 doi:10.20944/preprints202207.0392.v2

Article

Adaptive Forest Management under Climate Change: Some Adaption Criteria for Practical Purposes

D'Aprile, F.[a] and Gentilucci, M. [b]

[a] Dept. of Economics and Management of the University of Florence, Via delle Pandette, 32 - 50127 Firenze (FI), Italy (fdaforests@gmail.com)
[b] University of Camerino, School of Science and Technology, 62032 Camerino, Italy

Abstract: The compelling effects of climate change on forests may have been underestimated in the past few decades in practical forestry. Although the first attempts to draw attention to this complex problem appeared almost half a century ago, the debate has been conceptual rather than experimental and applicative. At first glance, the concerns were mainly related to sustainable forest management (SFM) issues, which obviously needed attention. Over time, the effects of climate change have been mainly considered in the context of the SFM; they started from various and somewhat different scales and goals. Over time, more research and awareness of the importance of SFM under the pressure of climate change have led to the development of a clearer field that can be defined as 'adaptive forest management' - to climate change. One of the characteristics of this discipline is to be featured by the absence of univocal methods and / or objectives to be pursued but to identify, verify, and adapt methods to the various climatic and forest types and conditions found in the field. Therefore, this work shows some phases of forest planning and management concepts and criteria over time and recalls some innovative and / or adaptive methods related to the approach to forest planning and management under climate change.

Keywords: forest management methods; adaptive forest management; climate change; ecological norm

1. Introduction

Changing climate conditions are known to influence forest tree growth response and the CO_2 cycle. Dendroclimatological research has shown that the climate signal, species composition, and growth trends have modified in different types of forest ecosystems during the last century. In forest management, local variability of climate trends is of primary importance as plants are influenced in their sites. Moreover, the interactions between climate variables (e.g.: temperature and rainfall) act as a whole climatic and microclimatic environment on the tree and therefore forest management and the relative interventions need to be designed, calibrated, and planned on the basis of the influence of climate on forest tree growth at the local level or, even better, a the forest unit level. Under current and demonstrated changes in climate variability at the geographic, regional, and local levels, tree growth shows variability and trends that can be non-stationary during time even at relatively short distance between sites. In forest planning and management, yield tables, site quality indices, age class, rate of growth, and spatial distribution are some of the most used tools and parameters. Efforts have been made to develop forest growth and yield models to forecast tree growth under current and future climatic changing conditions [1, 2, 3]. However, these methods do not implement the variability in trends of climate variables over time, although climate is the main driver in trends of forest and tree growth [4]. The risk that forest management under climate change conditions amplifies their negative effects is not negligible. For example, changed climate conditions can impact on temperature and/or precipitation thresholds critical to forest tree growth and/or on the resistance or tolerance to adverse abiotic or biotic conditions. Forest biomass, resilience, and CO_2 storage are susceptible to damage unless forest planning and management implement the relationships between climate variability and trends of tree growth. However, a positive aspect of climate change is that, in some respects, periods of favorable climate conditions can allow harvesting of higher amount of wood mass and storing more CO_2 than traditional management methods. The average length of either favorable or adverse periods often occurs within the average period of

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2022 doi:10.20944/preprints202207.0392.v2

validity of forest management plans (10 to 20 years). Under the spatial variability of climate change, adapting forest management to varied climate conditions is a priority that cannot be postponed [5]. Here, various conceptual approaches for implementing climate variability in forest management under climate change are shown in the view of continuative research development of strategies for adaptive forest management.

2. Adapting forest management to climate variability

Expected changes in temperate forest regional distribution, in suitability forest growth and resilience, in shifts of species diversity, and in regions that can potentially work as refuges for species migration have been introduced. Using climate variability and trends to predict or develop scenarios in the medium or long term for adaptive forest planning and management implements different aspects necessary to decision making. For example, cultural points of view of the stakeholders, policy and management options relative to bioclimatic and socio-economic issues at the current time and in the future, and the accuracy and reliability of the processes used to develop and make decisions. Climate change is a fundamental component of many aspects of sustainable forest management [6]. Therefore, a framework comprehensive of these components should consider:

the organizational potentiality of State agencies, public administrations, regulations, and local stakeholders to implement forest management under climate change;

- implementing the climate-aware practices in planning and management at all scales by forest resources managers to achieve balanced forest adaption, conservation, and uses;
- continued efforts and funding to communicate and support scientific and technical knowledge and expertise to managers in all fields related to adaptive sustainable forest management;
- and a systematic, continuous assessment, revision, and updating of both the effects of climate change on forest resources and the results and progresses obtained by effective implementation of climate-aware practices in planning and management.

Climate variables normally highly influences forest viability, resilience, growth, distribution, and health. Changes in their variability and trends over time pose various pressures on forest vegetation and its responses. In a context of climate change variability, using climate variables as environmental predictors is a challenge for understanding how to adapt strategies in forest planning and management. Adapting forest management to climate variability involves different components (e.g., socio-economic and cultural issues, silvicultural management, ecosystem services, wood harvesting, biodiversity conservation, carbon dioxide storage, etc.) that work and interact at different levels. In this scenario, one the targets to be taken into account is fostering large-scale and long-term forest ecosystems conservation and restoration as an effective solution to store higher carbon pools in the long term (authors). However, this objective faces the objections that active management is requested to sustain the cost of this option and, in particular, the growing human population increases the demand of timber. In the other hand, long-term conservation of forest ecosystems and old-growth forests are needed for biodiversity conservation, assisted migration, high-level of carbon dioxide storage, climate impact mitigation, water depuration and supply, and a source of scientific knowledge as an indispensable and unique problem-solving tool. In recent years, however, climate change and higher mobilization of forests resources (wood) has caused some reduction in the capacity of storing carbon of the European forests [2].

Another aspect of adaptive forest management is the uncertainty about the projection into long-term climate scenarios. Adaptive forest management is effective under slight or moderate climate change alterations, including carbon dioxide storage. At a wider scale, tree species can be managed in order to mitigate the impacts of large climate changes and increase the carbon pool, provided that the introduced species, ecotypes, varieties, or provenances are more resilient, ecologically productive, or more stress-tolerant than the local population(s). However, in this respect the suitability of different species and/or provenances of the same species requires further research and long-term monitoring to sort out the effectiveness of the decisions made. In addition, the limited

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2022 doi:10.20944/preprints202207.0392.v2

time available before more severe impacts of climate change take place [7] compels researchers, administrations, stakeholders, and governments to search for practical and efficacious solutions in the short- and medium- terms. This implies that forest management solutions and practices that work on the long-term appear veiled by a certain level of uncertainty even if they are effective and reliable in scientific and technical terms.

Another climate-change-related problem is the increasing demand of the water supply or storage provided by forests, at least in the regions where warming of temperature and/or reduction in rainfall occur. In countries or regions where intense or frequent wood harvesting is normally practiced, lowering stand density can help to complete the turn or the rotation period but at the expenses of the carbon pool as well as shortening the rotation period can diminish the carbon storage of both the biomass and the soil. The apparent benefit is only in terms of faster availability of timber.

The complexity of the climate change-forest management context increases further due to socio-economic issues, which are influenced by cultural issues. This underlines the expectations and demands that public and private forest ecosystem owners are called upon to consider, implement or satisfy through adaptation measures. For example, the public awareness of the extent of forest ecosystem services such as supply of drinking water, biodiversity conservation, defense from natural hazards, carbon sequestration, oxygen production, and air cleaning markedly converge in decisions relative to forest management.

Thus, whatever form of adaption forest management is chosen, its application will result in an increase or decrease of the carbon pool. The silvicultural strategies adopted under the various patterns and extent of climate changes are important to ensure permanent and ecologically balanced forest cover, which can find case by case the adaption strategy suitable to guarantee the supply of forests ecosystem services and timber production in the very long term. In this view, products deriving from long- and very long-term managed forests are likely to satisfactorily replace materials that absorb high levels of energy to produce.

3. Forest management and climate variability

Forest productivity is influenced by climate change as observed in many areas of the world [8-10]. Wood production is highly depending on photosynthesis and respiration of trees and directly relates to carbon storage and sink [11-14]. Thus, changes in climate patterns modifies forest productivity and its CO2 storage functions. Adaption forest management is assumed to develop strategies and planning tools to maintain or improve forest resilience with respect to climate change and its extreme events, and possibly enhance the role as carbon sink [15-17]. Under changing climate conditions, this requires that forest planning and management understand and implement these new conditions to avoid the risk to be ineffective.

4. The landscape planning level

Planning at the landscape level, which is supposed to include landscape ecology, is8 expected to detect and implement different bio-ecological, geological, physical, social, and economic characteristics, properties and phenomena that extend over the forest population or unit level; and the landscape level can highlight interactions of which traits or effects occur at the regional or wider scale. This aspect is relevant as the impacts/effects of climate change are multi-sectorial. However, the boundaries of the landscape level normally are limited in order to inferring processes and responses that occur at the forest unit level, which is of first concern for adaptive forest management under the constraints of climate change. In forestry, the landscape level is more effective in monitoring shifts of species and populations, large-scale climatic-environmental changes and their effects.

4.1. Development of sustainability planning and management models

Technical, scientific, social, economic, and cultural changes and progresses have reflected on forest planning methods and objectives during time. Forestry research on climate change tends to target mainly the assessment of impacts and the vulnerability of forests [18] rather than exploring how to manage forests by implementing climate change variability and trends. In recent years,

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2022 doi:10.20944/preprints202207.0392.v2

progresses were made in identifying ways to use climate variability parameters in forest planning and management

4.2. The forest unit level planning

Planning methods based on the environmental variability of the forest and the dynamics of tree species populations rely mainly on the demoecological and even synecological development of tree populations over time and space. Theoretically, they should better detect the complexity of planning mixed and uneven-aged forests; and, monitoring of plant population dynamics is a necessary tool for forest management. The local forest environment (i.e.: site, soil, micro- and mesoclimate, geology, uses, etc.) and growth relationships between species and their dynamics require to be identified relation to the environmental variability, which can include some biotic factors such as the effects of grazing on forest regeneration, parasites, stress indicators, or else, at the forest unit level. These methods (i.e., the 'The Ecological Normality [19a,b], 'Close to nature forestry'[20], 'Systemic sylviculture'[21]) are more effective when gradients in environmental variability are clearly identified or their variability is relatively abrupt, and multifunctionality of uses such as ecosystem services (including carbon storage), nature restoration, biodiversity conservation, and relatively continuative long-term timber production is demanded. Obviously, timber production is an option but not necessarily a tool.

The ecological parameters that characterize these methods vary on a case-by-case basis. They implement the dynamics of population parameters such as mortality, regeneration, intra and interspecific competition, self-thinning ratio, social position, health conditions, and their relationships with biotic and abiotic factors (e.g. plant associations, humus, soil, site, ETP / ETR, etc.). Their variability over time and space constitutes the ground on which to develop planning and management. This type of approach is also suitable for implementing or modelling the effects of climate change in forest planning and management [22]. In the practice, the high complexity of the parameters to be identified, measured, and analysed can by bypassed by using environmental and forest indicators. However, the analytical phase of these planning methods tends to require high initial costs of the investment and therefore the services and products supplied by the forest need to produce multi-source returns relatively constant over the long term.

5. Linear programming

From the simple forest planning methods merely based on spatial criteria to the models based on yield tables, productivity, or mean top height, *linear programming* shows a more advanced approach to forest planning due to the possibility of implementing different variables (i.e.: slope, soils properties, crown transparency, thinning intensity, etc.) in a dynamic and interactive way. Some advantages produced by this tool are good and sometime excellent ability to identify and predict variability in tree growth relation to the variation of one or more silvicultural and/or abiotic parameters, especially in pure and mono-aged stands. However, linear programming becomes difficult or less accurate when dealing with the complexity of the mechanisms and interactions between species at the forest level and/or their relationships with abiotic and biotic factors.

For example, multiple linear regression was applied to a 23 years-old black walnut (*Juglans nigra* L.) 28 hectares plantation in Australia. Results have shown that the mean top height used as a site quality indicator was highly associated ($R^2 = 0.91$, p-value $1.208e^{-008}$) with time of leaf coloration and fall, soil texture class at 100 cm depth, mottling at 50 cm depth, weed control, and presence of gravel along the soil profile [23]. Tree growth was very variable, ranging from highly productive to very poor with respect to the standards of black walnut plantations in the United States.

This approach to forest or plantation planning is flexible and open to implement a variety of factors influencing growth or other parameters. However, it shows some limits in implementing the dynamics of plant populations, complex interactions between abiotic and/or biotic factors. Using variability in trends climate variables to identify independent variables to model and predict growth responses through space and/or time is a challenge that can reveal unexpected results.

6. 'Close-to-Nature' Forestry

The term "Close to nature" (CTN) refers to various terms such as -forestry, -forest management, and -silviculture. CTN works with tree populations, their structures and natural processes, and sees the forest as a self-regulating ecosystem on which to base forest management. This approach develops forest management at the ecosystem or, at least, ecological level; multiple environmental and economic functions of the forest are considered. In particular, the purpose of forestry CTN is to achieve management objectives by providing the minimum human impact necessary to relatively accelerate natural forest processes. It may be noted that over time some distinctions have been discussed between "ecological" or "forest" approaches to management, which presume to distinguish between "productive" forest areas and "reserves" or "national parks". However, the meaning of the CTN forest management itself clearly explains the issue.

7. The 'Ecological Normality'

The 'Ecological Normality' is a concept in forest planning and, in general, applied ecology [24-29]. An attempt to integrate the advantages provided by both linear programming and the principles and criteria of 'close-to-nature' forestry was made by D'Aprile by elaborating the 'Ecological Norm' as a tool for forest planning in temperate forests [30, 31]. The use of ecosystem functions and production processes contributes considerably to the realization of this concept, unlike the management and cultivation modules that invest more and more energy and forces to modify complex biological, ecological, genetic and energetic systems [32]. Although the economic use of a forest ecosystem can operate by focusing now on one, now on the other economic aspect, the forest ecosystem is a functional unit in which all the components act and interact as much and as little as possible at the same time; excessive exploitation or pressure to use one or more functional forest processes is very likely to cause serious dysfunction or damage. For example, a framework of excessive timber harvesting can overwhelm the gross productivity of photosynthesis at the forest level, impact on the root systems absorption capacity, alter the production and possibly type of humus, and other processes, or the trophic-functional structures are degraded with regard to the biomass production rates and forest regeneration. If this happens, the resilience, functional stability, and resistance or tolerance to stress, including climate change effects, are seriously at risk because the ecosystem operates as a whole. Therefore, the more the processes, the characteristics, the ecological functions and the entropy of the forest are known and implemented in the management and use of this resource, the more the identification of ways, forms and techniques for a sustainable economic use or that respects the resilience limits of the forest is in balance with the ecosystem.

The term 'Ecological Norm' (EN) refers to forest management planning; the suffix 'ecological' prefigures the identification of a system of 'silvicultural normality' based on the main synecological characteristics of the forest, and where the forest auxometric and dendrometric characteristics derive from the demoecological and silvicultural analysis of the forest. The EN relies on that, while in the context of traditional forest management planning the unifying planning elements are frequently quantitative-productive models, in the EN the selective factor is the capacity to sustain the presence of forest structures and species composition that show a natural tendency to form stands in ecological balance with the local environment and its variability. In the EN, the forest is partitioned in 'Ecological Forest Units' (EFU) identified on the basis of the level of similarity of the main ecological characteristics of the forest units, case by case. In fact, the environmental homogeneity of the forest units favors the development of the forest towards similar structural and ecological patterns more in balance with the local abiotic environment. In economic terms, this entails greater guarantees of safety and validity of the forest management plan, which corresponds to lowering the investment risk in the long term. This is a relevant results in a sector where the risk factors are multiple, variable, and frequently outside the possibility of human control.

Thus, the EN shows a model of forest planning that results from the ecological structures locally developed by the forest whatever the uses of the past were, and the EFU is the main reference elements for forest planning and management. Site environmental similarity identifies the fundamental planning units as in relatively small areas such as those covered by forest management

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2022 doi:10.20944/preprints202207.0392.v2

plans, forest vegetation tends to develop ecological and structural homogeneity within similar environmental units. In other words, the EFU favors the development of ecologic forest structures more balanced with the local abiotic environment, hence the tendency to assume relatively homogeneous floristic and structural types; this requires monitoring the dynamics of forest processes between sites and forest stands within the EFUs.

In the EN, timber harvesting can be distributed among different tree species populations, where the quantity and type of the assortments removable are estimated on the basis of the dynamisms of the forest populations, which is previously analyzed by including also their variability over time and verifying the improvements - or worsening - of the ecological efficiency, stability, and resilience of the forest. For practical purposes, it is possible to transform the various abiotic and biotic factors into class values of forest and environmental indicators.

7.1. Criteria of the 'Ecological Forest Unit'

The development of the EFU results from the ecological-silvicultural analysis of the forest and precedes the elaboration of the EN, which varies with different cases. The classification of the EFU is carried out through a series of steps that constitute the procedural basis of the method.

The guiding criterion of the method is the synecological approach to forest analysis [33], which aims to produce a realistic estimate of the possible consequences of the different uses and impacts. This step is followed by the 'Analytical Planning Scheme' (APS), which establishes the basis for the development of the planning strategy. This 'scheme' is preparatory to the identification and elaboration of the EFU and the EN and emerges mainly from the results of the synecological analysis of the forest, which aims to identify the parameters of ecosystemic silviculture at the local level.

The synecological approach to forest analysis facilitates the understanding of which uses of the forest resource avoid or limit damage within the limits of ecological sustainability [34-37] and indicate how to improve forest ecological functions and structure, which often show various levels and types. The limits of ecological sustainability of uses are estimated in real cases based on the EN, and therefore may be more limiting or more flexible than those envisaged by traditional planning criteria. In EN, timber production is seen as one among the various services and goods produced by the forest [33, 38-40].

7.2. The Analytical Planning Scheme

The criteria expressed above are applied starting from the '*Analytical Planning Scheme*', which proceeds as follows:

a. forest characterization on a demoecological and phytosociological ground;
b. identification of sites environmentally similar based on both the abiotic factors (geology, exposure, slope, thermal inversion, soil depth, pH, drainage, etc.) and the biotic factors (forest structure, species composition, ecological indicators, etc.). This step takes into account the ecological interactions and the reciprocal influence exerted by both the biotic and abiotic components, such as type and modality of regeneration, humus quality, internal microclimate of the forest, periodicity in the availability of nutrients, etc. [41-44];
c. estimation of the development trends of the forest species composition and structure within the 'Ecological Forest Units';
d. comparison of the models identified through time within similar EFUs and through spatial variability between different EFUs;
e. selection of the EFUs with the more stable and ecologically efficient chronological series of structure development. These series show the models available within the forest or forested area to which refer planning and management. In other words, these sequences in each EFU are the real models of structure development developed locally, which represent the real dynamics of the forest ecosystem locally available that provides the models to follow.

This preliminary phase of planning is open to implement different techniques, technologies, and investigation methods that best adapt to different situations [45-47]. However, in practice, the set of ecological aspects and functions of the forest is difficult to identify and analyze. Therefore, the cognitive understanding of the forest focuses on the most important ecological aspects in light of the influence of the dominant ecological processes. For example, the growth and differentiation of the structure and composition of species are dominant processes in the case of former coppices, where variations in biomass distribution, population dynamics, regeneration, intra- and inter-specific selection, and ecological functions lead to significant changes in both abiotic and biotic conditions. [30, 48-54]. Given the importance of synecological and environmental factors, including climate change and variability, the characterization of the main phenotypes is another important step to achieve an understanding of the processes in place in relation to the characteristics of the site, environmental variability, previous silvicultural management and changes in the trends of climatic variables. In this context, it is also important to consider cases where tree morphological characteristics, growth rates, type and success of regeneration, and ability to cope with environmental stress show better than expected performance. In some cases, the synecological, dynamic and selective structural action of climbers also plays complex roles that need to be implemented in the study of the ecology of the forest [47, 55-57].

7.3. The models of the 'Ecological Norm'

The EN is identified by a set of characteristics and procedures and therefore does not depend on a rigid protocol that would limit the criteria on which the EN rests:

- The most ecologically stable, viable, and stress tolerant or resistant floristic-structural sequences are classified by the statistical analysis of the forest. For example, the distribution curves by age, diameter, and social position, the frequencies of the species by phytosociological class, the demo-ecological and phytosociological relationships, the regeneration indices, and the chronological series.
- The level of similarity of structure and specific composition of the stands within each EFU is compared to the respective EN model through various correlation and statistical techniques. The silvicultural management within each EFU shapes the forest towards the respective reference model of EN.

Once that the forest partitioning is defined in relation to the EFUs and the spatio-temporal series of forest structure and species composition are identified, it is possible to estimate the respective dendro-auxometric and ecological data such as basal area, mean top height, age class or diameter class, distribution of diameters, woody biomass, rates of growth, degree of cover of the canopy phytosociological associations, vegetation storeys, humus, mortality, regeneration indices, or else, which are used for both demo-ecological and dendro-auxometric purposes. Thus, the 'models' identified that result more functionally efficient, more stable, more viable or less altered show the EN as referring model(s). In fact, this approach aims to follow and support the natural spatial-temporal dynamics of the forest by minimizing possible alterations due to human interventions.

The most ecologically balanced structural development sequence is obtained by the analysis, comparison, and grouping of data through the use of statistical methodologies [58-61]. The statistic 'discretization' of the forest is one of the methods to process these sequences on a spatial basis; however, the statistical methodologies to apply can vary with real cases. For example, when sequences diverge from the reference model, such as in the transition from dense black locust coppices to mixed mesophilic oak forests with high specific diversity, the survey can be less detailed.

After the identification of the EU is completed, forest planning proceeds by correlating and comparing the sampling data to the parameters of the EN. This provides an estimate of the difference between the real variables with respect to the expected variables in quantitative terms, the level of ecological significance (local), the degree of alteration (similarity or dissimilarity) of the forest parcels with respect to the reference model (EN), and the type of possible and/or suggested interventions including the 'no silvicultural intervention' option. For example, an excess of basal area by age class and social position of a forest species in a given forest site in reference to the

 doi:10.20944/preprints202207.0392.v2

model of the EN could be harvested, provided that the economic provisions of the plan, which is multifunctional, support it. At the same time, the possibility of extracting this 'surplus' depends on the results of the local analytical framework. For example, it may result that this biomass is subject to rapid degradation with improvement of the humus and the soil water capacity, establishment of more demanding plant species, increase in the growth rate of the stands, faster intra- and/or inter-specific selection, and therefore higher carbon storage.

7.4. Potential pros and cons

This approach is suitable mainly for application on large forest surfaces such as parks, reserves, and public land. In fact:

- the progressive recovery of the forest to more balanced and ecosystemic forms of management does not manipulate but follows ecological processes that are analysed and modelled to identify the dynamics of the forest ecological structure and composition over time; this implies working through interdisciplinarity. Therefore, there are not assumptions or predetermined results on the validity – or less – of the *no-silvicultural intervention* option nor on the capacity of the forest to restore the most ecologically balanced structures, but only real and local data and models;
- The flexibility of the method is high;
- Improvements of the conservative, environmental, naturalistic, landscape, hydrogeological, scientific, and touristic functions, which are themselves multifunctional economic functions, are expected; they can produce return values higher than wood production only;
- The wood production of the forest is approached as an economic function among others, which means that it should not be pursued or rejected 'a priori' in any case. Where wood extraction takes place, silvicultural operations with negative economic balance can be reduced or even avoided, while the transition to organized silvicultural systems is gradual;
- In general, interventions tend to focus on small areas and apply technical and ecological qualitative criteria;
- The reduction of the harvested surface averages and the orientation towards cuts of higher unit economic value are favoured by the conversion to high forest, where the increase of the carbon dioxide storage capacity in the long term drives the type of intervention;
- the woody biomass increases and can further diversify, thus producing a higher range of products, higher elasticity and adaptability of the supply, which is an advantage with respect to fluctuations and changes in the markets, and more carbon storage;
- the reduction of the cut surfaces supports lower impact on the soil, on the hydrogeological structure and the landscape, and possibly increases the ratio between market prices and harvesting costs.

On the other hand, the method shows some difficulties, such as:

- the need for a consistent and extensive interdisciplinary work to develop the 'Ecological Norm';
- higher analytical, organizational, and administrative complexity;
- efficient coordination between management bodies and private properties;
- effective compliance between the plan's provisions, and timeliness of the management deeds;
- in some countries, the difficulty of organizing the use of private forests based on a broader and more complex model.

7.5. The 'Ecological Norm': Concluding remarks

The 'Ecological Norm' was initially developed as a methodology aiming to incorporate the criteria of 'forest management on an ecological basis' [62, 66, 67], which rests on ecological and demo-ecological parameters to estimate the possible sustainable uses of the forest as expressed by the characteristics and properties of the ecosystem, case by case.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2022 doi:10.20944/preprints202207.0392.v2

In the context of the use of natural resources, the optimization of the economic functions involves the reduction of the external energy supply, which includes the direct and indirect production costs. The sustainability of forest uses remains rests on a part of net primary productivity available to heterotrophic consumption, resilience, carrying capacity, and the natural developments of forest structures expressed in quantitative terms. It leads to detailed forest planning that fits within the cycles, functions, processes, and dynamisms of the forest ecosystem by placing silvicultural operations within the present 'ecological niches', where its modalities are defined by the ecological dominants of the forest ecosystem.

Although this method is mainly suitable for application in parks, reserves, large areas, and/or where multifunctional forest management is required, it can also be applied to forests in which, following the cessation of silviculture interventions or the reduction and/or change of forest uses, the processes of modification of the structure and species composition are active.

The risk of failure is little as the gradualness of application, the preliminary analysis and assessment, and the possibility of maintaining the previous use of forest units unchanged in the event that socio-economic and / or cultural factors require longer waiting times; all this makes the 'Ecological Norm' a flexible and progressively adaptable planning methodology.

8. Trends in climate variability and forest management

Climate variability and trends act on several functions and traits of forests and trees such as size-growth relationships, modifications of the mortality/natality ratio, tree growth and viability, stress tolerance, selection of genotypes, and susceptibility to disease and their spreading. All this reflects on the resilience and ecological productivity of the forests over space and time, and provides the ground on which to develop and practice adaptive forest planning and management, where carbon storage and its balance is a component of the ecosystem services.

Ordinary or traditional tools for forest planning and management such as yield tables, indices of fertility/productivity, or methods based only on quantitative estimates of growth distribution at the stand level are not designed to detect the variability in growth induced by climate changes and its trends in the short- and medium- term. However, this is very important in the practice of forest management planning. Therefore, implementing climate variability and trends in forest planning and management as ordinary parameters and tools is necessary, especially under the pressures induced by climate change on forest ecosystems.

8.1. Time as a key factor in climate change and tree growth

Forest research has shown that climate variability plays a relevant role in forest planning and management under climate change [4, 18, 69] as it influences the response(s) of forest and tree growth and the CO_2 cycle. Changing climate conditions can alter the temperature and/or precipitation thresholds critical to forest tree growth. Thus, forest planning and management need to implement the relationships between climate variability trends and the factors driving tree growth to mitigate the impacts of climate change on forest resilience, biomass, health, and CO_2 storage. However, local climate variability frequently shows alternation of peak and tough periods, including increasing trends. This raises the question whether periods of climate conditions favorable to growth can sustain harvesting higher amounts of wood mass and storing more CO_2 than traditional planning methods.

8.2. Non-stationary relationships between climate variability and tree growth

Locally, the similarity in the trend of climatic variables can differ markedly and irregularly over time (Fig. 1) and modify both the extension of the growing season and the months that influence the growth response of trees (Fig. 2).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2022 doi:10.20944/preprints202207.0392.v2

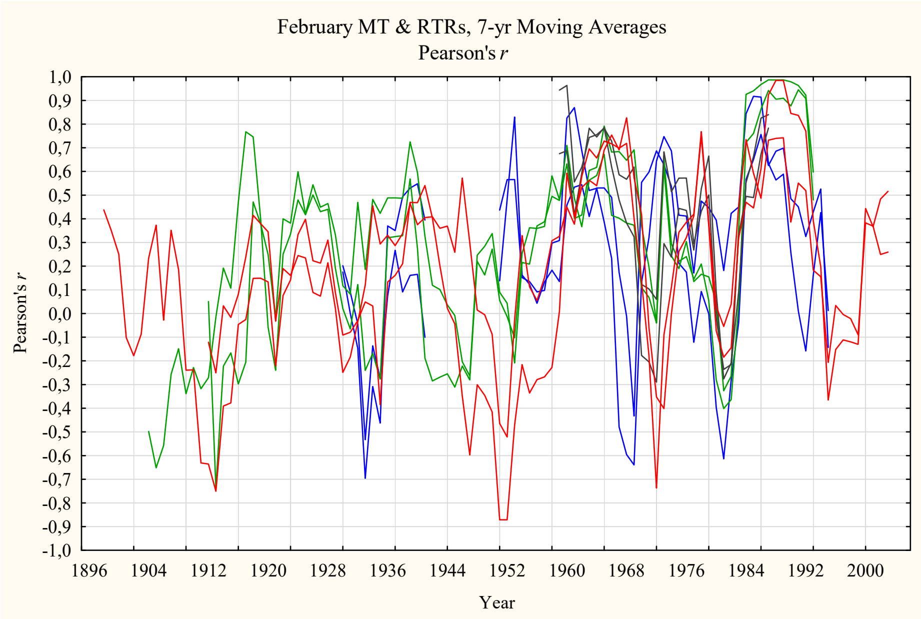
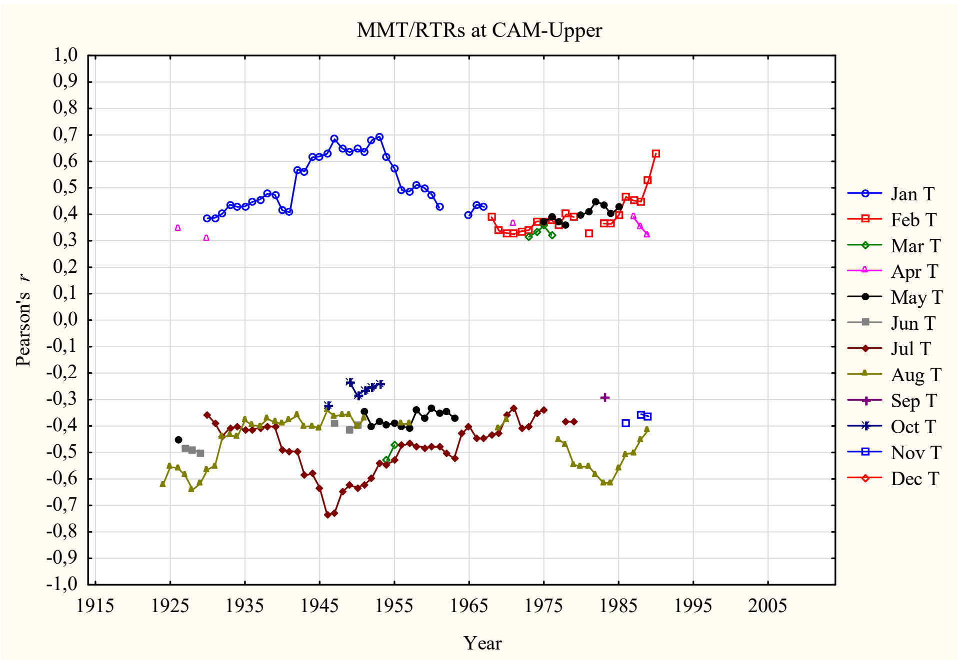


Figure 1. Non-stationary association of February mean temperature (MT) with residual tree-ring series (RTRs) in the growth year of silver fir in the Tuscan Apennines. The level of correlation of MT with RTRs changes markedly with site during the 20th century. Different colors represent different forest sites. High variability is observed in other months such as April, July, and September also. Source: [71].



Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2022 doi:10.20944/preprints202207.0392.v2

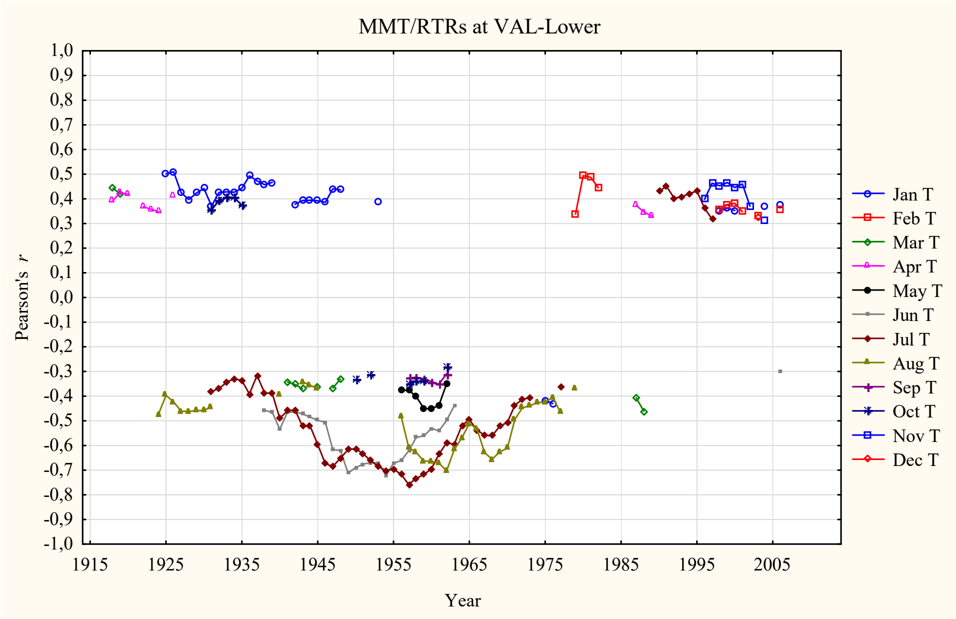


Figure 2. Statistically significant changes in the influence of monthly mean temperature (MMT) on tree ring growth of silver fir in two sites in the Tuscan Apennine Alps (Middle Italy) during the 20th century. Months with mean temperature associated to residual tree-ring series (RTRs) change during the 20th century and the level of correlation is non-stationary. For example, at the upper site (CAM-Upper, 1110m asl, above) the influence of January MT on tree ring growth declines during the 50's while the effect of February MT on silver fir growth increases afterward. At the lower site (LAV-Lower, 850m asl, below), the negative effect of July MT increases in the first half of the 20th century with the warmer period occurs in the 40's, remains negative during the 50's and no apparent influence on silver fir growth is observed after the 70's. In this region, summer MT continues to increase until recent years from the 70's. Source: [68].

8.3. Tree ring growth and periodicity

Fourier spectral analysis of tree ring series shows peak periods and subperiods with length similar to mean temperature (Tab.1). This suggests to verify whether these periods are similar to those observed in climate variables to test the hypothesis that silver fir ring growth follows cycles or periods similar to temperature and/or rainfall.

Table 1. Fourier spectral analysis shows periods (years) observed in long residual tree ring series (+80 yrs) of silver fir in the Tuscan Apennines (Middle Italy). Peak periods are yellow, and secondary peaks are grey. For example, grouping the occurrence of frequencies shows peaks such as 99.0, 49.5, 33.0, 19.8, 13.3, 6.6, etc., which have the common denominator 6.6. Source: [72].

ABE Upper	ABE Lower	CAM Upper	CAM Lower	LAV Upper	LAV Lower	VAL Upper	VAL Lower
(99.0)	(99.0)	(99.0)	(99.0)	(99.0)	(99.0)	(99.0)	(99.0)
49.5	49.5	49.5	49.5	49.5	49.5	49.5	49.5
33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0
24.8	24.8	24.8	24.8	24.8	24.8	24.8	24.8
19.8	19.8	19.8	19.8	19.8	19.8	19.8	19.8
16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5
14.1	14.1	14.1	14.1	14.1	14.1	14.1	14.1
12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4
11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
9.9	9.9	9.9	9.9	9.9	9.9	9.9	9.9
9.0	9.0	9.0	9.0	9.0	9.0	9.0	9.0
8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3
7.6	7.6	7.6	7.6	7.6	7.6	7.6	7.6
7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1

 doi:10.20944/preprints202207.0392.v2

6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2
5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8
5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2
5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7
4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3
4.13	4.13	4.13	4.13	4.13	4.13	4.13	4.13
3.96	3.96	3.96	3.96	3.96	3.96	3.96	3.96
3.81	3.81	3.81	3.81	3.81	3.81	3.81	3.81
3.67	3.67	3.67	3.67	3.67	3.67	3.67	3.67
3.54	3.54	3.54	3.54	3.54	3.54	3.54	3.54
3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41
3.30	3.30	3.30	3.30	3.30	3.30	3.30	3.30
3.19	3.19	3.19	3.19	3.19	3.19	3.19	3.19
3.09	3.09	3.09	3.09	3.09	3.09	3.09	3.09
3.00	3.00	3.00	3.00	3.00	3.00	3.00	3.00
2.91	2.91	2.91	2.91	2.91	2.91	2.91	2.91
2.83	2.83	2.83	2.83	2.83	2.83	2.83	2.83
2.75	2.75	2.75	2.75	2.75	2.75	2.75	2.75
2.68	2.68	2.68	2.68	2.68	2.68	2.68	2.68
2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61
2.54	2.54	2.54	2.54	2.54	2.54	2.54	2.54
2.48	2.48	2.48	2.48	2.48	2.48	2.48	2.48
2.41	2.41	2.41	2.41	2.41	2.41	2.41	2.41
2.36	2.36	2.36	2.36	2.36	2.36	2.36	2.36
2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30
2.25	2.25	2.25	2.25	2.25	2.25	2.25	2.25
2.20	2.20	2.20	2.20	2.20	2.20	2.20	2.20
2.15	2.15	2.15	2.15	2.15	2.15	2.15	2.15
2.11	2.11	2.11	2.11	2.11	2.11	2.11	2.11
2.06	2.06	2.06	2.06	2.06	2.06	2.06	2.06
2.02	2.02	2.02	2.02	2.02	2.02	2.02	2.02

Although this information is important from a theoretical point of view, the complexity of interactions between climate variability and forest growth and dynamics are difficult to implement in Sustainable Forest Management (SFM). Nonetheless, dynamics, growth, and structural modifications of forests can partially be explained and modelled by using *time*.

These concerns address forest planning and management under climate change to answer these questions:

1. Are traditional or rigidly scheduled forest management operations damaging or worsening the resilience of forest ecosystems and their ability to store CO_2?
2. Can *time* be used to adapt flexible forest management operations to variability in climate parameters proved to influence forest/tree growth?
3. Can *timing* in forest management be used to maintain both sustainable forest productivity and high rate of CO_2 storage?

Given these questions, forest management and silviculture that do not implement climate change conditions show four main situations; in a simplified scheme, silvicultural interventions can take place (Fig. 3):

when the rate of growth is decreasing: future productivity is altered; the minimum biomass capital risks to be damaged, and CO_2 storage is negatively affected (red line).

a) During a trough of the rate of growth: the minimum biomass necessary to preserve the resilience of the forest is damaged; the damage can be temporary (decades+) or permanent; CO_2 storage capacity is deficient – which can be read as an indirect emission of CO_2 since the balance is negative (magenta line).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2022 doi:10.20944/preprints202207.0392.v2

b) When the rate of growth is increasing: the planned wood mass can be used without compromising the resilience and recovery of the forest; CO_2 storage remains increasing (orange line).
c) During a peak period of growth: the wood mass harvested can be even higher than planned by using traditional planning schemes, and the rate of CO_2 storage can be above the average (green line).

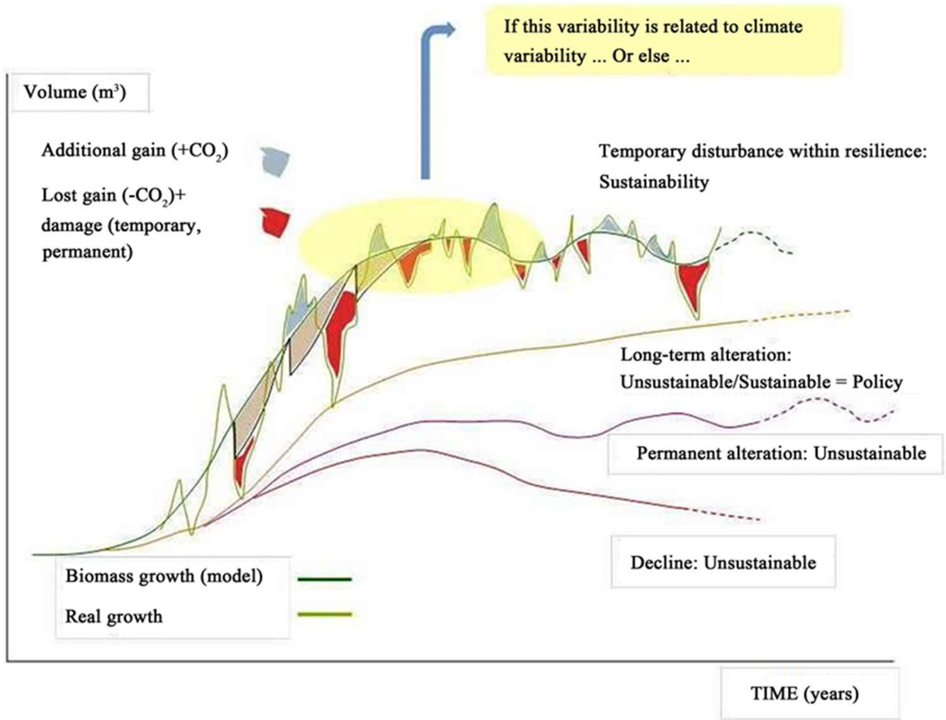


Figure 3. Schematical concept of timing and possible effects of silvicultural interventions and harvesting without implementing climate variability and trends.

- Light green line. Simplified theoretical volume development in a mono-aged stand.
- Dark green line. Real growth development (enhanced) including variability in local climate conditions. Temporary disturbance within resilience: Sustainable.
- Light blue line. Long-term alteration: unsustainable/sustainable → Policy.
- Orange line. Permanent alteration: unsustainable.
- Dark grey line. Decline: unsustainable.
- Red areas. Temporary or permanent losses in CO_2 storage and biomass production; forest damage.
- Light blue areas. Additional storage of CO_2, higher biomass production.
- Yellow areas. Traditional silvicultural interventions (i.e., thinning).
- Light grey ellipse. Variability in volume growth related to local climate variability.

The concept shown in Figure 3 schematizes the periods — which can be 6 - 7 years long in the Mediterranean area [5] — when the influence of climate variables on forest species growth increases or decreases. These periods can be used to plan management and silvicultural interventions on the basis of the variability in tree growth trends associated with climate variability during *time*. A necessary step is to identify the climate variables that influence tree growth of the species considered followed by the estimation of the upper and lower thresholds of these climate variables (i.e.: temperature and/or rainfall) that limit and/or promote the forest species growth at the local level. Once that the range of temperature and/or rainfall within which tree growth responds is identified, the periods when the rate of growth increases or decreases in accordance with historical series of climate variables (Fig. 4) can be approximated. It can be noted that the growth response to thresholds of temperature and/or rainfall is controlled mainly genetically and therefore it tends to be constant over long time, surely over the length of any forest management plan.

Thus, forest planning and management can work by scheduling periods for operations and interventions in the periods when the range of the threshold values of climate variables produce positive growth trends and, vice versa, by suspending them during the periods of decreasing tree growth. Since trends in climate variables tend to change over periods of a few years, dendroclimatological analysis can show how the inluence of climate variables on tree growth varies even in the medium-short term, where tree growth is intended as the periodic average increment of the stands.

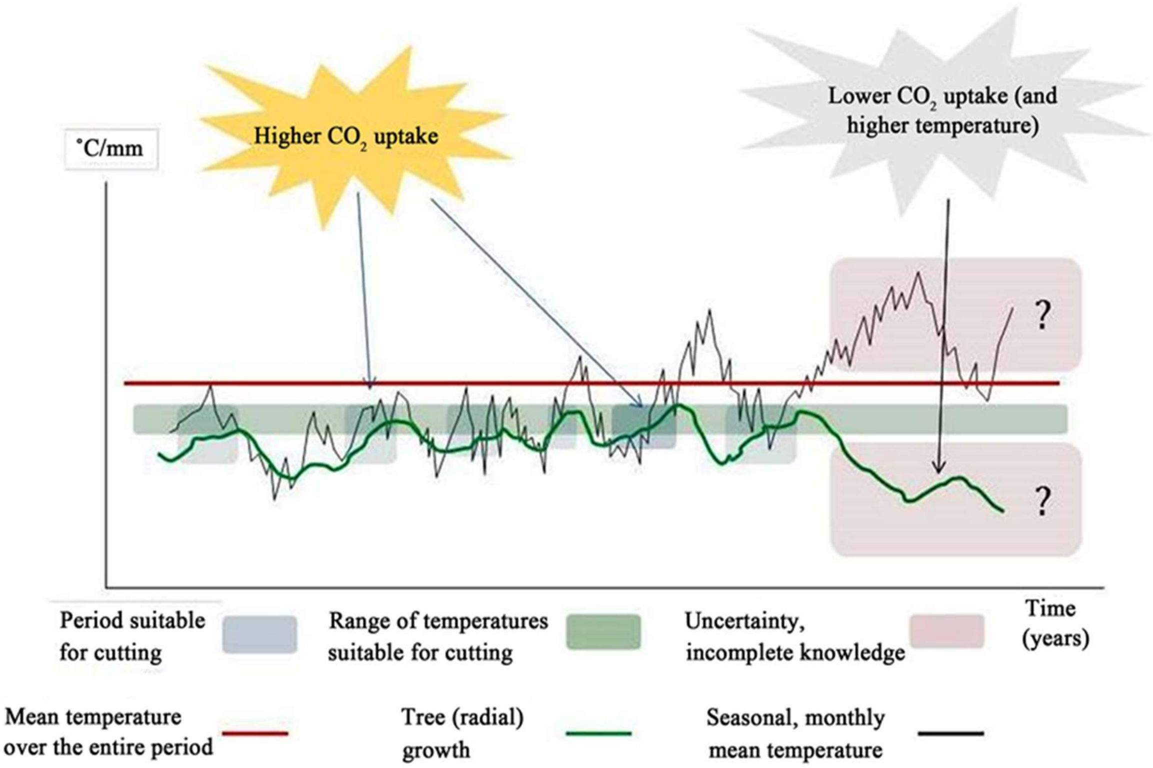


Figure 4. The concept. Periods of increase and decrease of stand growth crossed with a suitable range of temperature and/or rainfall thresholds for tree growth can identify time and period suitable for silvicultural interventions in forest planning and management. Source: [4].

8.4. The Climate Variable Thresholds: an example

Statistically significant levels of correlation between monthly mean temperature, monthly rainfall, and residual tree rings are observed in many forest sites, for example in the Tuscan Apennines (Middle Italy). Here, monthly mean temperatures associated with residual tree rings have changed during the 20th century (Fig. 5) and their level of correlation has been highly non-stationary over time. Once the association between climate variables and tree growth and its variability over time has been identified by dendroclimatological analysis, it has been possible to estimate the periods when the association shows a significant positive or negative influence on tree growth.

The example shown in Figure 5 schematizes the association of winter mean temperature (December of the previous year and January and February of the current year; DJF) with tree ring growth in beech, which increases from the late ‘50s onward. For example, before this period, DJF seems is little or no influent on beech growth. When the level of association shows r equal to or higher than 0.38, the corresponding threshold of DJF is >8.0°C. Or, before 1950 the influence of DJF on beech radial growth was weak or even null.

 doi:10.20944/preprints202207.0392.v2

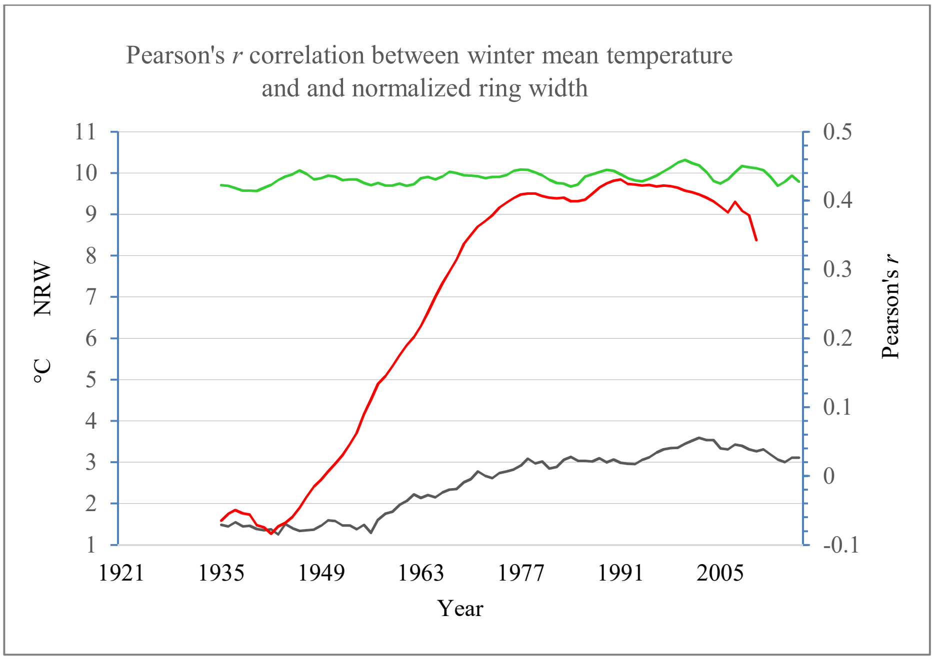


Figure 5. Pearson's *r* correlation (red line) between 29-years moving means of winter mean temperature (°C; grey line) and normalized ring width (NRW; green line) in beech stands in Mugello (Tuscany, Middle Italy). The Pearson's *r* scale (right) is modified to focus on the variability of the red line. Source: [73] (simplified).

8.5. Inputs of the thresholds

The climate variable thresholds can be used to estimate the time when an increasing trend of growth is expected to turn into decreasing, and vice versa. This can be made by monitoring the values of the mean temperature and/or rainfall of the months (or seasons) associated with the average stand growth in the years before interventions; this period is assumed to correspond to the average growth increment over the same period of the climate variable considered.

At this point, given these thresholds, linear, polynomial, curvilinear or exponential models can be used to estimate which monthly mean temperature and / or monthly rainfall of the current and previous year indicate favorable or unfavorable growth conditions with respect to the indices of the tree ring series (NRW). The positive or negative trend of radial growth is considered as the deviation, increasing or decreasing, from the medium-long term average value (e.g. two periods of 7 years, or more) of the NRW index. In other words, NRW values higher than the average for the period considered indicate a positive influence of the independent (climatic) variables on tree ring growth, while lower values show an influence of the climatic variables that reduces tree ring growth. For application purposes, this modeling must be calibrated by applying the results of dendrochronological monitoring and climatic variables by inserting the data produced by the "on-site" weather stations.

In the Mugello case study, model A) shows how the value of NRW_{15} relates to monthly climate variables in a certain year *i*. Model B) considers also the influence of two more parameters of the previous year (i – 1). However, since the difference in statistical significance between the two models A) and B) is small, for practical purposes it is suggested using model A) except for recalibrations to be performed on the basis of monitoring every 4-5 years. In the beech in Mugello, the average value over 15 years (7 + 1 + 7) of NRW (NRW_{15}) is 98.8; therefore, results with values lower than this indicate unfavorable conditions the lower they are, and vice versa. For example, a value of 89.2 of NRW_i indicates not to proceed with interventions while NRW_i equal to 104.5 shows favorable conditions and therefore the possibility of carrying out silvicultural interventions in the current year.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2022 doi:10.20944/preprints202207.0392.v2

A) $NRW_i = 79{,}8 + 0{,}07 * Lug\ P + 0{,}04 * Aug\ P + 0{,}76 * Feb\ Tm + 0{,}90 * Mag\ Tm$

$R^2 = 0{,}23$; Pr > model F = 0,001 (variance analysis)

B) $NRW_i = 70{,}2 + 0{,}07 * Lug\ P + 0{,}04 * Aug\ P + 0{,}61 * Feb\ Tm + 0{,}67 * Mag\ Tm + 1{,}05 * Oct\text{-}1\ Tm + 0{,}38 * Dic\text{-}1\ Tm$

$R^2 = 0{,}24$; Pr> model F = 0,003 (variance analysis)

Table 2 shows the climate variables and the significance values (*p*-values) that refer to a 'window' (moving average) of 15 years (7 + 1 + 7) to highlight the medium-term variability. As verified by Fourier spectral analysis (Table 1), the values of the 'windows' are multiples of 7 years. The *p*-values refer to the correlation of the moving averages (15 years) between the normalized indexes of the tree ring series and the series of monthly average temperatures and monthly rainfall. Only the months that have statistical significance are reported.

Table 2. Thresholds of monthly mean temperature (Tm) and monthly rainfall (P) relative to the increase or reduction of growth rate in beech (*Fagus sylvatica*) in Mugello [73].

Mean Temperature (Tm) *Current year*					
February			*May*		
Tm	Effect		**Tm**	Effect	
<2,5°C	Null/negative	*r* = 0,26 *p*<0,012	>12°C <14°C	Positivo	*r* = 0,24 *p*<0,018
>2,5°C	Positive		<12°C >14°C	Null/Negative	
Previous year					
October			*December*		
Tm	Effect		**Tm**	Effect	
<11°C	Null/neg	*r* = 0,22	>3°C	Positive	*r* = 0,22
>13°C	Null/negative	*p*<0,033	<3°C	Null/negative	*p*<0,032
Rainfall (P) *Previous year*					
July			*August*		
P	Effect		**P**	Effect	
<50mm	Null/negative	*r* = 0,29	<70mm	Null/negative	*r* = 0,23
>50mm	Positive	*p* <0,009	>70mm	Positive	*p* <0,038

In general, this type of modeling can be validated and/or calibrated by applying the results of dendrochronological and climatic monitoring carried out in the sampling areas and weather stations "onsite". These data are used to update dendroclimatological analyzes and plan interventions as ordinary forest management tools.

Table 3 shows an example of the application of the thresholds reported in Table 2 in order to foresee the year when silvicultural intervention can take place. For example, if we observe values such as those of Table 3 and then compare them with those of the upper and lower thresholds of Table 2, we obtain a situation like that of Table 3 - "Intervention"; the green color indicates the year in which the interventions can be carried out and the orange color warns not to make silvicultural interventions.

Table 3. The orange color indicates a year with negative or no effects on radial growth, the green color positive effects. The value -1 means 'previous year'.

Table 3							
Year	*Mean temperature*				*Rainfall*		*Intervention*
	October -1	*December -1*	*February*	*May*	*July*	*August*	
2020	14°C	5°C	1°C	12.5°C	20mm	30mm	No
2021	12°C	-2°C	4°C	13.5°C	25mm	20mm	No
2022	10°C	3°C	4°C	13°C	65mm	80mm	Yes

9. Discussion

The introduction of the upper and lower thresholds of climatic variables as one of the main factors for estimating the growth of forest trees at the level of homogeneous classes of site factors (e.g. elevation, slope, exposure, soil, humus, etc.) contributes to define the variability in the growth trend of trees in space and time. This aspect helps a lot to understand and calculate where and how the growth rate (and also the decrease) is distributed over the forest and how it varies over space and time. This is particularly important under the constraints imposed by the variability of climatic conditions, which determines periods of increase in the growth rate that alternate with periods of decrease in the rate. Under the effects of climate change and / or the need to implement carbon dioxide storage in plants as a strategy that contributes to limiting warming due to rising carbon dioxide levels in the atmosphere, a relevant factor for the sustainability of forest management is to avoid the extraction of woody biomass in quantities exceeding the increase in periodic production. This can be done by taking the excess productivity produced during periods of climatic conditions conducive to growth or that stimulate a higher growth rate, where the periodicity is indicated by the intervals between climatic conditions that increase growth and conditions that reduce it.

At the same time, it is probable that the improvement in the balance between the increase in total wood biomass, the productivity of the wood mass and percentage of it harvested, and the greater storage of carbon dioxide per unit of surface area is reflected in better economic values of both wood production and ecosystem services. For example, cutting during periods of increased wood production allows you to:

extract larger volumes with the same percentage increase per unit area;

- increase in forest biomass;
- carbon dioxide stored in plants and in the soil not to disperse but to continue to accumulate;
- avoid the extraction of wood when the growth rate is decreasing and / or the mass collected is higher than the productivity of the wood.

Thus, the monitoring of forest growth and climate variability and their relationships becomes an ordinary tool for forest planning and management; and the planning of the distribution of the harvest can be promptly and easily adapted to changes in climate trends in the short and medium term.

In terms of forest planning and management under climate change, implementing climate variable thresholds in the framework of 'ecosystemic silviculture' can integrate the methods exposed above provided that the forest stands are grouped according to the ecological similarity of the sites. In fact, at the forest unit level, the composition and structure of species tend to become uniform when the ecological and environmental characteristics of the sites are similar. For example, the 'Ecological Forest Unit' can represent the basis on which to implement forest management based on thresholds of climate variables.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 27 July 2022 doi:10.20944/preprints202207.0392.v2

10. Conclusion

In general, forest planning and management under climate change is unlikely to adhere to a sort of 'technical' and / or 'preordained' scheme to be rigidly applied. Rather, in most cases, strategies and tools for forest planning and management in the context of climate change require detailed knowledge of forest ecology, growth, dynamics, boundaries and environmental thresholds to be developed and applied in accordance with trends in climatic variability. Other relevant factors, such as genetic and/or phenotypic plasticity or adaptability, success or failure of natural generation, or else, should be ascertained at the forest ecosystem level, while responses can differ greatly.

Certainly, strategies, methodologies and techniques for forest management in a climate change regime should refer to some valid and applicable methods and models that identify the criteria to be used. However, these criteria require careful consideration and analysis of the climatic, environmental, and forest context, thus adapting strategies, methods and techniques to the local reality, where models for effective forest management to climate change are developed.

Funding: This research received no external funding

Acknowledgments: The topics were developed by the main author through stages of research developed under different institutions, starting with The University of Florence; Monash University (Australia); and the Research Centre for Forestry and Woods (CREA - Italy).

Conflicts of Interest: The authors declare no conflict of interest".

References

[1] Ashraf, M. I., Meng, F. R., Bourque, C. P. A., & MacLean, D. A. (2015). A novel modelling approach for predicting forest growth and yield under climate change. *PloS one*, *10*(7), e0132066. doi:10.1371/ journal.pone.0132066
[2] Brang, P., Spathelf, P., Larsen, J. B., Bauhus, J., Boncčina, A., Chauvin, C., ... & Svoboda, M. (2014). Suitability of close-to-nature silviculture for adapting temperate European forests to climate change. *Forestry: An International Journal of Forest Research*, *87*(4), 492-503., https://doi.org/10.1093/forestry/cpu018
[3] Cescatti, A., & Piutti, E. (1998). Silvicultural alternatives, competition regime and sensitivity to climate in a European beech forest. *Forest Ecology and Management*, *102*(2-3), 213-223.
[4] D'Aprile, F., Tapper, N., & Marchetti, M. (2015). Forestry under climate change. Is time a tool for sustainable forest management?. *Open Journal of Forestry*, *5*(04), 329.
[5] Jandl, R., Spathelf, P., Bolte, A., & Prescott, C. E. (2019). Forest adaptation to climate change—is non-management an option?. *Annals of forest science*, *76*(2), 1-13.
[6] Nunes, L. J. R., Meireles, C. I. R., Pinto Gomes, C. J., & Almeida Ribeiro, N. M. C. (2019). Forest Management and Climate Change Mitigation: A Review on Carbon Cycle Flow Models for the Sustainability of Resources. *Sustainability*, *11*(19), 5276. https://doi.org/10.3390/su11195276
[7] IPCC, 2019: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press.
[8] Nemani, R. R., Keeling, C. D., Hashimoto, H., Jolly, W. M., Piper, S. C., Tucker, C. J., Myneni, R. B., and Running, S. W. (2003). Climate-driven increases in global terrestrial net primary production from 1982 to 1999, *Science*, 300, 1560–1563, https://doi.org/10.1126/science.1082750
[9] Boisvenue, C. and Running, S. W. (2006). Impacts of climate change on natural forest productivity–evidence since the middle of the 20th century, *Glob. Change Biol*., 12, 862-882, https://doi.org/10.1111/j.1365-2486.2006.01134.x
[10] Seddon, A. W. R., Macias-Fauria, M., Long, P. R., Benz, D., and Willis, K. J. (2016). Sensitivity of global terrestrial ecosystems to climate variability, *Nature*, 531, 229–232, https://doi.org/10.1038/nature16986
[11] Barber, V. A., Juday, G. P., and Finney, B. P. (2000). Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress, *Nature*, 405, 668–673, https://doi.org/10.1038/35015049
[12] Luo, Y. (2007) Terrestrial carbon-cycle feedback to climate warming, *Annu. Rev. Ecol. Evol.* S., 38, 683–712, https://doi.org/10.1146/annurev.ecolsys.38.091206.095808
[13] Peñuelas, J. and Filella, I. (2009). Phenology feedbacks on climate change, *Science*, 324, 887–888

[14] Reyer, C., Lasch-Born, P., Suckow, F., Gutsch, M., Murawski, A., and Pilz, T. (2014). Projections of regional changes in forest net primary productivity for different tree species in Europe driven by climate change and carbon dioxide, *Ann. Forest Sci*., 71, 211–225, https://doi.org/10.1007/s13595-013-0306-8
[15] Spittlehouse, D. L. and Stewart, R. B. (2004) Adaptation to climate change in forest management, *J. Ecosyst. Manage*., 4, https://doi.org/10.1186/s40663-017-0091-1
[16] Spittlehouse, D. L. (2005). Integrating climate change adaptation into forest management, *Forest. Chron*., 81, 691–695, https://doi.org/10.5558/tfc2014-134
[17] Bonan, G. B. (2008). Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests, *Science*, 320, 1444–1449, https://doi.org/10.1126/science.1155121
[18] Keenan, R.J. Climate change impacts and adaptation in forest management: a review. *Annals of Forest Science* 72**,** 145–167 (2015). https://doi.org/10.1007/s13595-014-0446-5
[19a] D'Aprile, F., 1998. Forest Planning Based on Ecologic Parameters of the Forest: the Ecological Normality. *In Proceedings of the International Conference on Indicators for Sustainable Forest Management*. IUFRO, F.A.O., CIFOR. Melbourne, Australia.
[19b] D'Aprile, F., 1998. Pianificazione forestale su base ecologico-selvicolturale: la "Norma Ecologica". Atti del *Secondo Congresso Nazionale di Selvicoltura per la Conservazione ed il Miglioramento dei Boschi Italiani*, pp.67-80. Accademia Italiana di Scienze Forestali, Consulta Nazionale per le Foreste ed il Legno, Direzione Generale per le Foreste, la Montagna e le Risorse Idriche. Venezia, 24-27 Giugno.
[20] Ciancio, O. (2010). Selvicoltura, assestamento, epistemologia ed etica. Dibattito scientifico o discussione da bar dello sport? *Forest@* 7: 111-119. - doi: 10.3832/efor0630-0007
[21] Nocentini S., Buttoud G., Ciancio O., Corona P. 2017 - Managing forests in a changing world: the need for a systemic approach. A review. *Forest Systems* 26 (1): eR01
[22] D'Aprile, F., Chiavetta, U. and Miozzo, M., 2017. Il Progetto LIFE AForClimate. Variabilità climatica come strumento di pianificazione della gestione forestale (The LIFE Project AForClimate. Climate variability as a tool for planning in forest management). *Sherwood*, 224: 19-21. LIFE 3.0 - LIFE Project Public Page (europa.eu)
[23] D'Aprile, F., 2003. Site Quality Factors Affecting the Growth and Viability of Black Walnut *(Juglans nigra*> L.) in an Australian Plantation. In: proceedings of the international transdisciplinary conference on *Decision Support for Multipurpose Forestry*. IUFRO, University of Natural Resources and Applied Life Sciences of Wien, U.S. Forest Service. April, 23-25, 2003, Vienna.
[24] Linser, Stefanie & O'Hara, Peter. (2019). Guidelines for the Development of a Criteria and Indicator Set for Sustainable Forest Management. 10.13140/RG.2.2.32430.36168/1.
[25] Angelstam P., Andersson K., Axelsson R., Elbakidze M., Jonsson B.G., Roberge J.-M. (2011). Protecting forest areas for biodiversity in Sweden 1991–2010: the policy implementation process and outcomes on the ground. Silva Fennica vol. 45 no. 5 article id 90. https://doi.org/10.14214/sf.90
[26] Valladares; F., Sanchez-Gomez, D. and Zavala, M.A. (2006). Quantitative estimation of phenotypic plasticity: bridging the gap between the evolutionary concept and its ecological applications. *Journal of Ecology* 94, 1103–1116 doi: 10.1111/j.1365-2745.2006.01176.x
[27] Pretzsch, H., Grote, R., Reineking, B., Rötzer, T., & Seifert, S. (2008). Models for forest ecosystem management: a European perspective. *Annals of botany*, *101*(8), 1065–1087. https://doi.org/10.1093/aob/mcm246
[28] D'Aprile, F. (2003). Silvicultural techniques and forest planning methods based on the dynamics of forest structure in Middle Italy. *Proceedings* of IUFRO Int. Conf. 'Decision Support for Multiple Purpose Forestry', April 23-25, Vienna.
[29] D'Aprile, F. (1998). Forest planning based on ecological parameters of the forest: the 'Ecological Normality'. *Proceedings* of IUFRO International Conference on Indicators for Sustainable Forest Management. 24-28 Aug 1998, Melbourne
[30] D'Aprile, F. (1998). Pianificazione forestale su base ecologico-selvicolturale: la "Norma Ecologica". Atti del *"Secondo Congresso Nazionale di Selvicoltura per la Conservazione ed il Miglioramento dei Boschi Italiani",* pp.67-80. Accademia Italiana di Scienze Forestali, Consulta Nazionale per le Foreste ed il Legno, Direzione Generale per le Foreste, la Montagna e le Risorse Idriche. Venezia, 24-27 Giugno
[31] D'Aprile, F. (1994). Indagine Preliminare per lo Studio su Basi Ecologico-Selvicolturali dei Boschi del Comune di Cavriglia (AR). *Research Thesis.* Università di Firenze, Istituto di Selvicoltura.
[32] Galoux, A.B.J. (1978). Ecosystem, open thermodynamic system. The oak forest of Virelles-Blaimont. *Radiat Environ Biophys* 15**,** 113–130 (1978). https://doi.org/10.1007/BF01323261
[33] Susmel, L. (1988). *Principi di ecologia. Fattori ecologici, ecosistema, applicazioni.* (Principles of Ecology. Ecological factors, Ecosystem, Enforcement). CLEUP Publisher, Padova (Italy).
[34] Hortal, Joaquín & Lobo, Jorge. (2006). A synecological framework for systematic conservation planning. Biodiversity Informatics. 3. 10.17161/bi.v3i0.26.

[35] Elliott, K. J., & Swank, W. T. (1994). Changes in Tree Species Diversity after Successive Clearcuts in the Southern Appalachians. *Vegetatio*, *115*(1), 11–18. http://www.jstor.org/stable/20046498
[36] Viola, F., & Cattaneo, D. (1984). Fertility and carrying capacity evaluation in forest ecosystems. *Economia Montana (Italy)*.
[37] López-Marcos, D., Turrión, MB., Bravo, F. *et al.* (2019). Understory response to overstory and soil gradients in mixed versus monospecific Mediterranean pine forests. *Eur J Forest Res* 138**,** 939–955. https://doi.org/10.1007/s10342-019-01215-0
[38] Sheppard, J.P., Chamberlain, J., Agúndez, D. *et al.* (2020). Sustainable Forest Management Beyond the Timber-Oriented Status Quo: Transitioning to Co-production of Timber and Non-wood Forest Products - a Global Perspective. *Curr Forestry Rep* 6**,** 26–40 (2020). https://doi.org/10.1007/s40725-019-00107-1
[39] Sing, L., Metzger, M.J., Paterson, J.S. Ray, (2018). A review of the effects of forest management intensity on ecosystem services for northern European temperate forests with a focus on the UK, *Forestry: An International Journal of Forest Research*, Volume 91, Issue 2, April 2018, Pages 151-164, https://doi.org/10.1093/forestry/cpx042
[40] Krumm, F., Schuck, A. and Rigling, A. (2020). *How to balance forestry and biodiversity conservation? - A view across Europe*. European Forest Institute. doi: 10.16904/envidat.196.
[41] Various Authors (1999). *Humic Substances in Terrestrial Ecosystems*. Edited by Alessandro Piccolo. Elsevier. ISBN 0-444-81516-3. Amsterdam, The Netherlands.
[42] Piccolo, A., Nardi, S. and Concheri, G. (1992). Structural characteristics of humic substances as related to nitrate uptake and growth regulation in plant systems. *Soil Biology and Biochemistry*, Volume 24, Issue 4, Pages 373-380, ISSN 0038-0717, https://doi.org/10.1016/0038-0717(92)90197-6.
[43] Martin, M., Fenton, N.J. and Morin, H. (2021). Tree-related microhabitats and deadwood dynamics form a diverse and constantly changing mosaic of habitats in boreal old-growth forests, *Ecological Indicators*, Volume 128, 107813, ISSN 1470-160X, https://doi.org/10.1016/j.ecolind.2021.107813.
[44] Khanalizadeh, A., Rad, J.E., Amiri, G.Z. *et al.* (2020). Assessing selected microhabitat types on living trees in Oriental beech (*Fagus orientalis* L.) dominated forests in Iran. *Annals of Forest Science* 77**,** 91. https://doi.org/10.1007/s13595-020-00996-4
[45] Hanewinkel, M., Lindner, M. and Bieling, A. (2013). MOTIVE (Models for Adaptive Forest Management). *CORDIS EU Commission*, Specific Programme "Cooperation": Environment (including Climate Change), Development of adaptive forest management models. Coordinated by FORSTLICHE VERSUCHS- UND FORSCHUNGSANSTALT BADEN-WUERTTEMBERG (Germany). https://cordis.europa.eu/project/id/226544/reporting
[46] Walker, W., Haasnoot, M. and Kwakkel, J. (2013). Adapt or Perish: A Review of Planning Approaches for Adaptation under Deep Uncertainty. *Sustainability*. 5. 955-979. 10.3390/su5030955.
[47] Ogden, A. and Innes, J. (2007). Incorporating Climate Change Adaptation Considerations into Forest Management Planning in the Boreal Forest. *International Forestry Review* - INT FOR REV. 9. 713-733. 10.1505/ifor.9.3.713.
[48] Chelli, S., Ottaviani, G., Tsakalos, J., Campetella, G., Simonetti, E., Wellstein, C., Bartha, S., Cervellini, M. and Canullo, R. (2022). Intra-and inter-specific leaf trait responses of understorey species to changes in forest maturity. *Forest Ecology and Management*. 506. 119977. 10.1016/j.foreco.2021.119977.
[49] Ruiz-Benito, P., Lines, E.R., Gómez-Aparicio, L., Zavala, M.A. and Coomes, D.A. (2013). Patterns and drivers of tree mortality in iberian forests: climatic effects are modified by competition. *PLoS One*. 8(2):e56843. doi: 10.1371/journal.pone.0056843. Epub 2013 Feb 25. PMID: 23451096; PMCID: PMC3581527.
[50] Amorini, E., Biocca, M., Manetti, M. and Motta, E. (1996). A dendroecological study in a declining Oak coppice stand. Ann. For. Sci. 53 (2-3) 731-742. DOI: 10.1051/forest:19960249
[51] Martin Š., Daniel V., Aytekin E., Radim M. (2015): The effect of coppice management on the structure, tree growth and soil nutrients in temperate Turkey. *J. For. Sci*., 61: 27-34.
[52] Tkach, V., Buksha, I., Slych, O., & Pasternak, V. (2021). Optimization of maturity age for coppice oak forests within Left-Bank Forest-Steppe in Ukraine. *Lesnicky Casopis*, *67*(3), 181-186.
[53] Fyllas, N.M., Koufaki, T., Sazeides, C.I., Spyroglou, G. and Theodorou, K. (2022). Potential Impacts of Climate Change on the Habitat Suitability of the Dominant Tree Species in Greece. *Plants*, 11, 1616. https://doi.org/10.3390/ plants11121616
[54] Scolastri, A., Cancellieri, L., Iocchi, M. and Cutini, M. (2017). Old coppice versus high forest: the impact of beech forest management on plant species diversity in central Apennines (Italy), *Journal of Plant Ecology*, Volume 10, Issue 2, Pages 271–280, https://doi.org/10.1093/jpe/rtw034
[55] Gianoli E. The behavioural ecology of climbing plants. *AoB Plants*. 2015 Feb 12;7:plv013. doi: 10.1093/aobpla/plv013. PMID: 25678588; PMCID: PMC4363473.
[56] Castagneri, D., Garbarino, M. and Nola, P. (2013). Host preference and growth patterns of ivy (*Hedera helix* L.) in a temperate alluvial forest. *Plant Ecol* 214**,** 1–9. https://doi.org/10.1007/s11258-012-0130-5
[57] Trèmolières M., Carbiener R., Exinger A. and Turlot, J.C. (1988). Un exemple d'interaction non compètitive entre espèces ligneuses: le cas du lierre arborescent (Hedera helix L.) dans la foret alluviale. *Acta Oecol* 9:187–209

[58] Segura, M., Duncan, R. and Maroto, C. (2014). Decision support systems for forest management: A comparative analysis and assessment. *Computers and Electronics in Agriculture*. 101. 55-67. 10.1016/j.compag.2013.12.005.
[59] Sokal, R.R. and Rohlf, F.J. (1995) *Biometry: The Principles and Practice of Statistics in Biological Research*. 3rd Edition, W.H. Freeman and Co., New York.
[60] Scherer-Lorenzen, M. *et al.* (2005). The Design of Experimental Tree Plantations for Functional Biodiversity Research. In: Scherer-Lorenzen, M., Körner, C., Schulze, ED. (eds) Forest Diversity and Function. Ecological Studies, vol 176. Springer, Berlin, Heidelberg. https://doi.org/10.1007/3-540-26599-6_16
[61] Camussi A., Möller F., Ottaviano E. and Sari Gorla, M. (1995). *Metodi statistici per la sperimentazione biologica*. Zanichelli, Bologna, 479 pp.
[62] Sarkar S. and Fuller, (2003). T. Generalized norms of reaction for ecological developmental biology. *Evol Dev*. 5(1):106-15. doi: 10.1046/j.1525-142x.2003.03016.x. PMID: 12492417.
[63] Dieckmann, U., Heino, M. and Parvinen, K. (2006). The adaptive dynamics of function-valued traits. *J Theor Biol.* 241(2):370-89. doi: 10.1016/j.jtbi.2005.12.002. Epub 2006 Feb 3. PMID: 16460763.
[64] D'Aprile, F. (2020). Forest planning based on ecological parameters of the forest: the 'Ecological Normality'. Proceedings of the IUFRO International Conference on Indicators for Sustainable Forest Management. 24-28 Aug 1998, Melbourne
[65] D'Aprile, F. (2003). Silvicultural techniques and forest planning methods based on the dynamics of forest structure in Middle Italy. In proceedings of IUFRO Int. Conf. *'Decision Support for Multiple Purpose Forestry*', April 23-25, 2003
[66] Attiwill, P.M. (1994). The disturbance of forest ecosystems: the ecological basis for conservative management. *Forest Ecology and Management*, Volume 63, Issues 2–3, Pages 247-300, ISSN 0378-1127,https://doi.org/10.1016/0378-1127(94)90114-7.
[67] Batavia, C. and Nelson, M.P. (2016). Conceptual Ambiguities and Practical Challenges of Ecological Forestry: A Critical Review, *Journal of Forestry*, Volume 114, Issue 5, Pages 572–581, https://doi.org/10.5849/jof.15-103
[68] D'Aprile, F., Tapper N., Baker, P. Bartolozzi, L., & Bottacci, A. (2012). Changes in the Relationships between Climate andSilver Fir (*Abies alba* Mill.) Growth during the 20th Century in the Tuscan Apennine Alps (Middle Italy). *Geophysical Research Abstracts*, Vol. 14, EGU2012-425-1, EGU General Assembly, Vienna, 2012.
[69] Alkama, R., Forzieri, G., Duveiller, G. *et al.* (2022). Vegetation-based climate mitigation in a warmer and greener World. *Nat Commun* 13**,** 606. https://doi.org/10.1038/s41467-022-28305-9
[70] Tognetti, R., Valentini, R., Marchesini, L.B., Gianelle, D., Panzacchi, P., Marshall, J.D. (2022). Continuous Monitoring of Tree Responses to Climate Change for Smart Forestry: A Cybernetic Web of Trees. In: Tognetti, R., Smith, M., Panzacchi, P. (eds) Climate-Smart Forestry in Mountain Regions. Managing Forest Ecosystems, vol 40. Springer, Cham. https://doi.org/10.1007/978-3-030-80767-2_10
[71] D'Aprile, F., Tapper, N., Bartolozzi, L., & Bottacci, A. (2011). Non-Stationary Similarity in Trends of Monthly Rainfall inthe Tuscan Apennine Alps. *Geophysical Research Abstracts*, Vol. 13, EGU2011-1170-1, EGU General Assembly, Vienna,2011
[72] D'Aprile, F. and Chiavetta, U. (2018). Climate variability in forest management: The AForClimate project. *Geophysical Research Abstracts* Vol. 20, EGU 2018-602, EGU General Assembly 2018.
[73] Chiavetta, U., D'Aprile, F., Monteverdi, C., Mazza, G. *et al*, (2018). Climate variability in forest management planning: The LIFE AForClimate project. SP (9).04 in Proceedings of the *IV National Congress of Silviculture,* pp. 455-456. Turin, 5-9 November 2018, Italy. ISBN 978-88-87553-24-6
[74] Hacket-Pain, A.J., Cavin, L., Friend, A.D. *et al.* (2016). Consistent limitation of growth by high temperature and low precipitation from range core to southern edge of European beech indicates widespread vulnerability to changing climate. *Eur J Forest Res* 135**,** 897–909. https://doi.org/10.1007/s10342-016-0982-7
[75] Biondi, Franco. (1993). Climatic signals in tree rings of Fagus sylvatica L. from the central Apennines, Italy. Acta Oecologica. 14. 57-71.
[76], Dimitar, D. (2019). DENDROCHRONOLOGY OF 358-YEARS-OLD EUROPEAN BEECH (FAGUS SYLVATICA L.) FOREST STAND FROM TREE-LINE ZONE OF THE BALKAN RANGE MOUNTAIN, BULGARIA. *Silva Balcanica*, 20(3). 19-26.
[77] Domen, A., Jožica, G., Jernej, J., Gregor, B., von Arx, G. and Peter, P. (2021). Different Wood Anatomical and Growth Responses in European Beech (Fagus sylvatica L.) at Three Forest Sites in Slovenia. *Frontiers in Plant Science*, 12. https://www.frontiersin.org/articles/10.3389/fpls.2021.669229 DOI: 10.3389/fpls.2021.669229 ISSN-1664-462X