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Remotely-sensed phenology of Italian forests: Going beyond the species

S. Bajocco[a], C. Ferrara[b,*], A. Alivernini[b], M. Bascietto[c], C. Ricotta[d]

[a] Council for Agricultural Research and Economics, Research Centre for Agriculture and Environment (CREA-AA), Rome, Italy
[b] Council for Agricultural Research and Economics, Research Centre for Forestry and Wood (CREA-FL), Arezzo, Italy
[c] Council for Agricultural Research and Economics, Research Centre for Engineering and Agro-Food Processing (CREA-IT), Monterotondo, Italy
[d] Department of Environmental Biology, University of Rome "La Sapienza", Rome, Italy

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ABSTRACT

Remotely sensed observations of seasonal greenness dynamics represent a valuable tool for studying vegetation phenology at regional and ecosystem-level scales. We investigated the seasonal variability of forests in Italy, examining the different mechanisms of phenological response to biophysical drivers. For each point of the Italian National Forests Inventory, we processed a multitemporal profile of the MODIS Enhanced Vegetation Index. Then we applied a multivariate approach for the purpose of (i) classifying the Italian forests into phenological clusters (i.e. pheno-clusters), (ii) identifying the main phenological characteristics and the forest compositions of each pheno-cluster and (iii) exploring the role of climate and physiographic variables in the phenological timing of each cluster. Results identified four pheno-clusters, following a clear elevation gradient and a distinct separation along the Mediterranean-to-temperate climatic transition of Italy. The "High-elevation coniferous" and the "High elevation deciduous" resulted mainly affected by elevation, with the former characterized by low annual productivity and the latter by high seasonality. To the contrary, the "Low elevation deciduous" showed to be mostly associated to moderate climate conditions and a prolonged growing season. Finally, summer drought was the main driving variable for the "Mediterranean evergreen", characterized by low seasonality. The discrimination of vegetation phenology types can provide valuable information useful as a baseline framework for further studies on forests ecosystem and for management strategies.

1. Introduction

Monitoring vegetation phenology helps to detect the changes in ecosystem functions, providing baseline data to track vegetation dynamics related to events such as drought, fire, spring frost, land use changes, climate oscillations, etc. (Peñuelas et al., 2004; Xiao et al., 2015; Bascietto et al., 2018; Workie and Debella, 2018). The recent establishment of the USA National Phenology Network (USA-NPN; https://www.usanpn.org/), the Pan European Phenology Project (PEP725; http://www.pep725.eu/), the GLOBE phenology project (https://www.globe.gov/web/phenology-and-climate), suggest the need for a greater understanding of biological responses to a changing environment at different geographical scales (Lim et al., 2018). Remote sensing observations of seasonal greenness dynamics take advantage of the potentialities of high temporal resolution satellites (like MODIS) and represent a valuable tool for studying vegetation phenology at scales consistent with ecosystem-level processes and regional climate information (White and Nemani, 2006; Polgar Caroline and Primack Richard, 2011; D'Odorico et al., 2015; Xu et al., 2017).

Remotely-sensed phenology is the study of the timing of vegetation seasonal pattern of growth, senescence and dormancy, in a spatially aggregated form (e.g. pixel size of metres to km) (Gonsamo et al., 2012; Broich et al., 2015). Observed remotely-sensed phenology patterns are the response of heterogeneous land surface conditions, integrating multiple species, age classes and canopy layers within the ecosystem (D'Odorico et al., 2015).

Satellite-based green indices, such as the Normalized Difference Vegetation Index, NDVI (Rouse et al., 1973) and the Enhanced Vegetation Index, EVI (Huete et al., 2002), represent effective proxies of vegetation photosynthetic performance by exploiting the interaction of visible light with leaf pigments, and of near-infrared (NIR) energy with internal leaf and canopy structures (D'Odorico et al., 2015). NDVI is the most common green index used to study vegetation; however, it tends to saturate over dense canopies, like forested areas, losing sensitivity (Gitelson, 2004). EVI was hence proposed as a modified NDVI, having a larger dynamic range and atmospheric and soil background correction. As a consequence, EVI is more responsive than NDVI to detect forest seasonal variations, especially for dense and large canopy background

* Corresponding author.
E-mail address: carlotta.ferrara@crea.gov.it (C. Ferrara).

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such as broadleaved forests (Huete et al., 2014; Broich et al., 2015; Wang et al., 2017).

The time series analysis of vegetation indices allows for quantifying intra-annual changes in vegetation activity timing and intensity (Lasaponara, 2006; Balzter et al., 2007; Suepa et al., 2016; Wu et al., 2017), relating these changes to environmental processes and dynamics (Rojas et al., 2011; Bajocco et al., 2017; Bascietto et al., 2018), measuring the start, the end and the length of the growing season (Reed et al., 1994; Balzarolo et al., 2016; Baumann et al., 2017; Garonna et al., 2018), along with assessing the plant communities rhythms of growth, greening and senescing (Puppi, 2011).

The phenological timing of plant communities is regulated by the seasonal period strategic for growth and reproduction according to synchronizing (e.g. temperature, rain, frost, drought risks, topography, latitude) and asynchronizing (e.g. resource competition, seed dispersal, pollination) factors (Wheelwright, 1985; Primack, 1985). The synchronizing factors tend to homogenize the phenological behaviour of different species, such that plant communities can be identified by a characteristic phenological pattern (Puppi, 2011). Macroecological investigations have shown that similar phenological responses characterize species belonging to similar eco-regions (Thuiller et al., 2004; Chuine, 2010) due to their plastic response to some environmental conditions such as temperature, water availability or photoperiod (Chuine, 2010). Remote sensing provides ideal data to base regional vegetation phenology classifications on, since they consistently measure vegetation processes and functions in time and space (Wessels et al., 2009).

Given the huge amount of remotely sensed data, effective computing strategies are necessary to exploit the phenological information provided by long-term time series and to reduce data redundancy and processing complexity (Siachalou et al., 2015). Several studies used phenological clustering to classify pixels with an identifiable seasonal behaviour. White Michael et al., 2005 used k-means clustering in order to identify NDVI-based pheno-regions with similar vegetation phenology and climate, aiming to recognize areas with a minimized probability of non-climatic forcing for long-term phenological monitoring; Mills et al. (2011) proposed an approach (Forest Incidence Recognition and State Tracking, FIRST) based on clustering NDVI data, to provide an early warning system for differentiating between normal and abnormal phenology; Bajocco et al. (2015) derived a phenological map by hierarchical clustering homogenous territorial units of fuel in terms of seasonal NDVI Fourier harmonics; finally, Hoagland et al. (2018) derived NDVI-based pheno-classes and pheno-clusters to distinguish owl sites from random sites, and create habitat suitability maps.

Within this framework, we applied a multivariate clustering approach to a long-term MODIS EVI time-series (2001–2017) for investigating the phenological variability of forests in Italy and examining the different mechanisms of phenology response to biophysical drivers. The objectives of this study are: (i) classifying the Italian forests into phenological clusters (i.e. pheno-clusters), (ii) identifying the main phenological characteristics and the forest compositions of each pheno-cluster and (iii) exploring the role of climate and physiographic variables in the phenological timing of each cluster.

2. Material and methods

2.1. Study area

Italy is located in southern Europe, extending for about 300,000 km^2; it consists of the entirety of the Italian Peninsula and the two Mediterranean islands of Sicily and Sardinia, in addition to many smaller islands. Italy is largely surrounded by the sea, with a coastline of about 7600 km, including the islands. The country features about 23% flat zones (0–300 m a.s.l.), 42% hilly areas (300–800 m a.s.l.), and 35% mountainous regions (> 800 m a.s.l.) that are grouped in two major mountain ranges (the Alps and the Apennines). Given the longitudinal extension of the peninsula and the mountainous internal conformation, climate of Italy is highly variable. In most of the inland northern and central regions, the climate ranges from humid subtropical to humid continental and oceanic. In particular, the climate of the Po valley geographical region is mostly continental, with harsh winters and hot summers. The coastal areas of Liguria, Tuscany and most of the South is generally characterized by Mediterranean climate. Conditions on peninsular coastal areas can be very different from the mountainous inner zones, particularly during the winter months when the higher altitudes tend to be cold, wet, and often snowy. The coastal regions have mild winters and warm and dry summers. Average winter temperatures vary from 0 °C on the Alps to 12 °C in Sicily, while the average summer temperatures range from 20 °C to over 25 °C.

According to the Corine Land Cover (CLC) map of 2006, the main land uses are: agricultural lands (47.1%), subdivided into arable lands (22.8%), permanent crops (8.6%) and permanent pastures (15.7%), and forests (31.4%). The most widespread broadleaved forest categories are: *Quercus petraea*, *Q. pubescens* and *Q. robur* (12.6%); *Fagus sylvatica* (12%); *Q. cerris* and *Q. frainetto* (11.7%). Among the coniferous forests, the most common are: *Picea abies* (6.8%), *Larix decidua* and *Pinus cembra* (4.4%); *Pinus nigra* and *P. leucodermis* (2.7%); and *P. pinea* and *P. pinaster* (2.6%).

2.2. Forest types data

The Italian National Forests Inventory (INFI) was realized according to three phases of sampling. In the first phase Italy was covered by a grid of 306,831 cells, each being 1 km2 wide and a random point was selected in each cell. In the second phase, on the basis of aerial photos, the first-phase points were photo-interpreted. A set of randomly sampled points were assigned into a forest type (FT) by ground inspection if a surrounding area larger than 5000 m2 matched the same FT. In the third phase a sample of approximately 7,000 second phase-points was randomly selected and forest metrics were measured on ground (see Fattorini et al., 2006 for detail). In this work, we referred to the third phase INFI points and the forest types (FTs) considered are listed in Table 1.

2.3. Phenology data

The enhanced vegetation index (EVI) was developed to optimize the vegetation signal through a decoupling of the canopy background signal and also reducing the atmosphere effects (Huete et al., 2014; Broich et al., 2015; Wang et al., 2017). EVI is computed as follows:

$$EVI = G \text{ x } (\rho_{NIR} - \rho_{red}) / (\rho_{NIR} + C_1 \times \rho_{red} - C_2 \times \rho_{blue} + L)$$

Where G is the gain factor, ρ is the surface reflectance (atmospherically

Table 1
List of the INFI forest types (FTs) analyzed.

Forest types	
CON1 - *Larix decidua, Pinus cembra*	Coniferous
CON2 - *Picea abies*	
CON3 - *Abies alba*	
CON4 - *Pinus sylvestris, Pinus montana*	
CON5 - *Pinus nigra, P. laricio, P. leucodermis*	
CON6 - *Pinus pinea, P. pinaster*	
DECB1 - *Fagus sylvatica*	Deciduous broadleaved
DECB2 - *Quercus petraea, Q. pubescens, Q. robur*	
DECB3 - *Quercus cerris, Q. frainetto, Q. trojana*	
DECB4 - *Castanea sativa*	
DECB5 - *Ostryacarpinifolia*	
DECB6 - Hygrophilous woods	
EVEB1 - *Quercus ilex*	Evergreen broadleaved
EVEB2 - *Quercus suber*	