CLIMATE VARIABILITY IN SUSTAINABLE FOREST MANAGEMENT

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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 changed in different types of forest ecosystems during the last century. Tree growth also shows variability and trends that can be non-stationary during time under current and demonstrated changes in climate variability at the geographic, regional, and local levels, even at relatively short distance between sites. Yield tables, site quality indices, age class, rate of growth, and spatial distribution are some of the most frequently used tools and parameters in forest planning and management. However, these methods do not involve climate variability during time although climate is the main driver in trends of forest and tree growth. Previous research warns that forest management under changing climatic conditions could amplify its negative effects. For example, changing climate conditions may impact on temperature and/or precipitation thresholds critical for forest tree growth. Forest biomass, resilience, and CO_2 storage may be altered and damaged unless forest planning and management implement the relationships between climate variability and trends of tree growth. A positive aspect is that periods of favourable climate conditions may allow harvesting higher amounts of wood mass and storage of more CO_2 than traditional planning methods and, the average length of both favourable and adverse periods may lie within the valid period of a forest management plan. Here, we show a conceptual development to implement climate variability in forest management in the view of further research experimentation.

Keywords: climate change, forestry, sustainability, time, management.
Parole chiave: cambiamenti climatici, foreste, sostenibilità, tempo, gestione.

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1. Introduction

Changes of climate conditions influence energy fluxes, cycles of nutrients and materials, primary productivity, biodiversity, ecological functions and carbon equilibria of forest ecosystems; time factors influence physical, biological, ecological, and climatic processes and functions. For example, seasonality, cycles, periodicity, and trends in climate variables; tree growth, forest growth, and forest metabolic activities (i.e., photosynthesis and respiration) are commonly known to be time-related.

A real risk for sustainable forest management (SFM) under changing climatic conditions is that negative effects may be amplified. In fact, variability in trends of climate variables can highly influence forest growth by either increasing or reducing it in different periods. Changing climate conditions may also impact on temperature and/or precipitation thresholds critical for forest tree growth and stress; alterations or damage to growth response, resilience, and CO_2 balance, which are not completely known, may occur. However, the distribution, rate of growth, and volume of wood in traditional forest planning and management is frequently based on yield tables or similar tools, age classes, site quality indices, and spatial distribution criteria. These methods do not implement the effects of changing climate conditions on forest growth variability and trends over time. Thus, this approach cannot identify and estimate when, how, and where the forest and its parcels go through periods of increasing and decreasing growth that is driven mainly by climate variability. Moreover, temporal changes in silvicultural and harvesting operations may lead to an increase of carbon emissions.

Normally, forest management emphasizes growth rates and biomass productivity as expressions of species and site. Until recently, the influence of climate variability on growth dynamics has not been included in forest planning and management. Here, we show a conceptual development aiming to highlight a relevant physical factor in forest planning and management; that is time. Although time is a typical tool of forest planning, it has traditionally been used just as a technical parameter to assess forest yield and/or age classes, and to schedule forest operations. Today, its relevance as a physical factor that regulates forest growth, dynamics, and functionality in relation to the effects of climate variables needs to be implemented in SFM for the development of mitigation and adaption strategies under the effects of changing climate conditions, including CO_2 storage. Under this scenario and the consequent risks, SFM and operations could be planned and/or scheduled in periods when climate variables that influence tree growth responses are within thresholds related to positive growth response. By using this approach, silvicultural operations and harvesting are likely to use mainly climate variability to assess forest growth responses.

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

Biodiversity and climate are components of the complex regulatory mechanism that balances the energy exchange between Earth and Space. Biodiversity can also be seen as the result of complex interactions between the molecular (i.e., DNA) level and the atmospheric level during natural evolution; in other words, the evolution and adjustment of the energetic balance between Earth and Space. In recent decades, the concentration of CO_2 in the atmosphere has reached high levels in a relatively short time. Among its effects on climate and vegetation, there has been global warming and modification of the CO_2 cycle.
Today, research shows that using and managing forests needs to implement climate-plant-CO_2 relationships for the mitigation of impacts of climate change and the development of adaption strategies in forest management, including CO_2 storage.

2.1 The Context
Changing climate conditions normally interact with forest growth at the local level within regional scenarios. The influence of variability and intensity of climate alterations at the forest level may be even stronger than regional trends would predict (D'Aprile *et al*., 2009). At the local level, similarity in trends of climate variables can differ markedly and irregularly over time. Changing climate conditions can also modify both the extent of the growing season and the months that influence the occurrence of tree growth response. Therefore, the complexity of interactions between climate variability and forest growth and dynamics requires an effort to make it applicable to the reality of SFM. Dynamics, growth, and modifications of forest structures can be partially identified and modeled through time in forest planning and management.

2.2 Time in forest monitoring and planning
In forest ecology, it may be noted that:
- Cause-effect relationships mainly concern the analysis of fluxes of energy and matter(s); these relationships take place through biodiversity and ecological groups of species;
- In forest ecosystems many variables interact through the complexity of their dynamics and properties. Therefore, indicators and models are needed to interpret the complexity of cause-effect relationships and how they work;
- In this scenario, changing climate conditions add complexity to the management of forests and land and their effects are not yet completely understood;
- Understanding the cause-effect relationships intrinsically involves the variable *time*. In fact, time is a powerful and necessary driver of physical, biological, ecological, and climatic processes and functions.

2.3 Trends in climate variability and forest growth at the site level
2.3.1 Non-stationary similarity in climate variability
Our research (D'Aprile *et al*., 2010) has shown that in the Apennine Alps (Middle Italy) during the 20th century, the trends in monthly mean temperature are non-stationary, their similarity varies highly and iregularly among sites and can even be opposite in sign in some periods; similarity in trends among sites also varies with season. This phenomenon can occur even between sites at short distance. Similar results have been found with respect to monthly rainfall (D'Aprile *et al*., 2011).

2.3.2 Non-stationary trends in tree growth
We also investigated the similarity in tree-ring growth (*Abies alba* Mill.) at the forest sites of the meteorological stations at Abetone (Pistoia), Camaldoli (Arezzo), La Verna (Arezzo), and Vallombrosa (Florence) (Table 1). Results have shown high and irregular non-stationary similarity in tree ring chronologies among sites and, to a lower extent, along elevation gradients within forest sites (Fig. 1).

2.3.3 Climate/tree growth relationships during the 20th century
The evidence of high and irregular non-stationary similarity in trends of both climate variables and tree-ring chronologies in the same sites would suggest verifying any association between climate variability and tree growth trends. Thus, we investigated the climate/tree-ring correlations to determine if there have been temporal fluctuations in the strength of the associations.
Running-means correlation analysis showed that the tree-ring/climate relationships vary markedly during the 20th century. In particular, we found that correlations vary highly in strength and also in sign (Fig. 2), and months that influence tree growth change through decades (Fig. 3) (D'Aprile *et al*., 2012).
In other words, the association between climate variables and tree growth varies among sites and throughout months during the 20th century in the Tuscan Apennine Alps (Middle Italy)

3. Questions for Research Development

The scenario and results shown raise these questions:
1) Do traditional or rigidly scheduled forest management operations damage or alter the resilience of forest ecosystems and their ability to store CO_2 under changing climate conditions?
2) Can time be used to adapt flexible forest management operations to the variability over time of climate factors 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?

3.1 Forest utilization under changing climate conditions

The impacts of climate change on forest management and silvicultural treatments can be summarized by four main situations. Harvesting may occur in periods when (Fig. 4):

- The rate of growth faces troughs. The minimum biomass necessary to preserve the resilience of the forest is damaged. Damage can be temporary (decades) or permanent; CO_2 storage capacity is deficient or reduced - which may also be read as an indirect emission of CO_2 as the balance is negative (red line);
- The rate of growth decreases. Future productivity is damaged; the minimum biomass capital may be altered, and CO_2 storage is negatively affected (magenta line);
- The rate of growth increases. The planned wood mass can be used without compromising the resilience and recovery of the forest; CO_2 storage is increasing (orange line);
- The rate of growth is in peak periods. The wood mass harvested can be even higher than planned, and the rate of CO_2 storage can be above the average (green line).

Under changing climate conditions, a real risk is that interventions (thinning, cutting, harvesting) occur in a period unfavourable or adverse to forest species growth, which is not detected or shown by traditional forest planning and management. In this case, the mass of wood to harvest predicted by the forest management plan may be higher than the real productivity of the forest; the productive or stable biomass of the forest is reduced. A side effect is that CO_2 storage diminishes as the rate of growth decreases. Under these circumstances, the process would lead to indirect emission of CO_2 by consuming more wood mass than is produced (negative balance) and lowering the potential CO_2 storage - as the forest biomass is smaller and the growth rate decreases. Vice versa, the extraction of wood during a period of favorable climate conditions that produce positive trends in forest growth may allow harvesting higher wood mass than planned by using yield tables or growth indices; the productive capacity or stable biomass of the forest is intact. Moreover, CO_2 storage may be higher as the rate of growth increases and the wood mass after harvesting is higher.

4. Conclusions

The objective of the method is to identify the periods in climate variables - which seem to be 6-7 years long in the Tuscan Apennine Alps (Middle Italy) - when forest species growth is positive (or negative) - and plan management and interventions by following the variability in growth trends caused by climate variability during time (Fig. 5).

This can be achieved by identifying the upper and lower thresholds of climate variables (i.e., temperature and/or rainfall) for forest species growth. Once the range of temperature and/or rainfall within which tree growth responds is identified, it is relatively easy to identify the periods when growth increases or decreases in correspondence with historical series of climate variables.

It can be noted that the response of growth to thresholds of temperature and rainfall is genetically determined and therefore remains consistent through centuries (and longer). So, thresholds can be investigated and identified once for many decades in the future.

Frequently, forest planning and management are disposed for interventions over periods of 5-10 years. As growth trends cover periods of a few years (5-15), short-term climate variable analysis compared with climate thresholds can show the growth trend over the period. This makes it possible to identify periods for operations and interventions within the range of temperature and/or rainfall thresholds that produce positive growth trends.

Table 1. Elevation (m. asl), available period (year) of data available, and distance (km)between the four meteorological stations. The sites are listed by decreasing elevation. Abetone is ABE, Camaldoli is CAM, La Verna is LAV, and Vallombrosa is VAL.

	Elevation	*Period*	*Distance*		
			LAV	*CAM*	*VAL*
ABE	1340	1931-2000	112.3	100.1	84.6
LAV	1120	1924-2006	-	13.2	30.4
CAM	1111	1885-1996	-	-	22.3
VAL	955	1872-2006	-	-	-

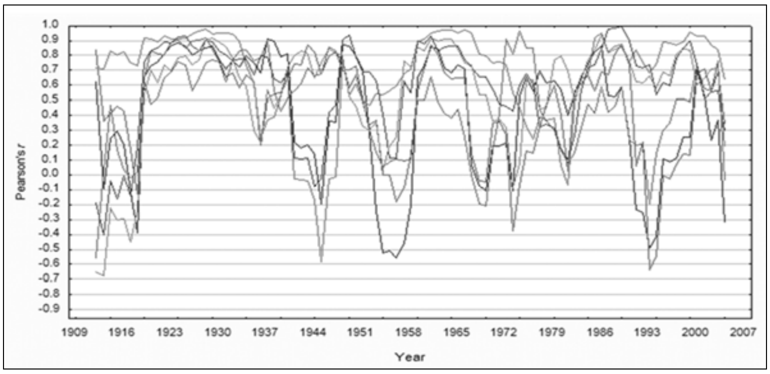

Figure 1. Non-stationary correlation of 7-year moving averages between residual tree-ring chronologies among the upper study stands of silver fir in the Apennine Alps during the period 1909-2007. Paired sites are Abetone-Camaldoli, Abetone - LaVerna, Abetone-Vallombrosa, Camaldoli-La Verna, Camaldoli-Vallombrosa, and La Verna-Vallombrosa. (Source: D'Aprile *et al*., 2012).

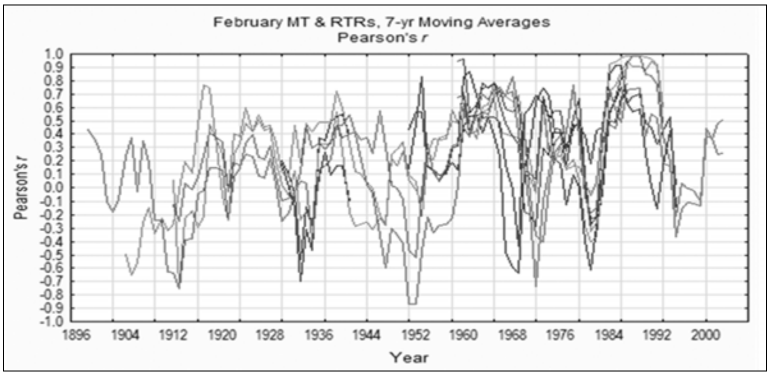

Figure 2. Non-stationary association of monthly mean temperature (MMT) with residual tree-ring chronologies (RTRs) in February of the growth year. The correlation of MMT with RTRs varies highly with month and site during the 20th century. The upper and lower study stands at Abetone (Pistoia), Camaldoli (Arezzo), La Verna (Arezzo), and Vallombrosa (Florence) are shown in the graph. (Source: D'Aprile *et al*., 2012).

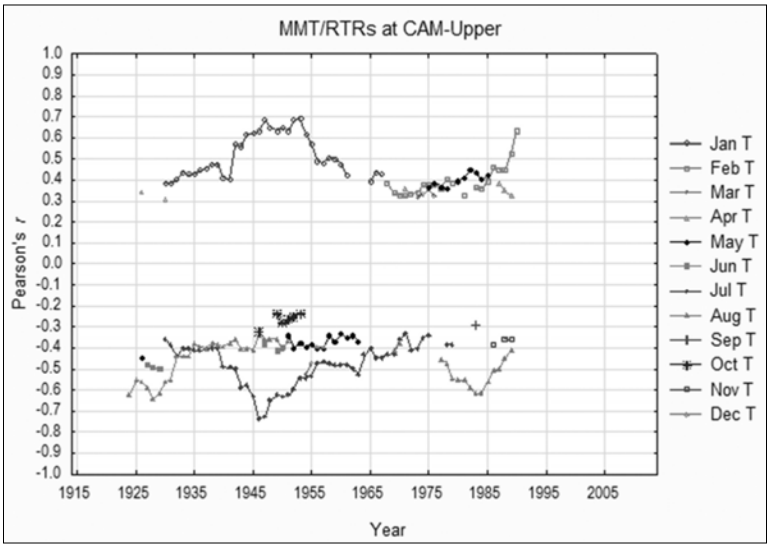

Figure 3. Statistically significant levels of correlation between monthly mean temperature (MMT) and residual tree-ring chronologies (RTRs) at the study stands at Camaldoli upper site (CAM-Upper) in the Tuscan Apennine Alps. MMT associations with RTRs change during the 20th century and their level of correlation is highly non-stationary. (Source: D'Aprile *et al*. 2012).

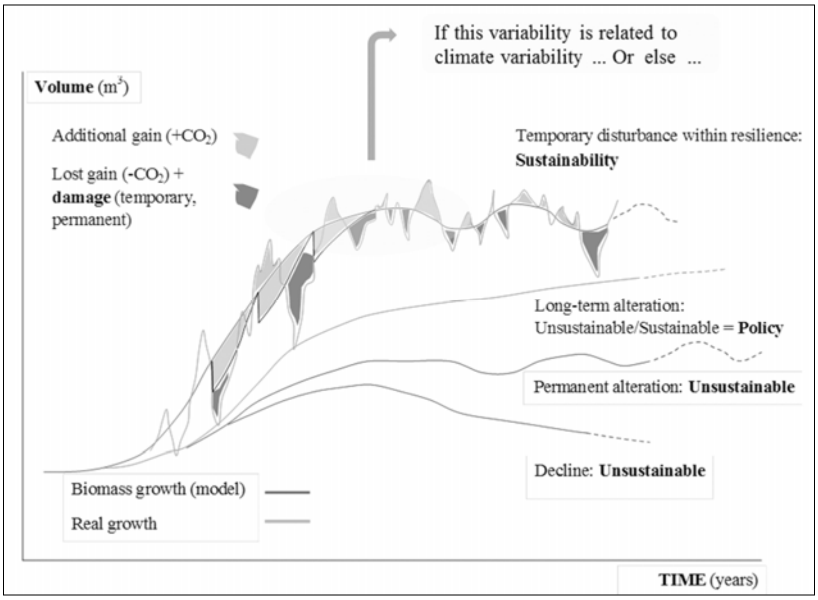

Figure 4. Timing and possible effects of silvicultural interventions and harvesting without implemening climate variability and trends.

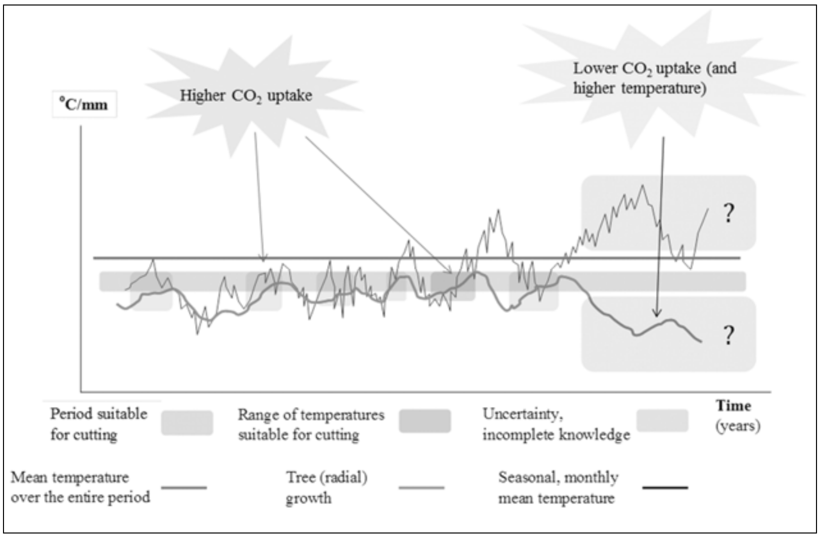

Figure 5. Periods of growth increase crossed with a suitable range of temperature and/or rainfall thresholds for tree growth can identify time and length in forest planning, management, and intervenetions.

RIASSUNTO

Variabilità climatica nella gestione forestale sostenibile

É noto che il cambiamento delle condizioni climatiche influenza la risposta di accrescimento delle piante ed il ciclo della CO_2. La dendroclimatologia ha mostrato che segnale climatico, composizione specifica ed andamento dell'accrescimento si sono modificati in diverse tipologie di ecosistemi forestali durante l'ultimo secolo. Sotto gli attuali e dimostrati cambiamenti della variabilità del clima a livello geografico, regionale e locale, l'accrescimento degli alberi mostra variabilità ed andamenti che possono essere incostanti nel tempo anche a distanze fra siti relativamente brevi.
Nella pianificazione e gestione forestale, tavole dendrometriche, alsometriche, indici di fertilità o qualità stazionale, classi di età, e distribuzione spaziale sono alcuni tra i parametri e strumenti più usati. Tuttavia, questi metodi non considerano la variabilità climatica nel tempo sebbene il clima sia il fattore principale nell'andamento della crescita dell'albero e della foresta. Ricerche precedenti hanno avvertito riguardo al rischio che la gestione forestale sotto i cambiamenti climatici possa amplificarne gli effetti negativi. Per esempio, i cambiamenti del clima possono avere impatti su soglie di temperatura e/o precipitazione critiche per l'accrescimento; biomassa forestale, resilienza ed immagazzinamento della CO_2 possono venire danneggiati a meno che la pianificazione e la gestione forestale comprendano le relazioni fra variabilità del clima e gli andamenti di accrescimento delle piante forestali. Un aspetto positivo però è che periodi con condizioni climatiche favorevoli possono permettere prelievi maggiori ed un più alto stoccaggio di CO_2 rispetto ai metodi di pianificazione usuali. Inoltre, la durata media dei periodi favorevoli ed avversi sembra giacere entro il periodo di validità di un piano di gestione forestale odierno. Qui mostriamo uno sviluppo concettuale per l'uso della variabilità del clima nella gestione forestale nell'ottica della continuazione della ricerca.

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