Annals of Silvicultural Research
50(2), 2025: 52-57
https://creajournals.crea.gov.it/asr/

Technical note

Monitoring hybrid poplar plantations using continuous canopy photography: influence of clone and water status

Francesco Chianucci[1*], Sara Bergante[1], Pier Mario Chiarabaglio[1], Marco Bascietto[2]

Received: 7/03/2025 Accepted: 30/07/2025 Published online: 3/11/2025

ABSTRACT Hybrid poplar plantations are essential for bioenergy, pulp and paper industries, and contribute to carbon sequestration and environmental restoration. Effective plantation management, including monitoring of canopy structure, is crucial to maximize productivity, but traditional inventory methods often lack the spatial and temporal resolution needed for precision forestry application. In this study, we evaluated use of continuous canopy photography for continuous monitoring of poplar plantations. Daily canopy attributes like foliage cover and leaf area index were derived from time-lapse trail cameras. Three poplar clones (Soligo, I-214, and Neva), having differing growth rates and drought tolerances, were tested under different water (irrigated vs non-irrigated) regimes. We demonstrated that continuous canopy attributes allow to quantify significant variations in canopy cover, associated with both clone type and water status. Non-irrigated trials exhibited early senescence and canopy decline, while irrigated clones showed more robust canopy development. We concluded that continuous cameras offer a low-cost, effective solution for improving hybrid poplar plantation management by timely tracking the ability to respond to varying environmental conditions and optimizing resource use.

KEYWORDS: Precision forestry, proximal sensing, trail camera, tree phenology.

Introduction

Hybrid poplar plantations are strategically important for industrial wood production, due to their fast growth, high biomass yield, wood quality and adaptability to various environmental conditions (European Panel Federation 2021, Liu et al. 2022). Accordingly, such plantations are crucial for multiple industries, including bioenergy, pulp and paper, and timber production, offering a sustainable source of raw materials (European Panel Federation 2021). Additionally, hybrid poplars play a key role in carbon sequestration and land restoration, making them important for climate change mitigation, carbon farming, environmental restoration efforts (Zhang et al. 2020, Cantamessa et al. 2022, Vaglio Laurin et al. 2022).

Poplar plantations typically consider single-clonal species, while the cultivation models can vary from short rotation, polycyclic plantations, and agroforestry systems (Bergante 2022). Due to their specific features (fast growth, short rotation) poplar plantations require accurate and frequent data (Orság et al. 2024). While traditional forest inventory cannot satisfy this prompt information needs, precision forestry technologies hold strong potential to collect frequent, detailed, spatially-explicit data on poplar plantations, enabling more informed decision-making (Fardusi et al. 2017). By integrating precision forestry into hybrid poplar management, forest managers can therefore optimize resource allocation, enhance productivity, and ensure the sustainability of these plantations in the face of changing environmental conditions (Chianucci et al. 2020, Fardusi et al. 2017).

Repeated forest information is a prerequisite for precision forestry plantation management. Day-to-day management and long-term decision-making include a variety of tasks like planning harvests, monitoring tree health and status, and apply timely intervention, such as irrigation, fertilization, pest control, and other management practices. Satellite remote sensing is a cost-effective choice for repeated forest monitoring. However, satellite data requires calibration with field data to relate optical vegetation indices to biophysical variables such as leaf area index (LAI; Bajocco et al. 2024). Additionally, the spatial resolution of satellite data is often not suited for finer scale applications, such as tree health monitoring. While unmanned aerial vehicles (UAV) can be used to address finer spatial resolution requirements (Romano et al. 2024), these systems are less suited for continuous monitoring, which inherently implies frequent data collection, high costs and time-consuming processing steps.

As alternative to aerial and satellite sensing, continuous camera monitoring can be considered a cheap, simple, and highly automatable proximal sensing solution (Sonnentag et al. 2012, Brown et al. 2020, Chianucci et al. 2021). These camera systems are based on field repeat photography, allowing daily monitor of canopy structure and supporting nearly real-time management than is possible with remote sensing observations. Recently, Chianucci et al. (2021) proposed a continuous camera system using the time-lapse feature of commercial trail cameras in tree canopies, which further reduced cost and equipment of field monitoring. These systems have been also used in agricultural crops to support precision forestry application and monitoring (McCarthy and Raine 2022, Sakamoto et al. 2012), but they have been rarely used in tree crops, although a review indicated their potential for tree plantations (Putra et al. 2020).

1 – CREA - Research Centre for Forestry and Wood – Italy
2 - CREA - Research Centre for Engineering and Agro-Food Processing - Italy
*Corresponding author: francesco.chianucci@crea.gov.it

http://dx.doi.org/10.12899/asr-2679

With reference to hybrid poplar plantations, many clones are considered, which exhibit different growth patterns, crown and leaf-shape, water-use efficiencies, and responses to environmental factors, such as irrigation and fertilization (Rosso et al. 2023). These clonal differences directly impact canopy structure, making essential to monitor their changes at fine spatial and temporal scales. Continuous in *situ* monitoring with digital canopy photography can therefore provide a means to capture variations in canopy development and dynamics, allowing forest managers to assess how different clones respond to irrigation and other environmental inputs.

In this study, we tested whether continuous canopy attributes measured through repeat photography can be used to monitor poplar plantation and discriminate the effects of clone and management practices (in this case, irrigation). To this end, we selected three widely used poplar hybrid clones (*Populus ×canadensis* Mönch) with contrasting biomass yields and drought tolerances:

(i) "Soligo" is highly suited for short-rotation coppicing due to its disease resistance, fast early growth and dense canopy, despite a low-medium tolerance to drought.

(ii) "I-214" is a wide cultivated clone; it provides good biomass production and large tree crown; has demonstrated stable behavior over time in different cultivation situations, although it prefers well-drained soils.

(iii) "Neva" displays higher drought tolerance then the other clones, making it adaptable to harsher growing environments, at the expense of a lower biomass yield compared to Soligo and I-214.

The study advanced use of continuous camera in poplar plantations, as continuous data were used to evaluate use of canopy information not only for phenology (Chianucci et al. 2025), but also for supporting precision forestry application, e.g. comparing different impact of clone and irrigation on canopy structure and development.

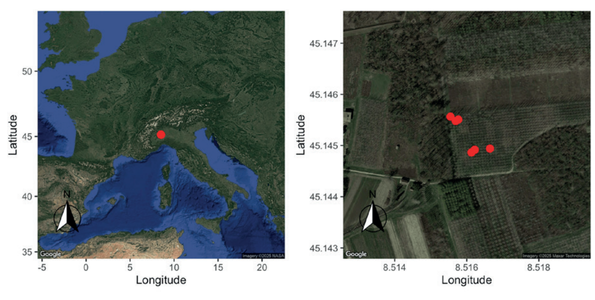
Material and Methods

Study area

The trial was carried out in 'Azienda Mezzi' experimental farm (CREA - Research Centre for Forestry and Wood) in Casale Monferrato, Northern Italy (Fig. 1). The farm covers about 200 ha in the flooding area of Po River, on sandy or sandy-loam soils. Climate is sub-continental with an average mean annual temperature of 13.5 °C and total annual rain of 700 mm (average of the last 20 years). A poplar stand was established in spring 2017 using two-year-old poplar poles of three different clones. The plantation layout is square, the space between trees in 6 x 6 m. Minimum plot hosts 9 trees and it's replicated 3 times.

Two irrigation treatments were applied: irrigated trees *versus* non-irrigated. In the former, irrigation is performed 4 times per year, during vegetative period (from April to October) by sprinkler method, furnishing about 35 mm for each treatment. During the first years, the weeds were controlled by disk-harrowing, following which only one mulching control per year was applied.

Figure 1 - Study area.



Continuous camera was installed for monitoring each clone x treatment, for a total of six cameras used in the monitoring. The camera was mounted on a shelf, with the sensor placed at a minimum distance of 40 cm from the stem, at a height of 3-4 m (Fig. 2).

Figure 2 - Installation of the camera trap in the poplar plantation.

Continuous camera acquisition and processing

We used the continuous camera system developed by Chianucci et al. (2021), which involves using the time-lapse feature of a standard trail camera, which was installed on a target tree and oriented upward. A transparent screen was mounted above the camera, to protect the camera sensor from direct raindrops, with the screen inclined to ease rainflow.

Continuous images were acquired daily using the trail camera from March to December 2022. The observation period varied between the time series, with the common observation period for all cameras from 14th March to 28th October. The camera was set to acquire 24 daily images between 14:00 and 18:00. We selected this time range to avoid maximum direct light in the images and provide a compromise between battery duration and daily acquisition time range.

Canopy images were then downloaded for subsequent image processing. A pre-filtering procedure removed images smaller one-third of the mean image size calculated for each time series, which indicated bad image acquisition due to adverse meteorological conditions (Ryu et al. 2012, Chianucci et al. 2021). The remaining images were processed using the "coveR" (Chianucci et al. 2022)

R package. The processing workflow involves removing the time-stamp portion of the image, selecting the blue channel of the image and applying a binary threshold (Otsu's 1979 method; Fig. 3) to classify image pixels into gaps or canopy. Gap fraction was then used to calculate foliage cover (FC) as:

$$FC=1-(Ng/N) \qquad \text{(eq. 1)}$$

where Ng is the number of gap pixels and N is the total number of image pixels. Foliage cover varied from 0 (full sky) to 1 (non-transparent crowns, 100% canopy cover) We focused on FC as it is estimated with high accuracy from this digital photographic technique (Chianucci 2015, 2020) and does not require assumption about large gap size or leaf angle distribution as for calculating Leaf Area Index from this method (Chianucci 2020). The variable is also widely used in forest inventory and for modeling canopy structure from optical theory (Majasalmi et al. 2014, Nilson and Kuusk 2004). The *coveR* package also allows to read the image metadata to assign the date to each processed image.

Figure 3 - Original (top) and classified (bottom) image using the coveR (Chianucci et al. 2021) package.

From each cover estimate, a daily value was calculated by considering the mean value for each day, consistently with a recent study (Chianucci et al. 2025). To reduce noise in the raw series, we computed a rolling average, with a moving window of 5 days.

Results

Time series of foliage cover obtained in the hybrid plantations using continuous cameras are shown in Figure 4. During the monitoring period, four main rainy events occurred, which were concentrated in the vegetation period (Fig. 4). Overall, irrigated trials showed higher foliage cover than non-irrigated ones during drier months (June - August), irrespective of the clone considered. In addition, non-irrigated trails showed a clear premature summer decline, which resulted in a more asymmetrical phenological curve (Fig. 4 and 5).

Figure 4 - Time series of foliage cover obtained from continuous camera in hybrid poplar plantation with different clones and water status. The red dotted lines indicate four rainy events occurred during the monitoring period (June 24, precipitation: 29 mm; July 5, precipitation: 42 mm; August 18, precipitation: 13 mm; September 24, precipitation: 16 mm). A rolling mean average is applied for obtaining a daily cover series.

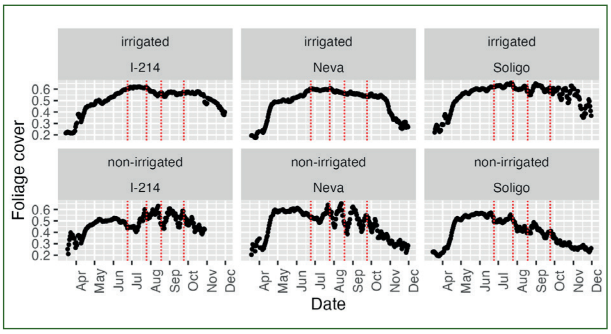
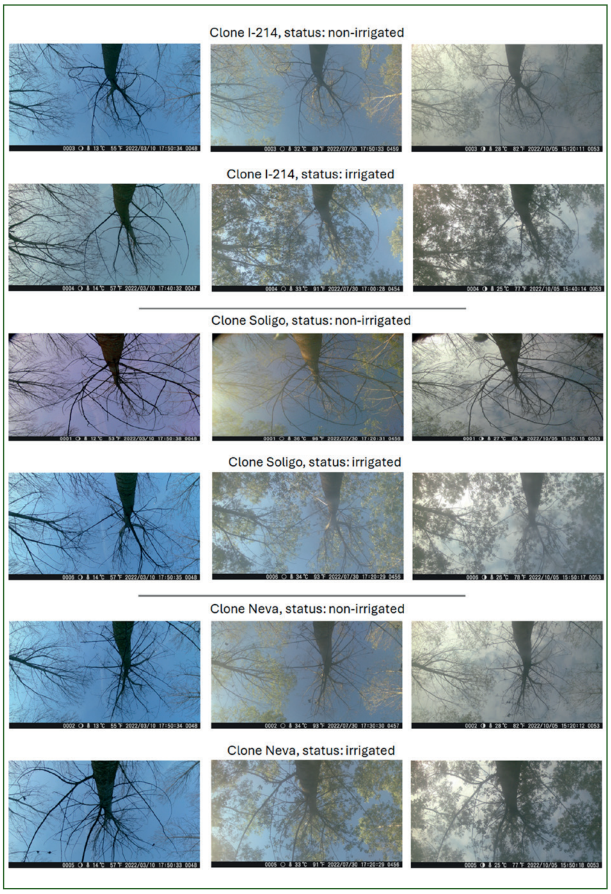


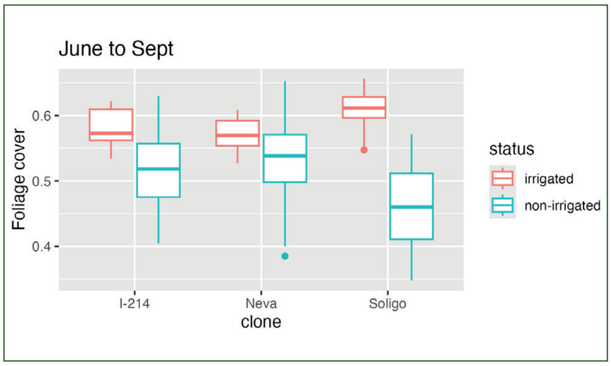
Figure 5 - Temporal differences in foliage cover according to water status in poplar clones. From left to right: leaf-off period (10 March); leaf-on period (30 July); leaf senescence period (5 October).



Non-irrigated trials showed larger day-to-day variations in cover, which was more pronounced in the periods close to the rainy events (Fig. 4). Visual inspection showed that the main images issues occurred in these periods were the presence of direct sun in the images (e.g. sun-glares), due to non-diffuse sky acquisition, and the influence of rain. Interestingly, we attributed the larger variability observed in non-irrigated trails as the lower foliage cover in these stands increased the influence of sun-glares in the images, due to higher transmitted light below the canopy.

Visual comparison confirmed that both clone and water status influenced canopy cover. The differences were also pronounced considering the mean summer foliage cover, particularly for the "Soligo" clone (Fig. 6).

Figure 6 -Differences in summer foliage cover according to clone and water status. The outliers referes to a value < 1.5x(Q3-Q1), i.e., the interquartile range.



Discussion

We showed that continuous estimates from time-lapse digital photography can capture differences in canopy structure and allow precise tracking of phenological transition stages in poplar plantations, including variability tied to clone type and irrigation status. Notably, we showed that non-irrigated trials exhibit a clear early summer decline and anticipated senescence. The outcome supports using continuous photography for precision forestry applications, from early-warning monitoring to providing water and nutrients based on actual plantation needs, thereby adapting to varying seasonal weather conditions.

The strength of this methodology lies in its simplicity, affordability, and scalability. The proposed monitoring system is based on standard, off-the-shelf trail cameras, while the processing of images is based on a free, open-source R package, which further eases adoption of this method. Another advantage of trail cameras, compared with other continuous monitoring systems, lies in their independence from many supplies which are often limited in forest/plantation conditions, including power supply, storage capability and file transmission systems (Chianucci et al. 2021). In addition, some trail cameras also feature a data transmission protocol system, which can make the data acquisition and transmission largely automated, allowing nearly real-time monitoring (Chianucci et al. 2021).

When considering the time series, we found that larger day-to-day variability was observed in non-irrigated trials, particularly close to rainy events. Also irrigated Soligo showed daily variability in autumn. In non-irrigated trails, we attributed the results to the larger influence of direct sunlight, due to lower canopy cover and higher crown porosity, which resulted in higher direct light transmittance. Poplar plantation has typically low LAI values (<3; Romano et al 2024), which could make canopy photography more sensitive to illumination conditions compared to denser canopy, which are dominated by small gaps (Chianucci 2015). For this reason, we recommend to acquire images much closer to sunrise than those we acquired in these experiments; e,.g,. acquiring images at 18:00-19:00 in summer (later acquisition may create the issue of low-light conditions; Chianucci et al. 2025).

To reduce the variability, we applied a moving average approach, but other solutions can be tested e.g., filtering out earlier acquisition (Chianucci et al. 2025). Alternatively, continuous phenological curves can be fitted from the raw data, e.g. using a double-logistic (Beck 2006) or a modified double-logistic function (Elmore et al. 2012) to reduce noise in the time series. This procedure also allows inferring key phenological transition stages (e.g. maturity, senescence, start and end of season) which can inform precision forestry practices.

Overall, irrigated Soligo and I-214 trials showed larger canopy cover, which are inherent in the clones' ability to display a denser crown and higher LAI than Neva (Rosso et al. 2023). Conversely, non-irrigated trials indicated that Soligo was threatened by drought conditions, with pronounced difference between irrigated/non-irrigated cover in this clone, while Neva confirmed its higher resistance to drought conditions, yet characteristics of the clone (Rosso et al. 2023). This highlights the importance of genotype selection in response to climate variability and reinforces the relevance of clone-specific monitoring tools in forest management. In this line, drought resistance and the response to climate variability are key traits for improved tree breeding.

While we used the monitoring method *per se* to monitor poplar plantation, the digital canopy photography estimates can also be used to calibrate aerial or satellite measurements (Romano et al. 2024). In this line, repeat photography has also the advantage of providing continuous measurements, which can be used to validate, complement and upscale multi-temporal remotely-sensed information over the course of the growing season (Sonnentag et al. 2012, Ryu et al. 2012, Chianucci et al. 2021), while also calibrating canopy biophysical metrics such as LAI from optical satellite vegetation indices (Bajocco et al. 2024).

Despite its strengths, the method has also limitations. Sensitivity to illumination variability, particularly in open canopies, may affect consistency in image-derived canopy attributes. Also, while image acquisition is straightforward, long-term deployment requires some manual control, especially for battery replacement and periodic data acquisition and quality check. Future improvements could involve integrating automated and more professional cameras such as security webcams, along with the automation in image acquisition, storage, and quality screening (Chianucci et al. 2025).

Conclusions

Repeat photography offers a powerful, low-cost, scalable solution for high-frequency canopy monitoring in hybrid poplar plantations, offering both operational benefits and a strong foundation for future research in phenotyping, drought response, and remote sensing calibration. The ability to detect clone-specific responses to water availability and phenological transitions highlights its potential not only for early warning systems but also for scaling up remotely-sensed observations. Therefore, this contributes to the growing field of precision forestry, particularly under climate-induced stress scenarios where real-time, clone-specific responses are essential for adaptive management.

Acknowledgements

Digital canopy photography data has been collected within CrowNet, a collaborative canopy and phenology tree monitoring network based on continuous cameras (https://canopyphotography.wordpress.com/crownet/).

The study was funded by the Research Project "Sistema di monitoraggio multiscalare a supporto della pioppicoltura di precisione nella Regione Lombardia" (PRECISIONPOP) funded by the Lombardy region, Italy (grant number: E86C18002690002) and by the MRV4SOC project, funded under the European Horizon programme (contract no. 101112754).

References

Bajocco S., Ferrara C., Savian F., Ginaldi F., Puletti N., Crecco L., Bregaglio S., Chianucci F. 2024 - LAIr: *an R package to estimate LAI from Normalized Difference Vegetation Index*. SoftwareX, 27: 101776.

Beck P.S.A., Atzberger C., Høgda K.A., Johansen B., Skidmore A.K. 2006 - *Improved monitoring of vegetation dynamics at very high latitudes: A new method using MODIS NDVI*. Remote sensing of Environment 100 (3): 321-334.

Bergante S. 2022 - *Poplar tree for innovative plantation models*. Annals of Silvicultural Research 47: 48-52. http://dx.doi.org/10.12899/asr-2344

Brown L.A., Ogutu B.O., Dash J. 2020 - *Tracking forest biophysical properties with automated digital repeat photography: A fisheye perspective using digital hemispherical photography from below the canopy*. Agricultural and Forest Meteorology 287: 107944.

Cantamessa S., Rosso L., Giorcelli A., Chiarabaglio P.M. 2022 - *The environmental impact of poplar stand management: a life cycle assessment study of different scenarios*. Forests 13: 1423. https://doi.org/10.3390/f13091423

Chianucci F. 2015 - *A note on estimating canopy cover from digital cover and hemispherical photography*. Silva Fennica 50 (1): 1518. https://doi.org/10.14214/sf.1518

Chianucci F. 2020 - *An overview of in situ digital canopy photography in forestry*. Canadian Journal of Forest Research 50 (3) 227-242.

Chianucci F., Bajocco S., Ferrara C. 2021 - *Continuous observations of forest canopy structure using low-cost digital camera traps*. Agricultural and Forest Meteorology 307: 108516.

Chianucci F., Puletti N., Grotti M., Ferrara C., Giorcelli A., Coaloa D., Tattoni C. 2020 - *Nondestructive tree stem and crown volume allometry in hybrid poplar plantations derived from terrestrial laser scanning*. Forest Science 66 (6): 737-746.

Chianucci F., Ferrara C., Puletti N. 2022 - *coveR: an R package for processing digital cover photography images to retrieve forest canopy attributes.* Trees 36 (6): 1933-1942.

Chianucci F., Lenzi, A., Minari E., Guasti M., Gisondi S., Gonnelli M., Innocenti S., Ferrara C., Campanaro A., Ciampelli P., Cutini A. 2025 - *CrowNet: a trail-camera canopy monitoring system*. Agricultural and Forest Meteorology 372: 110596.

Elmore A.J., Guinn S.M., Minsley B.J., Richardson A.D. 2012 - *Landscape controls on the timing of spring autumn and growing season length in mid-Atlantic forests*. Global Change Biology 18 (2): 656-674.

European Panel Federation 2021 - *European poplar and poplar plywood industry: a multi-tool to tackle the climate change and to contribute to the achievement of the objectives of the European Green Dea*l.

Fardusi M.J., Chianucci F., Barbati A. 2017 - *Concept to practice of geospatial-information tools to assist forest management and planning under precision forestry framework: A review*. Annals of Silvicultural Research 41: 3-14.

Liu J., Li D., Fernández J.E. 2022 - *Variations in water-balance components and carbon stocks in poplar plantations with differing water inputs over a whole rotation: implications for sustainable forest management under climate change*. Agricultural and Forest Meteorology 320: 108958. https://doi.org/10.1016/j.agrformet.2022.10895.

Majasalmi T., Rautiainen M., Stenberg P. 2014 - *Modeled and measured fPAR in a boreal forest: Validation and application of a new model.*Agricultural and Forest Meteorology 189: 118-124.

McCarthy A., Raine S. 2022 - *Automated variety trial plot growth and flowering detection for maize and soybean using machine vision*. Computers and Electronics in Agriculture 194: 106727.

Nilson T., Kuusk A. 2004 - *Improved algorithm for estimating canopy indices from gap fraction data in forest canopies*. Agricultural and Forest Meteorology 124 (3-4): 157-169.

Orság M., Berhongaray G., Fischer M., Klem K., Ceulemans R., King J. S., Trnka M. 2024 - *Elevated CO concentration alleviates the negative effect of vapour pressure deficit and soil drought on juvenile poplar growth*. Central European Forestry Journal 70 (2): 51-61.

Otsu N. 1979 - *A threshold selection method from gray-level histograms*. IEEE Transaction on System, Man and Cybernetics 9: 62–66.

R: *A Language and Environment for Statistical Computing. R Foundation for Statistical Computing* Vienna Austria 2024. [Online]. Available: https://www.R-project.org [2025, March 6].

Putra B.T.W., Soni P., Marhaenanto B., Harsono S.S., Fountas S. 2020 - *Using information from images for plantation monitoring: A review of solutions for smallholders*. Information Processing in Agriculture 7 (1): 109-119.

Romano E., Brambilla M., Chianucci F., Tattoni C., Puletti N., Chirici G., Travaglini D., Giannetti F. 2024 - *Estimating canopy and stand structure in hybrid poplar plantations from multispectral UAV imagery*. Annals of Forest Research 67 (1): 143-154.

Rosso L., Cantamessa S., Bergante S., Biselli C., Fricano A., Chiarabaglio P.M., Gennaro M., Nervo G., Secchi F., Carra A. 2023 - *Responses to drought stress in poplar: what do we know and what can we learn*? Life 13 (2): 533.

Ryu Y., Verfaillie J., Macfarlane C., Kobayashi H., Sonnentag O., Vargas R., Ma S., Baldocchi D.D. 2012 - *Continuous observation of tree leaf area index at ecosystem scale using upward-pointing digital cameras*. Remote Sensing of Environment 126: 116-125.

Sakamoto T., Gitelson A.A., Nguy-Robertson A.L., Arkebauer T.J., Wardlow B.D., Suyker A.E., Verma S.B., Shibayama M. 2012 - *An alternative method using digital cameras for continuous monitoring of crop status*. Agricultural and Forest Meteorology 154: 113-126.

Sonnentag O., Hufkens K., Teshera-Sterne C., Young A.M., Friedl M., Braswell B.H., Milliman T., O'Keefe J., Richardson A.D. 2012 - *Digital repeat photography for phenological research in forest ecosystems*. Agricultural and Forest Meteorology 152: 159-177.

Vaglio Laurin G., Mattioli W., Innocenti S. 2022 - *Potential of ALOS2 polarimetric imagery to support management of poplar plantations in Northern Italy*. Remote Sens 14: 1–14. https://doi.org/10.3390/rs14205202

Zhang Y., Tian Y., Ding S. 2020 - *Growth carbon storage and optimal rotation in poplar plantations: A case study on clone and planting spacing effects*. Forests 11: 1–15. https://doi.org/10.3390/F11080842