Assessment of forest GPP variations in central Italy

A. Rodolfi, M. Chiesi, G. Tagliaferri, P. Cherubini, and F. Maselli

Abstract: A debate is in progress concerning the possible effects of climate changes on the primary production of both natural and artificial ecosystems. The current investigation builds on the hypothesis that trends of increasing air temperature observed in several Italian regions should positively affect productivity of mountain forest ecosystems. Temperature rise in the Mugello valley (central Italy) in the period 1986–2001 was first confirmed by the analysis of data from a local station. The effects of this rise on the productivity of deciduous forest ecosystems (dominated by beech, *Fagus sylvatica* L.) were then analysed through estimates of the fraction of absorbed photosynthetically active radiation (FAPAR) derived from the US National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer satellite normalized difference vegetation index (NDVI) data. The use of a simplified parametric model (C-Fix) then allowed the combination of these FAPAR estimates with meteorological data (temperature and radiation) to produce annual values of forest gross primary productivity (GPP). Finally, validation of these GPP estimates was carried out by a comparison with dendrochronological measurements taken in the study forests. Because tree measurements were affected by external factors not exclusively related to forest GPP (stand aging, management practices, etc.), the comparison gave positive results only after applying a detrending operation to both series of annual GPP estimates and dendrochronological data. These results are a first indication that the rise in temperature that has occurred in Italy in the last decades has positively affected the productivity of mountain forest ecosystems.

Résumé : Un débat est en cours en ce qui concerne les effets possibles des changements climatiques sur la production primaire des écosystèmes naturels et artificiels. Cette recherche est basée sur l'hypothèse voulant que la tendance à une augmentation de la température de l'air observée dans plusieurs régions de l'Italie affecte positivement la productivité des écosystèmes forestiers de montagne. La hausse de température dans la vallée de Mugello (centre de l'Italie) durant la période de 1986 à 2001 a été confirmée pour la première fois par l'analyse des données d'une station locale. Les effets de cette hausse sur la productivité des écosystèmes forestiers feuillus (dominés par le hêtre, *Fagus sylvatica* L.) ont ensuite été analysés à l'aide d'estimations de la fraction absorbée du rayonnement photosynthétiquement actif (FARPA) dérivées de données de l'indice de végétation différentielle normalisé selon NOAA-AVHRR. L'utilisation d'un modèle paramétrique simplifié (C-Fix) a ensuite permis de combiner ces estimations de FARPA avec les données météorologiques (température et rayonnement) pour produire des valeurs annuelles de productivité primaire brute (PPB) de la forêt. Finalement, la validation de ces estimations de PPB a été réalisée à l'aide de comparaisons avec des mesures dendrochronologiques prises dans les forêts étudiées. Puisque ces dernières mesures étaient affectées par des facteurs externes pas toujours exclusivement reliés à la PPB de la forêt (vieillissement des peuplements, pratiques d'aménagement, etc.), les comparaisons ont produit des résultats positifs uniquement après avoir appliqué une opération de redressement aux séries d'estimation de PPB et aux données dendrochronologiques. Ces résultats sont une première indication que la hausse de température survenue en Italie au cours des dernières décennies a positivement affecté la productivité des écosystèmes forestiers de montagne.

[Traduit par la Rédaction]

Introduction

An important area of research aims at assessing the possible causes and effects of climate variations, which in most areas correspond to evident trends in temperatures and rainfall. Following the increased attention of the scientific community and the mass media, the Intergovernmental Panel on Climate Change (IPCC) was created in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP). In its latest report, the IPCC indicates that, for Europe, the most evident consequences of these changes will be an increase in temperature and a decrease in summer precipitation accompanied by a tendency towards extreme events (IPCC 2001). These effects should be particularly evident in most southern European countries.

Regarding Italy, the analysis of meteorological time series recorded at a number of stations spread over the whole national territory indicates an increase of air temperature, which occurred approximately in the last century (Maugeri and Nanni 1998; Brunetti et al. 2000). Such an increase was particularly evident from 1980 to 2003 (Brunetti et al. 2006) and had a magnitude that is more or less comparable to estimates obtained for the whole Northern Hemisphere by Jones et al. (1999). The temperature increase was generally higher

Received 17 July 2006. Accepted 11 January 2007. Published on the NRC Research Press Web site at cjfr.nrc.ca on 19 October 2007.

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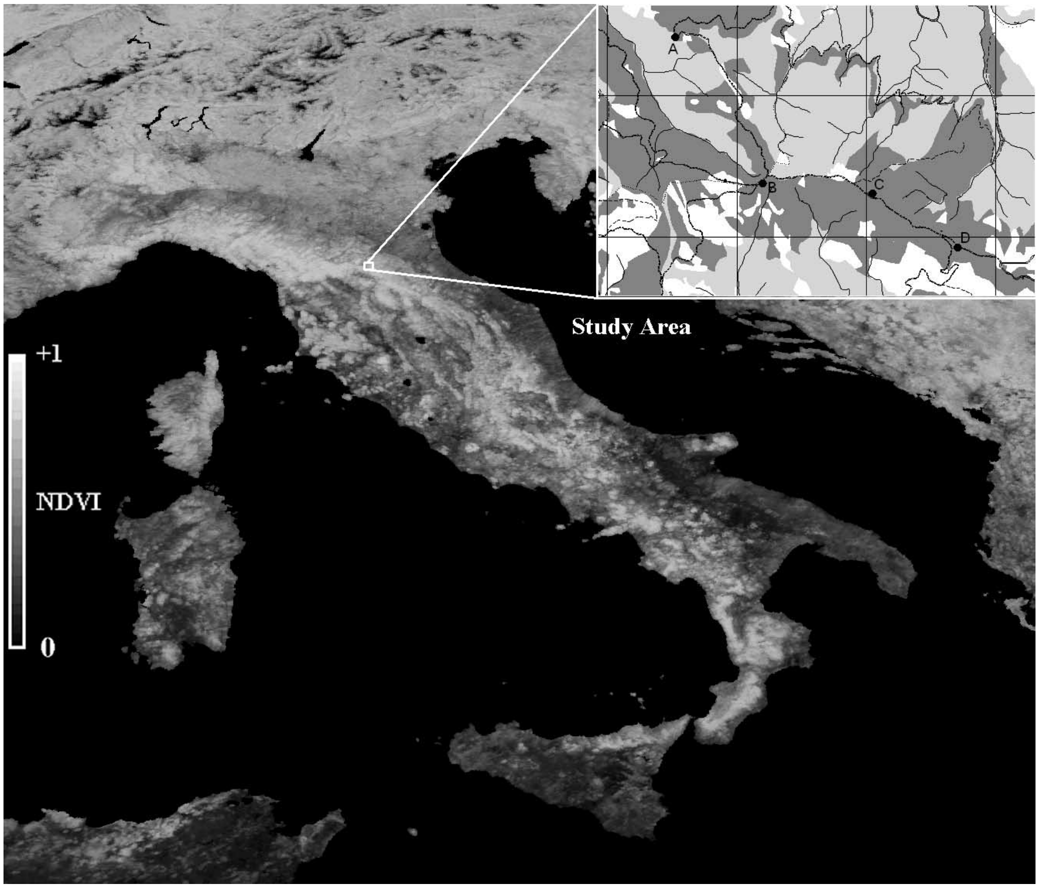
 doi:10.1139/X07-010

Fig. 1. National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer image of August 2001 showing the position of the study area in Italy and, in the enlarged rectangle, a map with the location of the four beech stands examined. In the latter map, heavily shaded areas are high forest, lightly shaded areas are coppices, and open areas are pastures and agricultural areas. The grid spacing is 1 km. Broken lines are the road network, and continuous lines are streams.



in summer (up to 2.0 °C in the last 20 years) than in autumn–winter (0.5–1.0 °C in the same period). However, the complex Italian orography and its position in the middle of the Mediterranean Sea imply strong effects of local air circulation, which cause high spatial and temporal climate variability (Pasquale et al. 2005).

Changes in temperature can affect both natural and artificial ecosystems with consequences that are all under discussion. More specifically, temperature increases are expected to induce increases in vegetation gross primary productivity (GPP) of forest ecosystems placed in temperate–cold zones (Scarascia-Mugnozza 2000). Such climatic variations should in fact positively influence the length of the growing season and the photosynthetic activity of vegetation whose growth is mainly limited by temperature and only marginally affected by other environmental factors (Odum 1971; Hughes 2002).

The validation of this hypothesis over wide areas should be based on the availability of long-term series of forest production estimates. However, obtaining such a series is not simple by conventional methodologies because of intrinsic problems of spatial and temporal measurement scales (Waring and Running 1998). Recent studies have demonstrated that a simplified Monteith modelling approach based on the use of remotely sensed estimates of the fraction of absorbed photosynthetically active radiation (FAPAR) is able to evaluate both gross and net productivity patterns of Italian forest ecosystems (Chirici et al. 2007; Maselli et al. 2006). This is obtained by the application of C-Fix, a parametric model that combines FAPAR estimates derived from normalised difference vegetation index (NDVI) data with meteorological measurements (temperature and radiation) (Veroustraete et al. 2002, 2004). However, these works did not evaluate possible interyear productivity variations over relatively long time periods. Although this evaluation is feasible from a technical viewpoint, its validation remains problematic because of the above-mentioned complexity of obtaining multiyear series of reference forest productivity measurements.

The present proposal is that such validation can be pursued by the use of dendrochronological data collected in representative forest stands. In fact, such data are informative about the accumulation of woody biomass occurring in the forests over a rather long time period (Bascietto et al. 2004). However, dendrochronological measurements are strongly affected by several factors, such as stand age, forest management operations, etc. This renders necessary the application of statistical operations to correctly highlight climate-driven forest productivity variations (Fritts 1976).

Building on these considerations, the current work aimed first at ascertaining the existence of temperature increases in a mountain zone of central Italy during a 16 year period

Table 1. Characteristics of the four beech stands in the study.

	Topography					Forest characteristics			
Plot	Longitude	Latitude	Elevation (m a.s.l.)	Slope (°)	Aspect (°)	Mean DBH (cm)	Mean height (m)	Density (no./ha)	Leaf area index
A	11.44°E	44.06°N	983	11.5	259.9	18.0	13.0	1250	6.0
B	11.45°E	44.05°N	1019	10.0	224.4	20.0	13.5	930	5.5
C	11.46°E	44.05°N	1075	21.0	215.7	19.5	15.0	940	5.4
D	11.47°E	44.05°N	1045	10.9	207.7	22.0	16.0	780	6.2

(1986–2001). The effect of such increases on forest productivity were then evaluated through the use of C-Fix. Finally, this productivity change was validated by comparison with annual increments of woody biomass derived from dendrochronological measurements.

Study area

The study area was situated in the upper part of the Mugello Valley (central Italy, 11.45°E, 44.06°N), and consisted of four adjacent forest stands (Fig. 1). All these stands are located within a radius of about 3 km at a mean altitude of about 1000 m a.s.l. The area is characterized by relatively cold winters with a mean temperature of 9.3 °C. The warmest months are July and August with a mean temperature of about 18 °C, whereas the coldest month is January with a mean temperature of about 1 °C. Snow cover is usually present 1 month per year (January–February). The annual precipitation is around 1400 mm.

All four forest stands are characterized by the presence of European beech (*Fagus sylvatica* L.) and are inside the Giogo-Casaglia forest area, which is managed by the regional government of Tuscany. These stands, whose main characteristics are given in Table 1, were originally managed as a coppice, which is now under conversion into a high forest. The four stands were recently subjected to thinning operations, which strongly reduced tree density. These operations were carried out between 1993 and 1997 but in different years and with different intensities, which were not precisely recorded in the local forest management plan.

Study data

Ancillary data

A forest map was drawn up from the forest management plan of the area to obtain information concerning tree species distribution. The map is available in a digital format at the nominal scale of 1 : 10 000.

Meteorological data were derived from nearby weather stations. The use of records from different stations was necessary to obtain a long and consistent data set. Daily temperatures were taken from the station at Firenzuola (422 m a.s.l.; approximately 10 km from the forest sites), and precipitation data were obtained from the station at Razzuolo (637 m a.s.l.; less than 4 km from the forest sites). In all cases, the temporal series taken into consideration were the years 1986–2001. Furthermore, daily air temperatures were taken only for 1999 from the weather station at Passo Giogo (880 m a.s.l.), which is adjacent to the selected forest areas.

Remotely sensed data

National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) images were derived from the archive of Istituto di Biometeorologia, Consiglio Nazionale delle Ricerche, Firenze (IBIMET-CNR), for the period 1986–2001. These images are 10 day maximum value composite (MVC) normalized difference vegetation index (NDVI) data geolocated in a latitude–longitude reference system with a pixel resolution of 0.01° (Bolle et al. 2006). The procedure applied to obtain these images consisted of their georeferencing by a nearest neighbour resampling algorithm, a radiometric calibration of the first two channels to derive top-of-atmosphere reflectances following Bolle et al. (2006), and the computation of NDVI values to finally obtain MVCs on a 10 day basis (Holben 1986).

Dendrochronological data

In each forest site, 12 trees were selected and cored by a 0.5 cm diameter increment borer in July 2002. In particular, two different cores (one opposite the other) at breast height were collected from each tree and they were analyzed in the dendrochronological laboratories of the Swiss Federal Institute of Snow and Landscape Research WSL, Birmensdorf, Switzerland.

Cores were carefully mounted on channelled wood, seasoned in a fresh-air dry storage, and sanded a few weeks later so that their transversal section became visible. All the tree rings were dated by counting the number of tree rings from bark to pith. Ring-width measurements were made to the nearest 0.01 mm, using LINTAB measurement equipment and the TSAP software package (Frank Rinn, Heidelberg, Germany). The raw ring widths of the single curves of each dated tree were plotted, cross-dated visually, and then cross-dated statistically by (*i*) the *Gleichläufigkeit* (there is no English equivalent to this term), which is the percentage agreement in the signs of the first differences of two time series, and (*ii*) the Student's *t* test, which determines the degree of correlation between the curves. Standard methods were used to build an average series for each tree and for each site (Fritts 1976; Cook et al. 1990).

Data processing

Extrapolation and analysis of meteorological data (annual and monthly)

Daily meteorological data for the whole study period (1986–2001) were reconstructed for each forest stand by adapting the available weather measurements to the local conditions of the study stand. This was carried out by first computing linear regressions between the minimum and maximum daily temperatures collected at Firenzuola and Passo Giogo for 1999. The conversion formulas obtained were applied to the whole daily data series of Firenzuola (1986–2001). Next, the MT-CLIM procedure (Thornton and Running 1999) was used to determine the correct minimum and maximum temperatures and solar radiation for the four forest stands based on their topographic positions (altitude, slope, and aspect).

Regarding daily precipitation, all four stands were within limited horizontal and vertical distances from the Razzuolo measurement station (less than 4 km and about 350 m, respectively). The proximity of the studied sites to the station where the precipitation data was collected, in addition to the well-known complexity of extrapolating daily rainfall, led to the choice of applying no conversion equation to these data.

The temperature and rainfall data extrapolated at the study stands for the period 1986–2001 were used to draw a thermopluviometric diagram characterizing the recent climate of the area.

Extraction and analysis of NDVI data

A preliminary visual examination of the available 10 day NOAA AVHRR NDVI images indicated that they contained a variable number of pixels with erroneous values. Therefore, a specific procedure was applied for the reduction of all these defects, which is fully described in Escadafal et al. (2001). This procedure consisted of a preliminary cosmetic filtering applied to all original images to identify isolated anomalous pixels and replace them by local NDVI averaging. This was followed by an additional correction aimed at removing atmospheric contamination for periods with high cloud cover. This last algorithm, originally proposed by White et al. (1997), is based on the concept that abrupt decreases in NDVI followed by relatively fast recoveries (within approximately two or three 10 day periods) can be safely attributed to the effects of clouds. Therefore, such decreases can be removed and replaced by a moving average operation. The application of the complete correction procedure yielded 10 day MVC images of a quality considered acceptable for subsequent analysis.

The AVHRR imagery was produced from atmospherically uncorrected data, which requires an additional transformation aimed at making the NDVI values compatible with top-of-canopy estimates. This was done by applying a normalization factor of 1.35, derived from Maselli (2004) and Bolle et al. (2006). Moreover, a further correction factor (0.936) was applied to the AVHRR NDVI imagery after 2000, when a transition from the NOAA-14 to the NOAA-16 satellite acquisitions occurred. In fact, the NDVI values from the latter satellite were found to be consistently higher than those from the previous ones (Bolle et al. 2006).

The four study stands are adjacent to pastures and agricultural areas (see Fig. 1), which makes almost all AVHRR pixels occupied by mixed cover types. For this reason, a procedure had to be applied to extract the NDVI values of the beech forest from the images. The procedure applied was that proposed by Maselli (2001), which is capable of extracting the pure NDVI values of cover classes whose distribution is known from a higher resolution map. Using the available forest map as a reference, NDVI values of the beech forest were extracted by applying the locally calibrated end-member identification method of Maselli (2001) to all available NDVI images. This produced thirty-six 10 day NDVI values for each beech stand and for each year over the period 1986–2001.

Computation of forest GPP

GPP data were obtained for each forest stand by the application of the parametric model C-Fix (Veroustraete et al. 2002, 2004). This model relies on the use of FAPAR estimates, which were currently gathered from the previously extracted NDVI data by the linear equation (Myneni and Williams 1994)

$$[1] \qquad \mathrm{FAPAR} = a(\mathrm{NDVI}) + b$$

where NDVI is the top-of-canopy NDVI data for the forest and a and b are 1.1638 and –0.1426, respectively. These FAPAR data were then combined with meteorological data to derive GPP estimates according to the following equation

$$[2] \qquad \mathrm{GPP} = \varepsilon \sum_{i=1}^{t} (\mathrm{FAPAR}_i \times \mathrm{SR}_i) T_{\mathrm{cor}}$$

where ε is the light use efficiency coefficient of absorbed photosynthetically active radiation (APAR; g C·MJ^{-1}), FAPAR is the fraction of photosynthetically active radiation absorbed (dim), T_{cor} is the temperature correction factor accounting for the effect of daily air temperature on photosynthesis, and SR is solar radiation (MJ·m^{-2}·day^{-1}). In the current case, daily air temperature and solar radiation were computed by MT-CLIM as described previously, whereas an ε value of 1.1 g C·MJ^{-1} was chosen for the light use efficiency coefficient following Veroustraete et al. (2004) and Maselli et al. (2006).

Trend analysis of the various data series

The possible changes in air temperature during the study period were first investigated by applying linear trend analyses to the relevant values averaged over the 10 day periods. To this aim, mean daily air temperature over each of these periods was first computed. All four forest stands were considered together, because they were characterized by very subtle differences in temperature computed by MT-CLIM. Next, linear trend analyses were performed by the application of a usual least-squares method to the data of all thirty-six 10 day periods over the 16 study years.

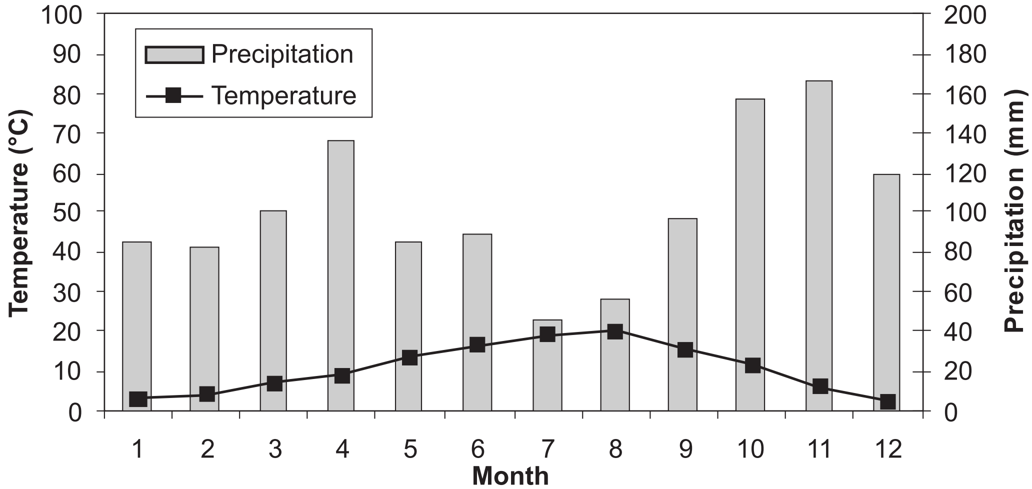
The forest NDVI data were subjected to trend analyses similar to the temperature data. This was done by applying the same least-squares method to the NDVI-derived FAPAR estimates of each 10 day period over the 16 years. In this case too, the values of the four stands were considered jointly, again because they were almost identical.

Finally, the same trend analysis was applied to the GPP estimates of each 10 day period. The trend analyses for each 10 day period were followed by similar analyses over annual GPP values for each forest stand.

Regression of forest GPP against dendrochronological data

The validation of the annual GPP variations previously found was made against the available annual ring widths measured over the study years (1986–2001). Several investigations have shown that such ring widths are indicative of the woody biomass accumulated by trees during different

Fig. 2. Thermopluviometric diagram obtained by processing the meteorological data collected from 1986 to 2001 and extrapolated to the study stands (see text for details). Months are (1) January to (12) December.



growing seasons (e.g., see Bascietto et al. 2004; Chiesi et al. 2005). As mentioned above, the analysis had to take into account the possible effects of stand aging and human disturbances on tree-ring growth, which could mask possible consistent trends in woody biomass accumulation.

A preliminary correlation analysis was performed between the original annual GPP estimates found previously and the relevant ring-width values obtained by the analysis of the tree rings. Next, a detrending operation was applied to both data series to reduce the possible influence of the mentioned disturbing factors. This was obtained by applying the following equation to the annual series of both measured ring widths and estimated GPP values:

$$[3] \qquad Y_{\mathrm{detr}} = \frac{Y - \overline{Y}}{\sigma_Y}$$

where Y_{detr} is the detrended value of the annual core increment or GPP, Y is the original value, and $\overline{Y}$ and σ_Y are the relevant 3 year moving mean and standard deviation (i.e., computed over the previous, current, and following years with respect to each sample year). This operation is widely applied in statistical and ecological studies as a means to remove the effect of disturbing factors from the analysis of time series data (Fritts 1976). Although substantially reducing the effects of possible trends, such detrending should not alter other major statistical properties of the original data, and in particular, it should not introduce artificial correlation between independent data series (e.g., see Cook et al. 1990).

Results

Trend analyses

Figure 2 shows the thermopluviometric diagram reporting the mean monthly temperature and precipitation estimated at the study stands for the period 1986–2001. This diagram confirms the temperate–humid nature of the local climate and indicates that only limited water stress may exist in the hottest month (July). Mean summer rainfall (June–August) exceeded 190 mm, and mean summer temperature was 18.6 °C. These values indicate a climate that is much more humid than those generally considered as typical of Mediterranean environments with an arid summer season (Rapetti and Vittorini 1995). Therefore, rainfall was assumed not to be a limiting factor for plant growth during the whole year, which justified the removal of this parameter from subsequent analysis.

The results of the linear trend analyses of the temperature data are shown in Fig. 3*a*. Almost all slopes of the mean temperatures for each 10 day period during the 16 study years (1986–2001) are positive, which indicates general temperature increases during the observed period. These increases are particularly evident in late winter (February–March) and late spring (May–June) and can be expected to lengthen the growing season and to increase the photosynthetic activity of forest vegetation.

These expectations are mostly supported by the trends in the forest NDVI data series (Fig. 3*b*). These are positive for most of the growing season, with evident peaks in late winter and summer–fall.

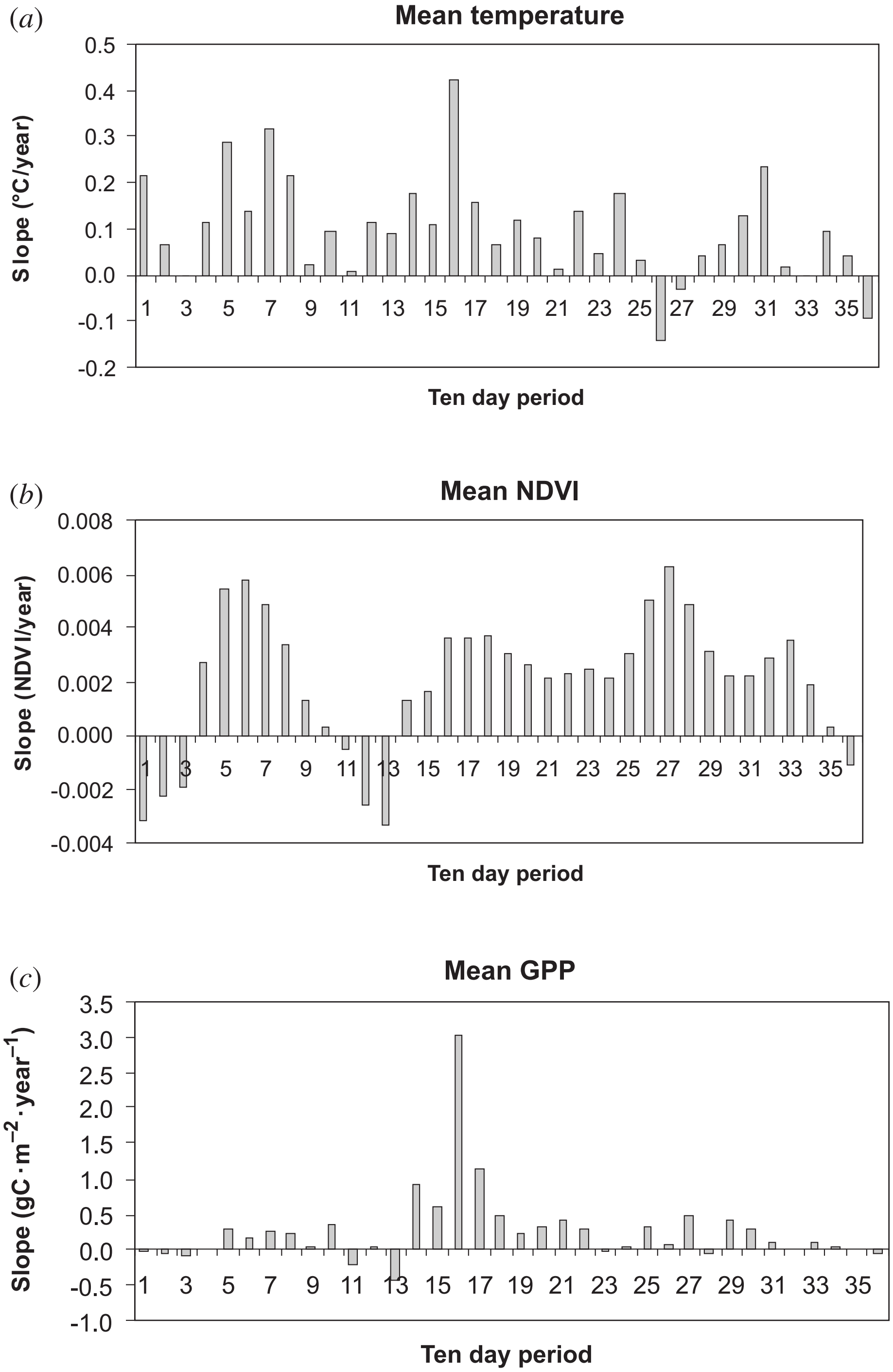
The combined effect of increasing temperature (and therefore of the temperature correction factor) and NDVI (and therefore estimated FAPAR) obviously results in GPP estimates showing increasing trends. This can be appreciated in Fig. 3*c*, where a clear peak in GPP increase can be noted during late spring.

As a consequence of the GPP increases found in some 10 day periods, the annual GPP estimates also show positive trends for all four forest stands. This can be noted in Figs. 4*a*–4*d*, where the annual GPP estimates for each stand are plotted against the years. All slopes of annual ecosystem GPP are positive and statistically significant (about 10 g C·m^{-2}·year^{-1}; $P < 0.05$).

Validation against ring width chronologies

The ring-width chronologies are also shown in Figs. 4*a*–4*d*. No consistent trend is present in these values, which can be explained by the previous consideration that tree-ring growth is affected by both forest ageing and management practices. The former factor tends to reduce the annual ring width growth because of both geometric (the same increase in woody biomass corresponds to progressively de-

Fig. 3. Linear trends found for each annual 10 day period for mean temperature values (*a*), mean NDVI (*b*), and mean GPP (*c*).



creasing radius increments while the stem grows) and eco-physiological reasons (woody biomass accumulation tends to level off as the stand trees senesce). Forest management practices instead have a more unpredictable effect, which is generally the combination of immediate forest disturbance and subsequent recovery (Wei et al. 2003; Black and Abrams 2004).

The possible effects of forest management operations can be appreciated by a careful examination of Figs. 4*a*–4*d*. The periods immediately following these operations (1996–1997) generally correspond to discontinuities in the increment patterns, i.e., growth releases after suppression. However, these patterns are quite irregular and not the same for all stands, most likely because of the previously mentioned complexity of the tree responses to forestry practices applied at slightly different periods.

The detrending operation applied to the annual core increments and GPP estimates removed most of these influences, thus enhancing the correlation between these two variables (Fig. 5). All correlations between detrended values are strongly increased with respect to the original data, becoming significant ($P < 0.05$) in one case and highly significant

Fig. 4. Measured ring width of the four study stands (*a*–*d* for stands A–D, respectively) derived from dendrochronological data (right-hand *y* axes) and annual GPP estimates obtained by C-Fix (left-hand *y* axes) for the 16 study years. Whereas the slopes of ring widths are close to zero, those of ecosystem GPP are positive and statistically significant (about 10 g $C \cdot m^{-2} \cdot year^{-1}$, $P < 0.05$). All correlations between the ring width and GPP estimates are very low (between −0.09 and 0.25) and not significant.

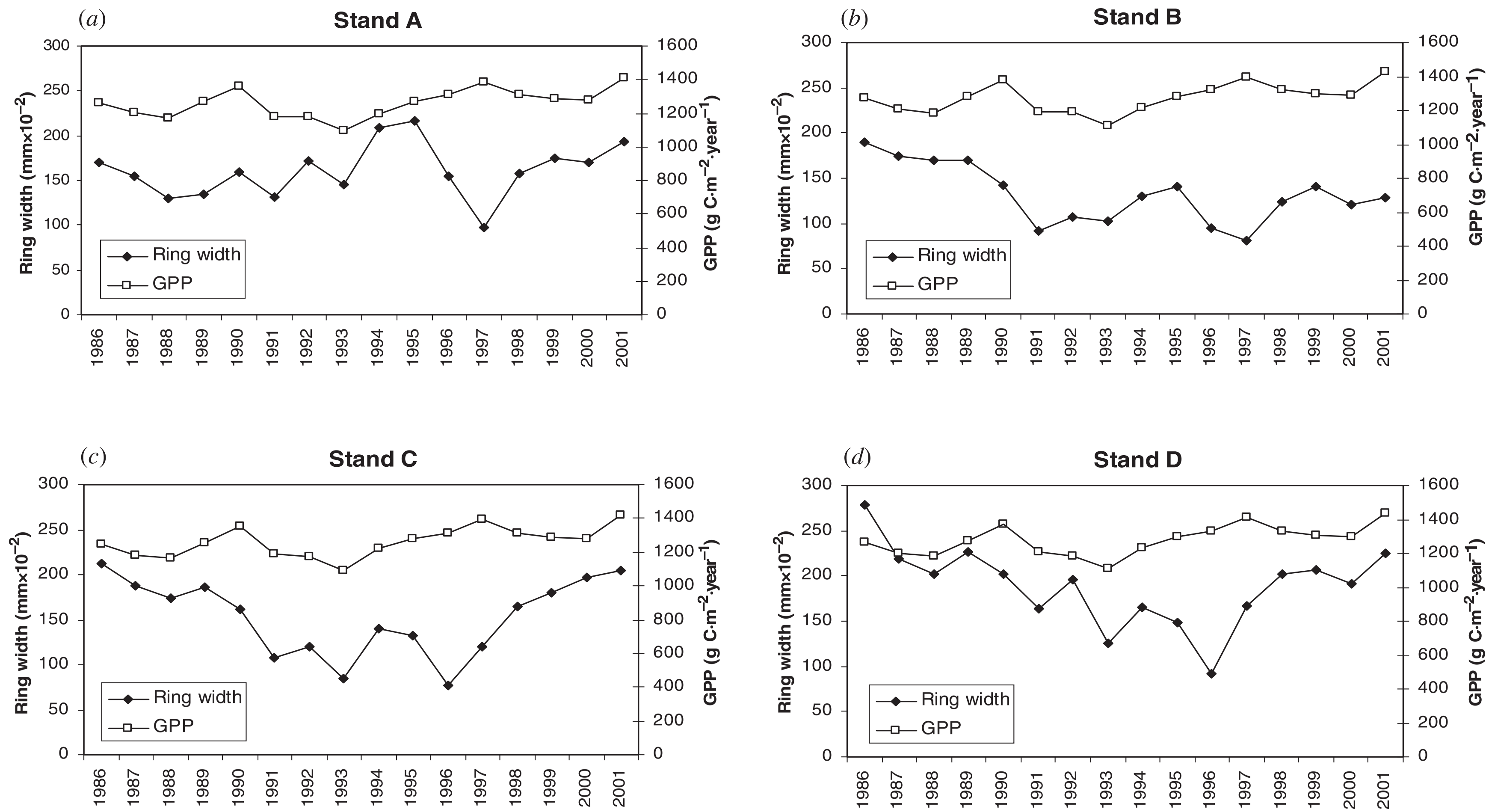
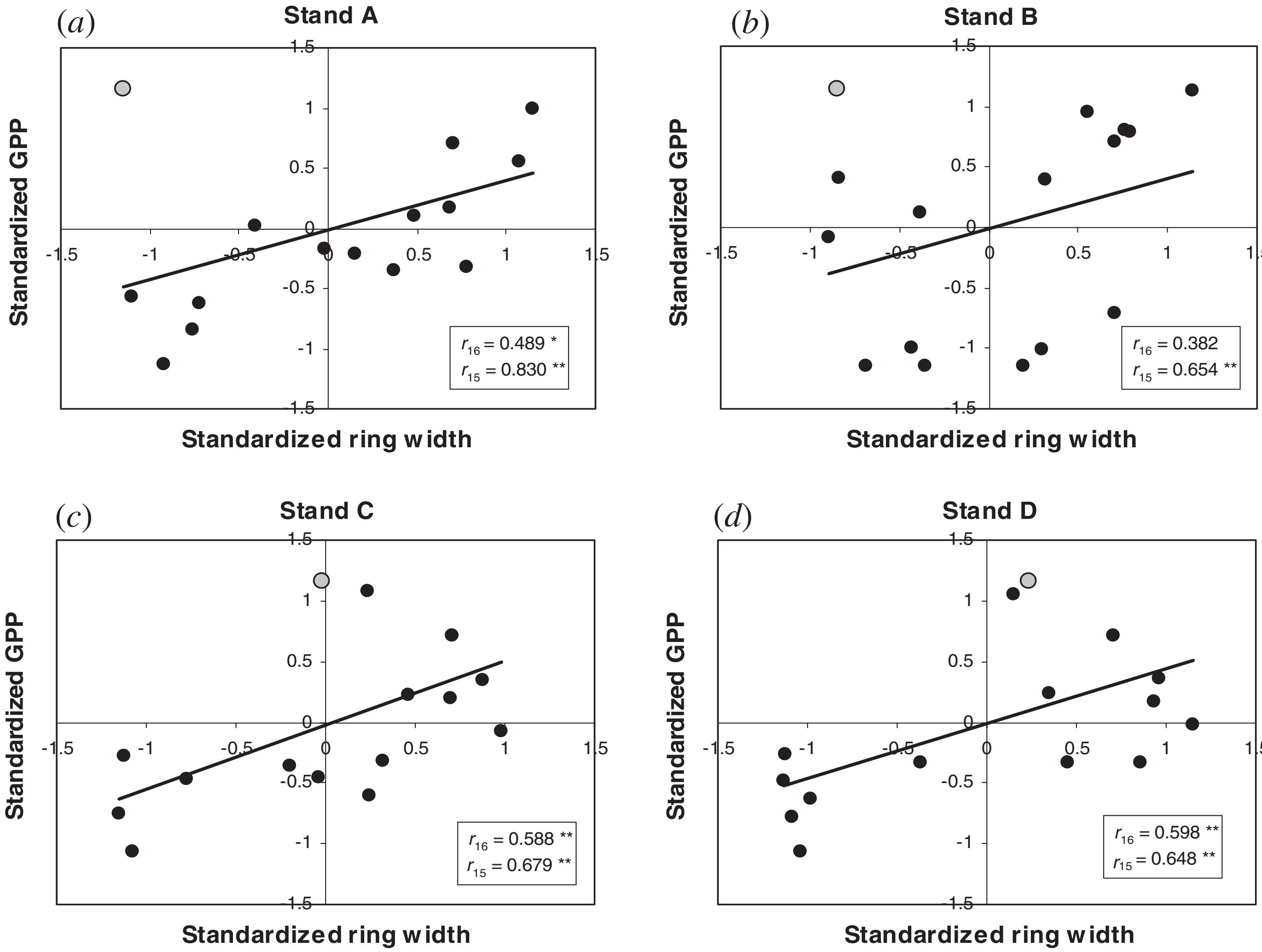


Fig. 5. Standardized measured ring width versus standardized estimated GPP for the four study stands (*a–d* for stands A–D, respectively). The upper correlations in each panel (r_{16}) are for all values in the data series, and the lower correlations (r_{15}) were computed after removal of the values of one year (1997, ●). Asterisks show significant correlations: *, $P < 0.05$; **, $P < 0.01$.



($P < 0.01$) in two cases. A further trial was made by removing the increment and GPP values of 1997, which was the year immediately followed the thinning operations. As can be seen in the same scatter plots, these values mostly correspond to outliers within the detrended correlation analyses, especially for the first two stands. Consequently, their removal leads to further improvement in the correlation between tree rings and GPP estimates, which all become highly significant.

Discussion and conclusions

The work reported in this paper is primarily aimed at evaluating the use of remotely sensed data to analyze the possible effect of climate changes on the photosynthetic capacity of a mountain forest ecosystem in central Italy. This was carried out by the use of multiyear (1986–2001) series of meteorological data and low-resolution NOAA AVHRR NDVI images. First, increases of air temperatures similar to those already found in other Italian areas were confirmed for most of the seasons of the period under examination (1986–2001). These increases corresponded to diffuse increases in NDVI-derived FAPAR estimates, which were particularly evident in late winter and spring–summer. Such findings are in agreement with the results of previous global studies and regional-scale investigations in Europe, which showed similar changes in vegetation photosynthetic activity consequent to temperature or rainfall variations (Kawabata et al. 2001; Ichii et al. 2002; Nemani et al. 2003; Stockli and Vidale 2004).

Forest productivity estimates were then derived from the combination of meteorological and remote sensing data through a parametric model (C-Fix). Following the increases of the original meteorological and FAPAR data, these estimates also showed clearly increasing trends during the study period. However, the existence of such trends was difficult to validate against independent ground data, such as woody biomass accumulation measurements derived from tree ring widths. In fact, the GPP estimates obtained corresponded to the global photosynthetic activity of all green species contained in the study stands (pixels). On the contrary, tree ring widths were related only to the upper layers of the forest ecosystems, which were strongly influenced by variations in tree density and trophic conditions determined by human activities. As a consequence, correlation analyses carried out between the original GPP estimates and measured core increments gave very poor results. The problem was circumvented by applying a detrending operation to both data series, which allowed the identification of significant correlations between them.

The current results are a first indication that productivity patterns of Italian forest ecosystems have actually changed in response to analogous changes in climatic limiting factors. In this regard, the positive effect of increasing temperatures currently found in forest mountain areas is the counterpart of the negative effect of decreasing rainfall recently found in Mediterranean coniferous ecosystems of the coastal plains, whose growth is mainly limited by water availability (Maselli 2004). Both these findings are particularly interesting in view of the computation of the national carbon budget of terrestrial ecosystems, which is essential to fulfil the Kyoto Protocol and consequent international agreements (IPCC 2001).

In general, a major limitation of the investigation carried out is due to the relatively brief time period examined, which is a consequence of the length of the currently available satellite data series. This is actually an inherent limitation of the approach that will be overcome only when longer time series of these data are produced. The same fact further constrains the use of more recent satellite data products, such as those derived from SPOT-VGT and TERRA-MODIS sensors, which were launched only a few years ago. Nevertheless, such use is very promising for future research on forest production variability, because of the enhanced radiometric, spectral, and spatial features of these data, which should guarantee a higher accuracy in the estimates obtainable.

Acknowledgements

The authors thank two anonymous CJFR referees for their comments, which improved the quality of the original manuscript.

References

Bascietto, M., Cherubini, P., and Scarascia-Mugnozza, G. 2004. Tree rings from a European beech forest chronosequence are useful for detecting growth trends and carbon sequestration. Can. J. For. Res. **34**: 481–492. doi:10.1139/x03-214.

Black, B.A., and Abrams, M.D. 2004. Development and application of boundary-line release criteria. Dendrochronologia, **22**: 31–42. doi:10.1016/j.dendro.2004.09.004.

Bolle, H.J., Eckardt, M., Koslowsky, D., Maselli, F., Melia-Miralles, J., Menenti, M., Olesen, F.-S., Petkov, L., Rasool, I., and Van de Griend, A. 2006. Mediterranean land-surface processes assessed from space. Springer Series: Regional Climate Studies. Vol. XXVIII. Springer-Verlag, Berlin.

Brunetti, M., Buffoni, L., Maugeri, M., and Nanni, T. 2000. Trends of minimum and maximum daily temperatures in Italy from 1865 to 1996. Theor. Appl. Climatol. **66**: 49–60. doi:10.1007/s007040070032.

Brunetti, M., Maugeri, M., Monti, F., and Nanni, T. 2006. Temperature and precipitation variability in Italy in the last two centuries from homogenised instrumental time series. Int. J. Climatol. **26**: 345–381. doi:10.1002/joc.1251.

Chiesi, M., Maselli, F., Bindi, M., Fibbi, L., Cherubini, P., Arlotta, E., Tirone, G., Matteucci, G., and Seufert, G. 2005. Modelling carbon budget of Mediterranean forests using ground and remote sensing measurements. Agric. For. Meteorol. **135**: 22–34. doi:10.1016/j.agrformet.2005.09.011.

Chirici, G., Barbati, A., and Maselli, F. 2007. Modelling of Italian forest net primary productivity by the integration of remotely sensed and GIS data. For. Ecol. Manage. **246**: 285–295. doi:10.1016/j.foreco.2007.04.033.

Cook, E.R., Shiyatov, S., and Mazepa, V. 1990. Estimation of the mean chronology. *In* Methods of dendrochronology: applications in the environmental sciences. *Edited by* E.R. Cook and L.A. Kairiukstis. Kluwer Academic, Dordrecht, Netherlands. pp. 123–132.

Escadafal, R., Bohbot, H., and Mégier, J. 2001. Changes in arid Mediterranean ecosystems on the long term through Earth observation (CAMELEO). Final Report of European Union contract No. IC18-CT97-0155. Space Applications Institute, JRC, Ispra, Italy.

Fritts, H.C. 1976. Tree rings and climate. Academic Press, London.

Holben, B.N. 1986. Characteristics of maximum-value composite images from temporal AVHRR data. Int. J. Remote Sens. **7**: 1417–1434.

Hughes, K.M. 2002. Dendrochronology in climatology: the state of art. Dendrochronologia, **20**: 95–116. doi:10.1078/1125-7865-00011.

Ichii, K., Kawabata, A., and Yamaguchi, Y. 2002. Global correlation analysis for NDVI and climatic variables and NDVI trends: 1982–1990. Int. J. Remote Sens. **23**: 3873–3878. doi:10.1080/01431160110119416.

Intergovernmental Panel on Climate Change (IPCC). 2001. Climate change. 2001. IPCC third assessment report. IPCC, Geneva. Available from http://www.grida.no/climate/ipcc_tar/ [accessed 27 June 2006.]

Jones, P.D., New, M., Parker, D.E., Martin, S., and Rigor, I.G. 1999. Surface air temperature and its change over the past 150 years. Rev. Geophys. **37**: 173–199. doi:10.1029/1999RG900002.

Kawabata, A., Ichii, K., and Yamaguchi, Y. 2001. Global monitoring of interannual changes in vegetation activities using NDVI and its relationships to temperature and precipitation. Int. J. Remote Sens. **22**: 1377–1382.

Maselli, F. 2001. Definition of spatially variable spectral endmembers by locally calibrated multivariate regression analyses. Remote Sens. Environ. **75**: 29–38. doi:10.1016/S0034-4257(00)00153-X.

Maselli, F. 2004. Monitoring forest conditions in a protected Mediterranean coastal area by the analysis of multi-year NDVI data. Remote Sens. Environ. **89**: 423–433. doi:10.1016/j.rse.2003.10.020.

Maselli, F., Barbati, A., Chiesi, M., Chirici, G., and Corona, P. 2006. Use of remotely sensed and ancillary data for estimating forest GPP in Italy. Remote Sens. Environ. **100**: 563–575. doi:10.1016/j.rse.2005.11.010.

Maugeri, M., and Nanni, T. 1998. Surface air temperature variations in Italy: recent trends and an update to 1993. Theor. Appl. Clim. **61**: 191–196.

Myneni, R.B., and Williams, D.L. 1994. On the relationship between FAPAR and NDVI. Remote Sens. Environ. **49**: 200–211. doi:10.1016/0034-4257(94)90016-7.

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 (Washington, D.C.), **300**: 1560–1563. doi:10.1126/science.1082750. PMID:12791990.

Odum, E.P. 1971. Fundamentals of ecology. 3rd ed. W.B. Saunders, Philadelphia.

Pasquale, V., Verdoya, M., Chiozzi, P., Bodri, L., and Bellani, S. 2005. Temperature signal in the underground for climate history reconstruction in Italy. Global Planet. Change, **47**: 36–50. doi:10.1016/j.gloplacha.2004.11.015.

Prince, S.D. 1991. A model of regional primary production for use with coarse resolution satellite data. Int. J. Remote Sens. **12**: 1313–1330.

Rapetti, F., and Vittorini, S. 1995. Carta climatica della Toscana. Pacini Editore, Pisa, Italy.

Scarascia-Mugnozza, G. 2000. Le foreste italiane e la riduzione dei gas serra nel rispetto del protocollo di Kyoto. Sintesi dell'incontro di Roma del 27–28 Marzo 2000. Available from http://www.dsa.unipr.it/sisef/Bulletins/Anno2000/no12.htm [accessed 27 June 2006.]

Stockli, R., and Vidale, P.L. 2004. European plant phenology and climate as seen in a 20 year AVHRR land-surface parameter dataset. Int. J. Remote Sens. **25**: 3303–3330. doi:10.1080/01431160310001618149.

Thornton, P.E., and Running, S.W. 1999. An improved algorithm for estimating incident daily solar radiation from measurements of temperature, humidity and precipitation. Agric. For. Meteorol. **93**: 211–228. doi:10.1016/S0168-1923(98)00126-9.

Veroustraete, F., Sabbe, H., and Eerens, H. 2002. Estimation of carbon mass fluxes over Europe using the C-Fix model and Euroflux data. Remote Sens. Environ. **83**: 376–399. doi:10.1016/S0034-4257(02)00043-3.

Veroustraete, F., Sabbe, H., Rasse, D.P., and Bertels, L. 2004. Carbon mass fluxes of forests in Belgium determined with low resolution optical sensors. Int. J. Remote Sens. **25**: 769–792. doi:10.1080/0143116031000115238.

Waring, H.R., and Running, S.W. 1998. Forest ecosystems: analysis at multiples scales. 2nd ed. Academic Press, San Diego, Calif.

Wei, X., Kimmins, J.P., and Zhou, G. 2003. Disturbances and the sustainability of long-term site productivity in lodgepole pine forests in the central interior of British Columbia — An ecosystem modelling approach. Ecol. Modell. **164**: 239–256. doi:10.1016/S0304-3800(03)00062-0.

White, M.A., Thornton, P.E., and Running, S.W. 1997. A continental phenology model for monitoring vegetation responses to interannual climatic variability. Global Biogeochem. Cycles, **11**: 217–234. doi:10.1029/97GB00330.