Aronsson and Carlén, 2000; Pukkala et al., 2010). Ultimately, forest productivity and yield will depend on both land quality, composition, and the structure of forests (Pretzsch, 2009). Moreover, forests' economic value also depends on forest ecosystem processes that remains neglected to date, as not all functions ensured by forests are marketed (Pearce, 2001). In addition to timber and non-timber forest products (NTFPs), the socio-economic services provided by forests (tourism, recreation), the indirect values generated by watershed protection or carbon storage (MacDonald and McKenney, 2020), and option or existence values (*i.e.* acknowledgement of possible future uses and benefits, or will to conserve) will contribute to forest value (Pearce, 2001), and will again primarily depend on forest area, growing stock, structure, composition and species diversity. Shifting to forest ecosystem services as an extended framework for forest economics is therewith turning a matter of increasing attention (Kant, 2003). This inclusive appraisal has also been recently translated into forest transition theory, with *forest ecosystem-service transition curves* put forward as a means to assess effects of forest transition processes on ecosystem services and their trade-offs (Wilson et al., 2017). Last, and beyond a service-driven analysis of forests, acknowledgement of the existence value of forests has arisen for more than a century, with development of ideas in environmental ethics providing substantial support to the intrinsic value of forests, as whole living systems worth of respect, and as sources of aesthetic and metaphysical experience for the human mind (HD

Thoreau, RW Emerson, and A Leopold as early influential thinkers; Callicott, 2000). Aesthetic value has also been shown to depend on structural forest attributes (e.g. Gobster, 1999). These aspects suggest that the present multi-dimensional perspective on forest transition does not only have an interest in widening the concept *per se*, but also deserves greater recognition in a land-use change perspective on forests.

4.2 Cumulative and irreversible impacts of a forest transition on forests: the need for integrative approaches

First and obviously, there are couplings in the temporal dynamics of these different attributes over a forest transition, and forest areas or resources generally undergoing depletion will come along with reductions in forest area, growing stock and tree stature, and diversity in tree species and habitats, and also subsequent services and values attached to these attributes (4.1). Conversely, the expansion of forest resources following the forest transition will be accompanied with restoration of growing stock, forest structure and productivity, and a more frequent occurrence of mature high forests. Acknowledging the range of goods and services delivered by forests thus allows capture the cumulative consequences of such concomitant forest changes, and should call for warning against land-use policies that over-estimate the benefit of converting forest lands to other uses in countries experiencing deforestation (Pearce, 2001). High-yield agriculture combined to sparing of natural land has been suggested as a land-use specialization strategy beneficial to wildlife in certain contexts (Green et al., 2005), although fiercely discussed (Fischer et al., 2014).

Second, forest composition and species diversity that contribute to both direct uses of forests and option and existence values conversely reflect irreversible losses over a forest transition (**Figure 4**). These changes therefore place a particular challenge onto the current deforestation of primary forests (Chazdon, 2003), lessen the natural optimism attached to forest expansion (e.g. Xu, 2011 in China), and question the ways of implementing truly multi-purposed forestry practices (Gustafsson et al., 2012). The issue is especially obvious where forest expansion relies on monocultures of a restricted number of often non-native tree species or genera (Savill et al., 1997; section 2.1). Over the longer-term, plantation forests may nevertheless i) provide newer forest habitats and favour species diversity (Bremer and Farley, 2010), also by increasing spatial habitat connectivity (Brockerhoff et al., 2008), as well as ii) reduce pressure on primary forests, as intensive forest production systems whose products are traded on open markets (Sedjo, 1999; Brockerhoff et al., 2008; Meyfroidt et al., 2010). In the

US (Hall et al., 2002) and in Europe, differences in plant species composition between ancient forests (present at the forest minimum) and recent forests following forest expansion have however been found. They suggest that species dispersion processes may strongly limit the possibility of plant composition recovery (Hermy and Verheyen, 2007), and highlight the role of the landscape matrix in these dynamics (Chazdon, 2003). In addition, changes in soil properties following exploitation (Chazdon, 2003) or past agricultural activities dating back to the Roman period (Dupouey et al., 2002; Dambrine et al., 2007) may irreversibly prevent the restoration of initial floristic composition, suggesting the need for human assistance in some contexts. Accordingly, it is now largely recognized that long-term land-use history and legacies of human activity provide a legitimate framework for interpreting current ecosystem structure and functioning (Foster et al., 2003).

In summary, the forest attributes changing over a forest transition have a generic significance that exceeds, by far, associated changes in the forest area. This multi-dimensional view of such transition stresses the often cumulative and sometimes irreversible impacts on goods and services delivered by forest ecosystems. Accounting for these changes in forest economics now forms a matter of emerging attention, and should deserve more consideration in economic approaches of land-use change.

5. Land abandonment, climate change, and environmentalism: a prospect on the late development of forest transition curves with Europe as a benchmark

The speculative course of late forest transition trajectories as regards forest area, growing stock, and forest composition and structure are represented in **Figure 6** and are referred to in the following.

5.1 How will the V-shaped area curve extend?

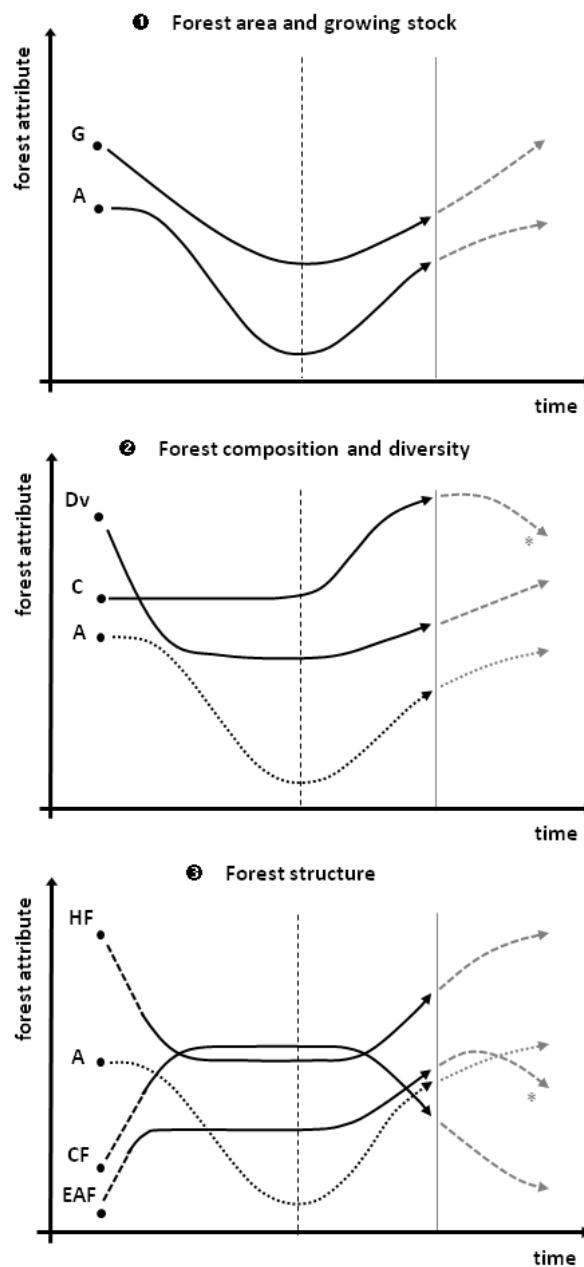
Forest transition has been experienced by many countries across the globe, and have been occurring from around two centuries ago up to recently (Meyfroidt and Lambin, 2011 and associated Fig 1). In Europe, forest area is logically expanding faster in late-transitioning countries than in the others, but is nevertheless increasing in all European countries, with a marked total progression of +17 Mha between 1990 and 2010, *i.e.* an average annual increase of 0.8% (MCPFE, 2011). Set in a global perspective, five European countries belong to the

top-10 countries with the highest relative net annual increase in forest cover over the past decades (FAO, 2010), together with the USA, India and China. Further, this increase has only slowly decreased over the last 20 years (FAO, 2010), suggesting that the European forest area, as early subjected to forest transition, is yet far from saturating.

As aforementioned, current forest reporting does not distinguish between afforestation and natural forest expansion as factors of forest development (MCPFE, 2011, Fig. 42). Future trends regarding the contribution of afforestation programs may also be hard to formulate, as they remain largely subjected to national forest strategies and the associated support funds allocated to these. Agricultural land abandonment, however, is a clear pan-European trend, and hence forms a much more certain contribution to future forest expansion. Also, the new European forest strategy intends to foster forest cover in view of promoting ecosystem service delivery (Köstinger, 2015)

Massive abandonment of marginal agricultural lands in Europe has so far been caused by technical agricultural progress driven by increase in labour opportunity cost, and intensification of agricultural production and ownership concentration fostered by the Common Agricultural Policy (Strijker, 2005). This trend has been detrimental to low-input agro-ecological systems and their biodiversity (Fonderflick et al., 2010), and is especially obvious in European mountain ranges since the mid 20th century (MacDonald et al., 2000). According to Strijker (2005), ongoing globalization of the agricultural trade, together with a decreased voluntarism of current agricultural policies, give no reason to anticipate any strong change in the abandonment of these marginal lands. Accordingly, Verburg et al. (2010) identified land abandonment as the prevailing future European land use change in a model-based exploration over 2000-2030. Keenleyside and Tucker (2010) suggest the figure of 3-4% as a reasonable estimate for physical land abandonment by 2030, corresponding to the impressive amount of 12.6 up to 16.8 Mha, on which forests may expand (a potential 6 to 8% of the present forest area; MCPFE 2011). It is thus likely that the European forest will keep on expanding in the next several decades at least. Such trend also implies a newer and delayed positive contribution to the total growing stock, with consequences for carbon sequestration and climate change mitigation (Rautiainen et al., 2017).

Figure 6. Prospective temporal dynamics of state variables describing forest area, growing stock, composition and structure in a later phase of the forest transition with European forest as a benchmark. Full black lines: trajectories observed during the forest transition (Figure 4). Dashed grey lines: theoretical extrapolation of these trajectories. Dotted black lines: the dynamics of forest area (A) is represented as a temporal reference in the different figures. Dotted vertical line: forest area minimum. Full vertical line: present time.



① Forest area (A) and total growing stock (G). A has still experienced recent increase, and it may keep on expand during several decades due to land abandonment in marginal agricultural areas. G has experienced the second strongest relative increase in the world, and benefits, though with a delay, from the expansion in A. It may further profit from a level of felling lower than that of natural increment. However, severe disturbances may slower this progression over the longer-term (not represented).

Figure 6 (caption continued)

② Forest composition described by two state variables including the proportion of coniferous species occupying the forest area (C) and the diversity in tree species (Dv). C, in areas where it has some relevance, may decrease following a will to return to more natural, disturbance-resistant, and biodiversity-oriented secondary forests, known in Europe as ‘forest conversion’. Forest conversion (*) may correspond to a late transitional event in the whole forest transition course. Dv should keep on increase, though at a slow rate, as some losses may be irreversible.

③ Forest structure described by three state variables including the proportion of high forests (HF), coppice forests (CF), and even-aged forests (EAF) in the forest area. HF/CF are assumed to keep on increasing/decreasing, respectively, following late CF conversion effort and the ongoing trend in land abandonment. The development of short-rotation coppice forestry to produce fuel wood may however set coppice forests to a minimum proportion. Following two distinct phases of increase (early exploitation of forests with associated harvesting methods, and late development of even-aged forestry following the forest transition), EAF may start decrease following return to more natural forests, defining a second aspect of forest conversion (*).

5.2 Growing stock: current dynamic, environmental hazards, and carbon issues

Growing stock accumulation currently shows no sign of saturation

With an average 156 m³/ha, Europe has the third largest regional growing stock in the world after South America, and Western/central Africa. Important increases in the growing stock of Europe’s forests have been acknowledged over the recent decades (FAO, 2010, MCPFE, 2011), amounting to +7.1 billion m³ in Western Europe over 1990-2010, and +8.6 billion m³ when including the Russian federation. This increase is the largest in the world, before North America (+8.0 billion m³) and Eastern Asia (+5.3 billion m³, FAO, 2010), *i.e.* regions that have also experienced a forest transition during the 20th century. On a relative scale, progress in the growing stock is considerable, as it represents an increase by 28% of the total growing stock over 1990-2010, behind Eastern Asia (+33.5%), and before North America (10.7%). Factors that contribute to increases in the growing stock include the past expansion of the forest area, and a net annual increment (NAI, gross increment minus natural losses) that remains above current felling (700 million cubic meters – or hm³ in the following – against 515 hm³ of annual felling over Western Europe, MCPFE, 2011). As aforementioned, forest area should progress in the next decades. In addition, NAI is favoured by the increasing growing stock (Bontemps et al., 2020), the rather young age of forests (73% of the forest area in Western Europe is lower than 80 years old, MCPFE, 2011), and enhancement of forest productivity by environmental changes (section 3). In a context where socio-economic factors related to ownership structure limit timber felling (see next section), there is again no early

indication of any saturation in the growing stock increase in a near future (see Bontemps et al. 2020 in France).

Disturbances: a moderate though rising threat on the growing stock

Depending on their importance, several drivers may however hinder this progression over the longer-term. Major forest disturbances – of which windstorms and fires – form first putative drivers of regular reduction in forest growing stock, as the exposure and vulnerability of forests to these hazards has increased (Seidl et al., 2011), and these may also turn more frequent/intense in a context of climatic change (Schelhaas et al., 2010; Usbeck et al., 2010), with increasing trust in this dependence (Cornwall, 2016). In an attempt to disentangle the respective contribution of climatic changes and forest changes on disturbance-related forest losses in Europe, Seidl et al. (2011) reported that these drivers were comparable in magnitude. Drought and heat wave risks are also acknowledged but will rather affect forest productivity and mortality in a less sudden way (Allen et al., 2010). Over the recent period, different storms have affected Europe's forests with storm damages covering >2.6 Mha. Significant timber losses include 165 hm³ in 1999 (*Lothar* and *Martin* storms in France, Germany, Switzerland and Scandinavia), 75 hm³ in 2005 (*Gudrun* storm in Sweden), and 50 hm³ in 2009-2010 (*Klaus* and *Xynthia* storms in France and Germany, MCPFE, 2011), all four events accounting for 0.9% of the growing stock of Western Europe within a ten years time. Fires have affected 1.4 Mha in Europe (0.3 Mha in Western Europe, MCPFE, 2011), *i.e.* 0.1% of the forested area, with however a more frequent occurrence in the Mediterranean and continental areas.

Forest exposure to windstorm and fire hazards is mainly related to forest area and to the total growing stock, all two attributes that have increased over the past decades. Factors of forest vulnerability also show similarities for these two hazards. For windstorm hazards, forest vulnerability will increase with greater growing stock per hectare and tree height, and is much higher on wet or unfrozen soils and in coniferous stands, in particular for Norway spruce (Schelhaas et al., 2010; Usbeck et al., 2010; Valinger and Fridman, 2011). Vulnerability to fire hazards increases with the proportion of coniferous species due to resin presence in tree stems, the growing stock per hectare, and topographic attributes (González et al., 2006; Schelhaas et al., 2010). Growing stock is also involved in the susceptibility of forests to drought hazards by increasing water consumption, and thus in the subsequent forest declines that cause depreciations or reductions in forest productivity (Ciais et al., 2005). Noteworthy, a

forest is thus progressively turning more vulnerable to disturbances, following increases in its area and growing stock, and in the proportion of conifer plantations, that form alleged features of the forest expansion phase after the forest transition (**Figure 4**). Climatic change may add its own contribution. If so, and depending on the magnitude and frequency of disturbance-related timber losses, growing-stock may be viewed as a self-regulating attribute, suggesting future slowing in its progression.

C sequestration vs energy substitution, an uncertain balance

Within a climate policy framework, a second driver of future growing stock evolution may stem from possible active carbon sequestration into forests (Kyoto protocol framework), despite there exists a recurrently debated potential conflict with management for energy (fuelwood) substitution and material valuation (timber wood) to save CO₂ emissions (Kirschbaum et al., 2003; Marland and Schlamadinger, 1997; McKechnie et al. 2011; Vanhala et al. 2013). Managing for dense or continuous cover forests indeed appears as an intangible means to sequester carbon into forests. Mixed strategies may also prove adequate depending on the integration scale from stand to forest sector (Vallet, 2005; Böttcher et al., 2008; Seidl et al., 2007; Garcia-Quijano et al., 2008). Today's perspective on the future balance between these strategies provides no easy assumption as regards evolutions of the growing stock. However, it may be noted that the future of Kyoto protocol, and the place of carbon sequestration in forests, faces substantial uncertainty and debate following closure of the first commitment period in 2012 (Plantinga and Richards, 2008 for the forest sector). By contrast, the valuation of energy wood as part of the future 'energy mix' may turn a more robust policy baseline in the EU, in a context where it ranks first as an energy importer and energy prices increase (EU, 2012). In the latter case, part of the strategy may also rely on highly-productive short-rotation coppices (e.g. of *Populus* species), possibly set on former agricultural lands (Kauter et al., 2003). Also, the more recent European strategy for bioeconomy (EU, 2015) intends to foster the use of 'green resources', including industrial and timber wood use for material substitution, with potential consequences on the European growing stock, though with large variations anticipated across the continent (Levers et al., 2014).

5.3 Forest composition and structure: forest conversion toward more resilient and natural forests?

The criticism of even-aged forestry

European forests are the legacy of centuries of human activity. While only 4% of forests are classified as undisturbed by man (MCPFE, 2011), even-aged forests cover 73% of the forest area. Coniferous forests extend to 50% of this area and are predominating in Northern and Central Europe. Issues in even-aged forestry have been identified that include the reduction in tree species diversity, and in forest-associated biodiversity (sections 2 and 4), the consequences of clearcuts on soil erosion and habitat fragmentation, the non-site adaptation of some introduced tree species, and the greater sensitivity of coniferous monocultures to storm, drought (Ols et al., 2020) and fire hazards, and to air pollution (section 5.2, Spiecker, 2003). Growing concern for a more sustainable management of forests (*Forest Principles* of the Rio conference, 1992, MCPFE conferences) and the societal demand for more natural and recreational forests have therefore promoted ideas for a *conversion* of Europe's forests (Spiecker, 2003; Dedrick et al., 2007; Kint et al., 2006), with a growing literature on the issue.

Features of current forest conversion policies

Conversion is multi-faceted and includes options related to both forest composition and structure. Managing stands for lower densities in order to reducing the growing stock (d'Amato et al., 2013) has also been advocated as a means to better resist environmental hazards, and enlisted as a dimension of the forest conversion (Spiecker, 2003). Forest composition may be modified by promoting broadleaved species and their admixture in conifer stands, to both favour stand resistance to hazards (Jactel and Brockerhoff, 2005; Knocke et al., 2008) and plant and animal diversity (Mielikaïnen and Hynynen, 2003). Building upon the appraisal that coniferous species have been planted far beyond their natural range over the continent, such composition shift may be fulfilled through simple promotion of natural regeneration of broadleaved, as observed at many places in Northern (Felton et al., 2010), Western (Kint et al., 2006; Harmer and Morgan, 2009) and Central Europe (Zerbe, 2002). Forest structure, in turn, is prone to shift from even-aged to irregular in age and size, with a view to approaching a more natural forest structure, to reducing habitat fragmentation and soil erosion ('continuous cover forestry'), and susceptibility to windthrow (Buongiorno,

2001; Mason, 2002). Continuous-cover forestry also favours carbon sequestration in forests (Seidl et al., 2008). Mixed conversion strategies including structural and compositional aspects are also considered (Hanewinkel, 2001).

Toward initiating a full forest transition in structural and compositional forest attributes?

After decades of promoting conifer plantations as a privileged forest production system, it may thus happen in the future that the proportion of such species be reduced, in forest areas where broadleaved species show ability to grow. While high forest structure should persist, it may also shift from even-aged to more irregular structures. When shifts in both attributes are crossed, the occurrence of uneven-aged mixed forests may logically increase in the forest resource, hereby moving closer to the structure of primary forests, yet of lower growing stock through active forest management. Hence, the term ‘forest transition’ would start to more largely apply to forest compositional and structural attributes, though strongly delayed in time with respect to forest area and other attributes (**Figure 6**).

These changes remain somewhat conjectural to date, as there is little evidence in favour of forest conversion on a pan-European scale. Among difficulties for a wide implementation, conversion implies costs and lower incomes when shifting from even-aged to irregular forest structure (Hanewinkel, 2001; Knoke and Plusczyk, 2001). It may also encounter critical limitations related to forest ownership structure (Van Herzele and van Gossum, 2009), in a context where private ownership exceeds 50% of the European forest area (102 Mha, MCPFE, 2011), with an increasing number of new forest owners not economically depending on their forests, and forest estates much smaller in size than public ownership (Van Herzele and Van Gossum, 2009; Wiersum et al., 2005). Last, there exists no legally-binding agreement – or European forest policy – that may support such forest transitions beyond the MCPFE conference resolutions (Specker, 2003), in a conflicting EU context on sovereignty vs subsidiarity and forest productivism vs protection issues (Edwards and Kleinschmit, 2013). Efficiency of the new European forest strategy in coordinating forest related policies has also received substantial criticism (Aggestam and Püchl, 2018). Regional voluntary programs are already ongoing (e.g. in Baden-Wurtemberg in Germany, Hanewinkel, 2001; in Scotland and Wales in the UK, Mason, 2002; in Sweden, Felton et al., 2010) that may serve as catalysts for newer forest management practices.

5.4 Returning forests and European 'wilderness': the ultimate step in forest transition?

Returning forests on physically abandoned farmlands (sections 2.4 and 5.1) are a significant contribution to expansion of natural forests in Europe. Their free development may be comforted by resurging concern and strive for a European 'wilderness' (defined by the IUCN as '*a large area of unmodified or slightly modified land [...] retaining its natural character and influence [...] which is protected and managed so as to preserve its natural condition*'). This request has been materialised in a recent resolution of the European Parliament ('Wilderness in Europe', February 3, 2009), advocating for a European wilderness policy, and inviting member states to develop large areas of wilderness, in a view that "*future generations can take enjoyment and benefits from the protected wilderness areas in Europe*" (Gyula Hegyi, member of parliament, cited in Barthod, 2010). Wilderness policies have been put forward as an opportunity for massively abandoned farmlands, whose social usefulness is questioned (Barthod, 2010). To some authors, such areas should even be totally withdrawn from any human intervention (so-called 'feral' nature, Schnitzler, 2014), to favour wildlife dynamics, and to foster paradigm change in nature 'conservation'. This extreme view on returning forests is however debated (Proença et al., 2012), and it may bring additional difficulties related to land ownership, land planning, fire risk, wildlife-population conflicts (Navarro and Pereira, 2012), loss of cultural legacy in inherited landscapes, or of floristic diversity (Höchtl et al., 2005; Fonderflick et al., 2010). Even without any further implementation of a European policy framework, returning forests on abandoned agricultural lands may define a more radical pathway to naturalness than the 'conversion' of current plantation forests towards more natural forest ecosystems. In this sense, they would contribute to the full completion of a 'forest transition' in some areas.

Conclusions

- The forest(-area) transition theory (Mather, 1992) has arisen from a geographer's perspective onto forests, and has generated a profuse literature over the past twenty years, in the context of tropical deforestation. By contrast, restricted attention has been paid to forest attributes other than forest area, with a discrete exception as regards forest growing stock.
- From a forestry perspective, several forest attributes are shown to undergo generic transient changes, concomitant to the forest transition, which include: 1) the growing stock that undergoes a parallel V-shaped trajectory, 2) the composition and diversity of forests with an increase in the proportion of conifers in temperate and tropical areas, and a loss in species diversity that may take long to recover, and 3) the structure of forest stands, with a further development of even-aged forestry, and progressive abandonment of coppice systems in favour of high forests. These aspects turn obvious as soon as forest cover is also seen as a manifestation of the tree populations that compose it.
- Noteworthy, returning forests on physically abandoned farmlands significantly contribute to forest expansion in developed countries. These forests remain largely ignored to date, and their influence to the dynamics of former attributes is unknown. Research efforts are needed to describe naturally returning forests and their possible dynamics.
- A later – and so far speculative – trend may arise in the end of forest transition dynamics in developed countries. It consists in promoting more natural forests in terms of composition and structure, and assumes a more gradual management. Such changes, known in Europe as 'forest conversion', are viewed as a means to develop more disturbance-resistant, biodiversity-beneficial and environment-oriented forests, with increasing growing stock, climatic change and growingly urban populations as contextual background. They may form a sub-transition *per se* in the whole course of forest transition.

- Forests returning naturally on abandoned farmlands may provide ultimate significance to the forest transition concept in some areas. In Europe, they may benefit from growing concern for fostering 'wilderness', and associated policies in the future. Such changes are called to play an increasing role in shaping tomorrow's forests, because of rapid changes in ecological and societal conditions.
- Acknowledging the multidimensionality of the forest transitions actually has not only a cognitive interest. It also highlights the many values and services provided by forest ecosystems in their connexion to the biologic, abiotic and human environment, beyond wood resource aspects. As such, it needs more attention in the socio-economic analyses of forest-related land-use change.

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