Estimation of gross and net primary production in a coastal forest area undergone to clearcuts

Marta Chiesi, Piero Battista, Lorenzo Bottai, Luca Fibbi, Francesco Manetti, Maurizio Pieri, Bernardo Rapi, Fabio Maselli

Abstract: The current study presents the application of a model combination strategy to analyse gross and net production in a Mediterranean pine wood ecosystem. The test site is in the San Rossore Regional Park (Central Italy), an area originally characterised by the presence of *Pinus pinaster* Ait and *Pinus pinea* L. Since 2004 the former species was attacked by an insect and was therefore subjected to clearcuts around 2012. The latter species, not affected by the insect, has continued to grow, reaching the senescent stage. The evolution of two large stands (i.e., one per species) in terms of gross and net primary production over the years 2013-2022 is then reconstructed by applying satellite-based and process-based models to different datasets: a daily meteorological one, a set of 16-day MODIS NDVI images at 250 m spatial resolution, a LiDAR image taken in 2015 and digital orthophotos referred to 2021. The study shows how this modelling strategy can be successfully used to analyse the influence of climate and management on this forest ecosystem, and to reconstruct the evolution of stands in different growing phase. Such assessment is relevant to provide the information required for sustainable forest management, concerning in particular carbon cycle ecosystem services.

Keywords: Mediterranean pines, development stage, *Matsucoccus feytaudi*, GPP, NPP.

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Introduction

Forest ecosystems play a fundamental role in the carbon (C) cycle at both local and global scales; studying and monitoring the main processes of these ecosystems is therefore fundamental [1,2]. This is generally achieved using two complementary tools, i.e., remote sensing and biogeochemical models. The former, in fact, provide synoptic and repetitive views of vegetation features and conditions at different spatial and temporal resolutions; on the other hand, the latter can simulate all main vegetation processes, and specifically forest photosynthesis and respirations. The two techniques are therefore suited to be combined for estimating forest C fluxes, and in particular gross and net primary production (GPP and NPP, respectively) [3].

An example of this approach is provided by the strategy developed and experimented by our research group [4]. This strategy consists in combining the outputs of a radiation use efficiency (RUE) model, Modified C-Fix, with those of a model of ecosystem processes, BIOME-BGC. The former requires remotely sensed NDVI images as a fundamental input, while the latter is driven by ancillary data descriptive of forest conditions. The results of the two models are finally combined taking into account the effects of forest disturbances through the use of the ecosystem equilibrium theory [4]. Owing to this configuration, the modelling strategy can be applied to analyze the response of forest ecosystems to climatic changes but is also suitable to investigate on the impact of human activities (forest thinning, clearcuts, etc.).

The current work illustrates how the modelling strategy can be applied to i) disentangle the contrasting impact of climatic and anthropogenic factors on forest ecosystems productivity and ii) estimate the respective evolutions in terms of GPP and NPP. The research is carried out in a Mediterranean coastal area, the San Rossore Regional Park (Central Italy), where two pine forest ecosystems are in different development phases due to the respective disturbance histories and the application of diversified management practices. Specifically, the impacts exerted during a decade (2013-2022) by these conditions on the evolutions of forest GPP and NPP are analyzed and discussed.

Materials and Methods

Study area

The San Rossore Regional Park is situated in a coastal plain close to Pisa (43.73° Lat. N, 10.28° Long. S; Figure 1). This area has been the subject of several investigations concerning all main forest processes, and particularly water and C fluxes, because it included a maritime pine (*Pinus pinaster* Ait.) forest where an eddy covariance flux tower was set at the end of 90es. This forest was then affected by the parasitic attack of an insect (*Matsucoccus feytaudi*) which damaged most pine trees, and was faced by extensive clearcuts carried out during 2009-2012 [5]. Since then, the forest is regrowing as a secondary ecological succession and most pine wood is now dense, with a mean height around 3÷5 m.

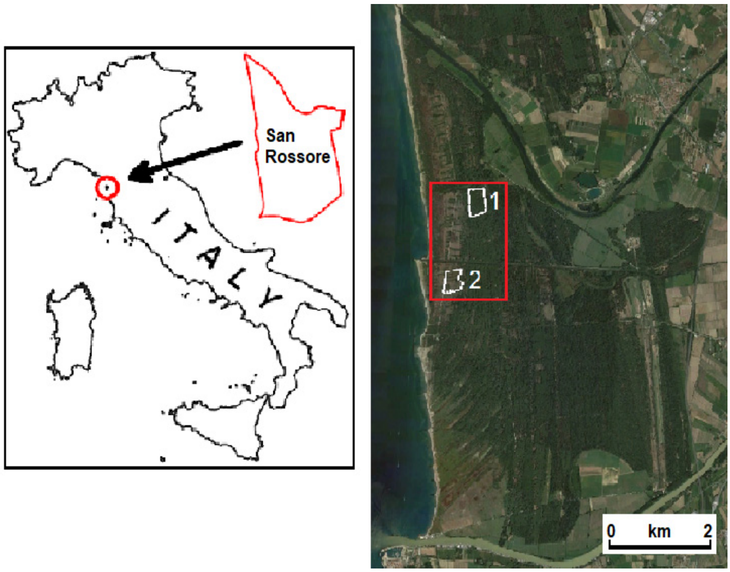


Figure 1 – Geographical position of the San Rossore Park in Italy (left) and 2021 Google Earth image of the park with the location of the selected pine forest stands (right). Stand 1 and 2 are dominated by umbrella pine and maritime pine, respectively.

An adjacent area of the Park, inner to the maritime pine stripe, is dominated by an umbrella pine (*Pinus pinea* L.) forest, which is not vulnerable to the *Matsucoccus* attack. Most of the stands covered by this species were planted more than 80-90 years ago, are now relatively dense and have a mean height of 20÷22 m [6].

The Park therefore includes two pine forest ecosystems which are subjected to the same climate but are in different development phases. This offers the opportunity to investigate on the impact of climatic and anthropogenic factors on forest gross and net primary production. The current study, in particular, focuses on two of the largest forest stands in the Park, the first covered by mature umbrella pines and the second covered by maritime pines which are rapidly regrowing after the clearcuts of 2009-2012 (Figures 1 and 2).

Study data

Daily meteorological data (i.e., minimum and maximum air temperature, precipitation and solar radiation) for ten years (2013-2022) were obtained applying the DAYMET and ERAD algorithms to the ground observations of the LaMMA Consortium [7,8].

NDVI images taken by the Moderate Resolution Imaging Spectroradiometer (MODIS) Terra/Aqua satellite sensor were downloaded from the NASA archive (https://modis.gsfc.nasa.gov). This archive contains pre-processed maximum value composite (MVC) images computed over 16-day periods, at a 250 m spatial resolution; those covering Tuscany over the same years as above (2013-2022) were further pre-processed in order to reduce residual atmospheric contaminations.

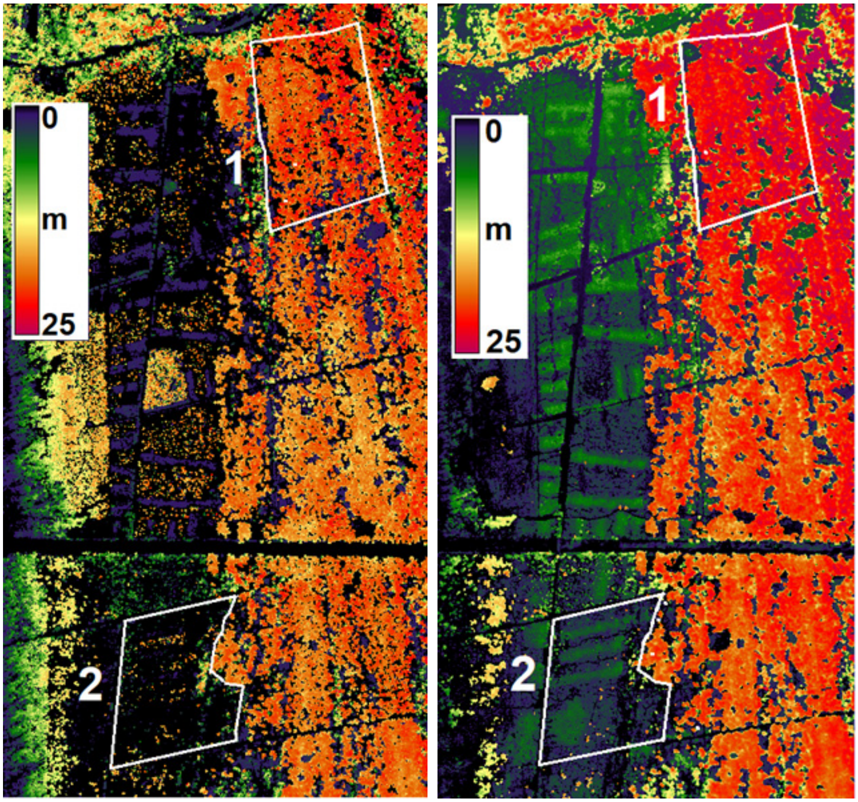
A high spatial resolution LiDAR acquisition taken over the Park by a low altitude aircraft flight in May 2015 was also utilized. The products available were 1-m spatial resolution Digital Surface and Digital Terrain Models (DSM and DTM, respectively), which were processed to obtain the Canopy Height Model (CHM) of the study area.

A digital orthophoto of the area was also available for 2021 (Figure 3). More specifically, frames from the August 2021 AGEA flight (flight altitude 2050 m, spatial resolution 0.15 m) were processed to obtain the DSM of the area; these data were processed by means of the Agisoft Metashape Professional software (Version 1.8.3). The main processing steps were the following:

- Georeferencing of the frames using the coordinates, the height of the photo-taking centers and the camera's flight attitude correction data (omega phi and kappa).
- Use of 12 Ground Control Points of known coordinates and elevation to improve the accuracy of the DSM regarding the height of the plants in the study area.
- Creation of 3D models by means of sequential processing steps, such as image alignment, creation of a dense point cloud and creation of 3D surfaces (tiled model).
- Building of the DSM from the dense cloud.
- Building of the DSM-based ortho-mosaic.

a b

Figure 2 – Photos of stand 1 (a) and stand 2 (b) taken in September 2023; the two stands are covered by umbrella pines and maritime pines, respectively.



a b

Figure 3 – CHM obtained from the ALS data of 2015 (a) and the orthophoto of 2021 (b) with superimposed boundaries of the umbrella pine (1) and the maritime pine (2) stands.

Modelling strategy

The main characteristics of the models applied (i.e., the satellite-based C-Fix and the process-based BIOME-BGC) and the combination of their outputs are summarized in the following paragraphs.

Modified C-Fix is a RUE model based on remotely sensed data that was proposed by [9] to improve the performance of the original version in water-limited environments. The new model version, in fact, in addition to air temperature, solar radiation and fAPAR, includes a water stress factor (Cws), that is computed by means of standard meteorological data and limits photosynthesis in cases of short-term water stress. Modified C-Fix, therefore, predicts the forest GPP of day i (GPP_i) as:

$$GPP_i = \varepsilon \cdot Tcor_i \cdot Cws_i \cdot fAPAR_i \cdot PAR_i \quad 1$$

where ε is the maximum radiation use efficiency (1.2 g C MJ^{-1} APAR); $Tcor_i$ is the MODIS temperature correction factor of the forest type following [10]; Cws_i is the water stress factor; $fAPAR_i$ is the fraction of absorbed PAR (derivable from remotely sensed vegetation indices) and PAR_i is the solar incident PAR. The water stress scalar of day i (Cws_i) is computed as:

$$Cws_i = 0.5 + 0.5\ AW_i \quad (2)$$

where AW_i is the ratio, bounded to 1, between rainfall and potential evapotranspiration, both cumulated over the preceding two months.

BIOME-BGC is a bio-geochemical model that simulates the storage and fluxes of water, C and nitrogen within the major terrestrial ecosystems [11]. It requires as input daily meteorological data, general environmental information (i.e., soil, vegetation and site conditions) and parameters describing the ecophysiological characteristics of the local vegetation. The model simulates photosynthesis, respiration and allocation processes corresponding to the requested study years, after having simulated the ecosystem quasi-equilibrium condition based on local eco-climatic features. The currently used model version (i.e., 4.2) includes parameter settings for seven main biome types that were modified to adapt to water-stress conditions.

C-Fix has the advantage of providing a direct remote sensing-based assessment of total forest GPP, while BIOME-BGC allows a complete simulation of all main ecosystem processes. This implies that BIOME-BGC functioning can be improved by multiplying its estimates for the ratio between C-Fix and BIOME-BGC GPP [4]. The same estimates can be corrected to account for the difference between actual and potential forest conditions, being the former mostly determined by natural and/or human-induced disturbances. Therefore, the ratio between the actual (measured or estimated) and potential (simulated by BIOME-BGC) growing stock volume (GSV) is taken as an indicator of the distance from ecosystem equilibrium and used to correct the photosynthesis and respiration estimates obtained by the model simulations. The actual forest NPP of day i (NPP_i) is consequently estimated as [12]:

$$NPP_i = GPP_i \cdot FC – Rgr_i \cdot FC - Rmn_i \cdot NV \quad (3)$$

where GPP_i, Rgr_i and Rmn_i represent the BIOME-BGC estimates of photosynthesis, growth and maintenance respirations, respectively, all improved by the combination with C-Fix GPP; the terms FC (forest cover) and NV (normalized volume) describe the ecosystem distance from the quasi-climax condition [4]. More specifically, NV is the mentioned ratio between actual and potential GSV and FC represents the fractional tree canopy cover obtained by combining NV and the potential tree leaf area index following Beer's law [4].

Data Processing

The data processing consisted of applying the combined modelling strategy to the two aforementioned forest stands: the first is an old-growth stand of about 15 ha dominated by umbrella pines, while the second is a stand of nearly 20 ha originally covered by the maritime pine, clearcut after the insect attack in 2012 and now occupied by a secondary succession (see also Figures 1-3).

The 2013-2022 daily meteorological data derived from the LaMMA database were combined with the NDVI values extracted from four MODIS pixels approximately coincident with the two stands. These data were used to drive Modified C-Fix (Equation 1), while a BIOME-BGC version parameterized for Mediterranean pines (both umbrella and maritime pines are included in this biome type) was applied using the ground datasets. Three series of GPP estimates were thus obtained, one yielded from the bio-geochemical model referred to both stands, the other two yielded from Modified C-Fix driven by the NDVI of the two stands (i.e., NDVI 1 for umbrella pine and NDVI 2 for maritime pine).

The application of BIOME-BGC also yielded NPP estimates descriptive of quasi-equilibrium condition. The actual status of the two stands was instead accounted for by the model combination strategy, i.e. through the application of Equation 3. The scalars required by this equation (NV and FC) were obtained from the analysis of the 2015 LiDAR dataset using the allometric relationships described in [13]. The two scalars were then annually updated by increasing the GSV values with the woody increments obtained from the conversion of the respective NPP estimates [14]. These model applications therefore yielded an additional series of annual NPP and GSV estimates for the two selected stands.

The evaluation of the modelling approach was performed by checking the reproduction of the NV values at 2021, year for which independent GSV observations were yielded by the analysis of the available orthophotos. The dependence of the estimated NPP series on the respective model drivers (i.e., the meteorological water stress factor and the NDVI) was finally evaluated by standard correlation analyses.

Results

Figure 4 shows the evolution of the meteorological water stress scalar (i.e. AW, as defined in Equation 2) in the study area during the examined 10-year period (2013-2022). A clear AW decrease is observed ($y = -0.018 x + 0.748$, $r^2 = 0.614$). This evolution is mostly due to a quite regular increase in mean air temperature, which induces a corresponding increase in land water demand, i.e., potential evapotranspiration (data not shown).

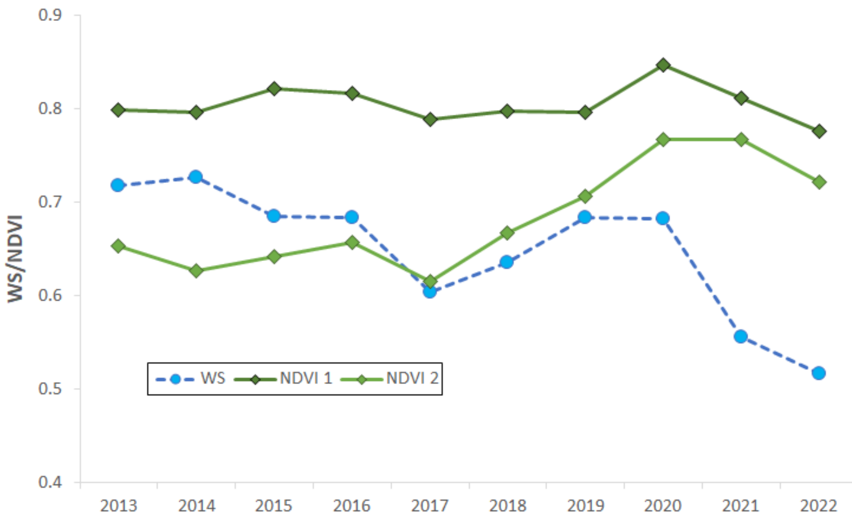


Figure 4 – Evolutions of WS (equalized to the AW scalar) and NDVI in the examined forest stands during the 2013-2022 period; NDVI 1 and NDVI 2 refer to stand 1 and stand 2, covered by umbrella pines and maritime pines, respectively.

The same figure shows the mean NDVI evolution of the umbrella pine (NDVI 1) and maritime pine (NDVI 2) stands. The former shows a nearly stable, high NDVI (i.e., equal to or higher than 0.8), which is dependent on the AW scalar (Table 1). This indicates that this forest stand maintains a nearly stable canopy cover, which is confirmed by the joint analysis of the two CHMs derived from the 2015 ALS data and the 2021 orthophotos (Figure 3a-b); in both cases, the pine tree canopy cover is over 0.8.

The maritime pine stand instead shows a NDVI increase in opposition to AW, i.e. from around 0.65 to about 0.8. This reveals the tendency to re-grow of the stand, typical of the secondary succession after the clearcuts of 2009-2012. Once again, the 2015 and 2021 CHMs corroborate this observation; in fact, while in the former almost no trees are detected, the latter reveals the presence of trees grown up to 6-8 m (see also Figures 2 and 3). This NDVI pattern is confirmed by the correlations of Table 1, particularly concerning the opposite trends of NDVI 2 and AW.

The use of these NDVI series to initialize the C-Fix model provides the GPP values shown in Figures 5 and 6. In the case of the umbrella pine stand, the simulated GPP is around 1900-2000 g C m^{-2} $year^{-1}$ and follows a slight decreasing trend (Figure 5), similar to that observed for AW. The same figure shows the evolution of NPP reconstructed after combining the outputs of two models and using the 2015 NV derived from the ALS data. The estimated NPP varies around 560 g C m^{-2} $year^{-1}$, with a minimum of 370 g C m^{-2} $year^{-1}$ in 2017 and a maximum of 733 g C m^{-2} $year^{-1}$ in 2020. The simulated NPP series is significantly dependent on both AW and NDVI (Table 1). The scalars of equation 3 used to initialize the simulation are descriptive of a mature forest (i.e., NV = 0.60 and FC = 0.72). This implies limited relative NV and FC increases simulated for the study period, which range from 0.58 to 0.64 and from 0.71 to 0.75, respectively. The correctness of this simulation is confirmed by the NV value estimated for 2021, that is very close to the observation (0.630 and 0.628 respectively).

Figure 6 shows the maritime pine evolutions of GPP, NPP and NV simulated as above. In the current case, the GPP increases from about 1380 to 1500 g C m^{-2} year^{-1} reflecting the already observed NDVI 2 increase in opposition to WS variation (see also Figure 4 and Table 1). The simulated NPP follows an increasing trend that is similar to that of NDVI, showing a highly significant correlation with this (Table 1). The NPP of this stand rises from about 500 to 1000 g C m^{-2} year^{-1}, concurrently with the NV scalar which increases from about 0.04 to 0.11, while FC rises from around 0.43 to 0.80. All these patterns are confirmed by the good correspondence between the NV values observed and simulated for the year 2021, which are both around 0.10.

Table 1 – Correlation between the major drivers and the simulated NPP at the selected pine forest stands (* = significant correlation, P<0.05; ** = highly significant correlation, P<0.01).

	NDVI 1	NDVI 2	NPP 1	NPP 2
AW	0.410*	-0.426*	0.773**	-0.547*
NDVI 1		0.364	0.645**	0.242
NDVI 2			0.197	0.931**
NPP 1				0.051

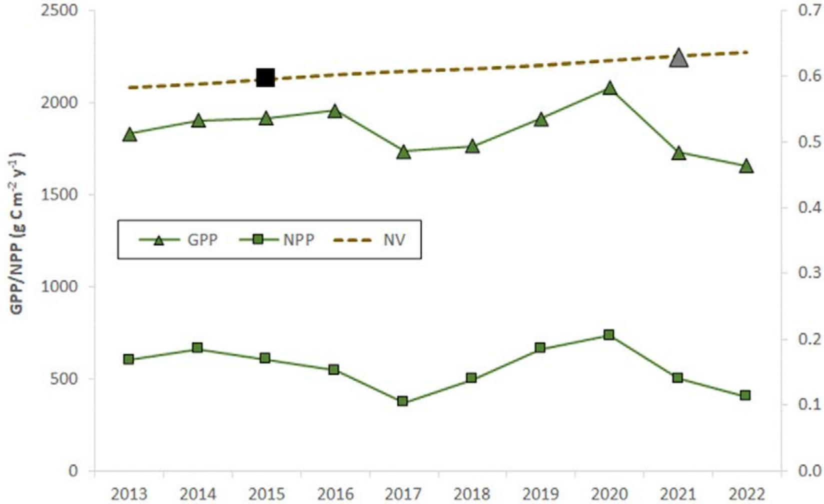


Figure 5 – Annual evolution of the GPP, NPP and NV of the umbrella pine stand during the 2013-2022 period; the black square and the grey triangle represent the NV values obtained from the ALS data of 2015 and the orthophotos of 2021, respectively.

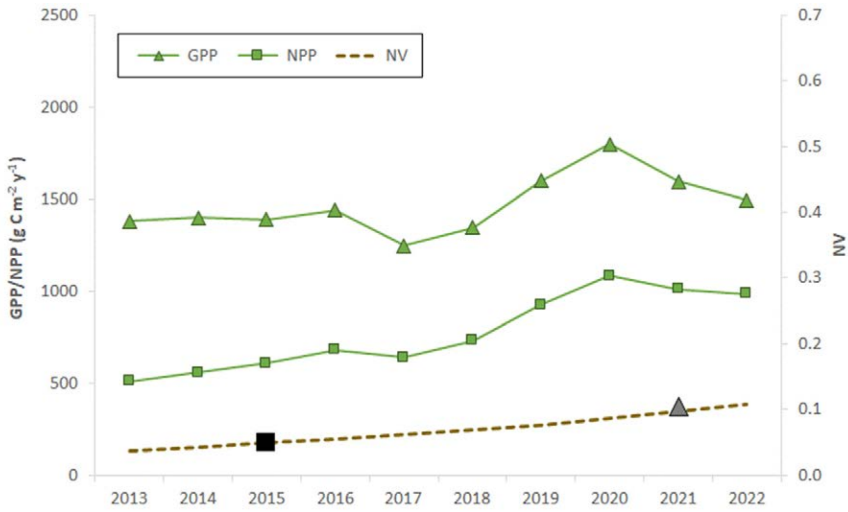


Figure 6 – Annual evolution of the GPP, NPP and NV of the maritime pine stand during the 2013-2022 period; the black square and the grey triangle represent the NV values obtained from the ALS data of 2015 and the orthophotos of 2021, respectively.

Discussion and Conclusion

The current study is based on the capability of Modified C-Fix to predict forest GPP in Mediterranean areas, which has been demonstrated in previous investigations [9]. A similar efficiency has been proved for the calibrated BIOME-BGC version to simulate all forest processes in the same region. The combination of the two model outcomes following the described strategy is then capable of predicting actual forest net C fluxes, i.e., affected not only by local climate and soil but also by anthropogenic disturbances.

Owing to these properties, the strategy can be applied to analyzing the impacts of both natural factors and human-induced disturbances on these fluxes. This has been currently done in a Mediterranean coastal area covered by two pine forest species in different development phases relying on the availability of ancillary and satellite data from various sources.

The results obtained show that the first stand, representative of the mature umbrella pine forest, is mostly controlled by meteorology, i.e., by the increasing dryness of the area, which induces slightly decreasing GPP and NPP trends. On the contrary, the second stand, representative of a secondary succession after clearcuts, counteracts the tendency to increasing dryness by rapid regrowing, which induces an almost constant increase of NDVI and, consequently, GPP. Still in accordance with the mentioned theory, the simulation of NPP is also affected by the progressive increase of the two vegetation scalars (NV and FC), which takes into account the intense biomass accumulation typical of the initial phase of a secondary succession. As a consequence, the NPP predicted for this stand starts from low values and rapidly increases up to relatively high levels. This phenomenon is obviously accompanied by an evident storage of woody biomass, which is testified to by the increasing tree canopy height observable in the field. The mean canopy height of the stand, in fact, rises from nearly 0 m in 2013 to 3-4 m in 2023.

While a complete validation of the GPP and NPP estimates found is not currently feasible, the mean values of these variables are comparable to those measured in similar environments. The average GPP values observed by an eddy covariance tower placed in the same area, in fact, were around 1600-1800 g C m^{-2} $year^{-1}$ [9].

The results currently achieved are affected by several sources of uncertainty. In addition to the limits of the modelling background, the use of different interpolated and remotely sensed input datasets inevitably introduces inaccuracy that cannot be quantified. In particular, a major uncertainty source derives from the different airborne sensors used to yield the CHMs of 2015 and 2021. In general, in fact, CHMs obtained from high spatial resolution ALS data are quite accurate, while this is less the case for CHMs derived from orthophotos [15]. This likely affects the results of the current analysis to a degree which is hardly quantifiable without independent observations collected on the ground.

The current work has therefore provided only a first indication of the potential of the proposed modelling strategy to quantify the different C accumulation capacities of forests subjected to the same meteorological constraints but in diverging development phases. Within this approach, the use of remotely sensed data collected from different sources is fundamental to characterise both the structure and the GPP of the different forest stands.

More generally, the capability to assess gross and net primary production is relevant for providing the information required for sustainable forest management, concerning in particular the ecosystem services linked to the C cycle. The potential of the strategy, however, should be confirmed by future investigations carried out using ground and remote sensing observations of both C fluxes and stocks taken in the same and other forest areas.

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