ORIGINAL PAPER

Probabilistic sampling and estimation for large-scale assessment of poplar plantations in Northern Italy

Piermaria Corona[1,2] · Francesco Chianucci[1] · Agnese Marcelli[2,3] · Damiano Gianelle[3] · Lorenzo Fattorini[4] ·
Mirko Grotti[1,5] · Nicola Puletti[1] · Walter Mattioli[1,2]

Abstract

In the recent decades, growing demand for wood products, combined with efforts to conserve natural forests, has supported a steady increase in the global extent of planted forests. In this paper, a two-phase sampling strategy for large-scale assessment of hybrid poplar plantations in Northern Italy was implemented. The first phase was performed by means of tessellation stratified sampling on high-resolution remotely sensed imagery, covering the survey area by a grid of regular polygons of equal size and randomly and independently selecting one point per quadrat. All the plantations spotted by at least one sample point were selected. In the second phase, we randomly chosen a subset of plantations by stratified sampling that were visited on the ground to collect qualitative and quantitative attributes. The resulting estimates were reliable, and the survey demonstrated relatively easy to be implemented and replicated. These considerations support the use of the proposed sampling strategy to frequently update information on fast-growing forest plantations within agricultural farms, like hybrid poplar crops. Moreover, the results of the case study here presented highlight the relevance of hybrid poplar plantations in Italy, in the context of sustainable development strategies under a green economy perspective.

Keywords Forest inventory · Two-phase sampling · Tessellation stratified sampling · *Populus* spp. · Hybrid poplar

Introduction

Growing demand for wood products, combined with efforts to conserve natural forests, has supported a 65% increase in the global extent of planted forests since 1990 (FAO 2015).

✉ Walter Mattioli
walter.mattioli@unitus.it; walter.mattioli@crea.gov.it

1 CREA, Research Centre for Forestry and Wood, V.le S. Margherita 80, I-52100 Arezzo, Italy

2 Department for Innovation in Biological, Agro-food and Forest Systems (DIBAF), University of Tuscia, Via San Camillo de Lellis s.n.c, I-01100 Viterbo, Italy

3 Sustainable Agro-Ecosystems and Bioresources Department, Research and Innovation Centre, Fondazione Edmund Mach, Via Edmund Mach, 1, I-38010 San Michele all'Adige, TN, Italy

4 Department of Economics and Statistics, University of Siena, Piazza San Francesco, 8, I-53100 Siena, Italy

5 Department of Architecture and Design, University of Rome La Sapienza, Piazza Borghese, 9, I-00196 Rome, Italy

As concerns Europe, in recent decades forest plantations for wood production have been supported by structural funds of European Commission (EC), to enhance the valorization of farmland: the main objectives are linked to the production of wood assortments for the timber industry, but also for biomass energy production, in compliance with the policies for climate change mitigation and adaptation. These considerations have supported a significant expansion of forest plantations (EUROSTAT 2019), especially by fast-growing tree species, like willows, poplars, eucalypts, Douglas fir, etc.

As distinctively concerns fast-growing forest plantations within agricultural farms, characterized by relatively short rotations and an intrinsic high dynamism in relation to the temporal variability of farmland destinations for cultivation, there is the need for a frequent updating of accurate and spatially detailed statistical data about tree species composition, stand structure and wood supply attributes (Wulder et al. 2008; Groot et al. 2015). Such needs may exceed the scope of conventional forest inventories, making room for *ad hoc* information sources (Alam et al. 2014).

Poplar is among the most used species for forest farming worldwide because of its great potential for woody

production due to its rapid juvenile growth, high photosynthetic capacity, high growth performance and high wood biomass production in a single growing season (Pointailler et al. 1997). The genus *Populus* is also cultivated for quality wood production, as it can be used as sawn timber, veneer and plywood (Cardias Williams and Thomas 2006). Poplar includes about 50 species and hundreds of cultivars, which can be cultivated either as high stands under rotations usually between 10 and 30 years or as short rotation coppice (2–5 years) (Johansson and Karačić 2011; Barontini et al. 2014). Some clones of hybrid poplars are characterized by fast-growing rates, which are partly induced by a set of physiological intrinsic characteristics (e.g., Casella and Ceulemans 2002; Dillen et al. 2010). According to several authors, poplar biomass growth ranges from 2 to 25 Mg ha^{-1} year $^{-1}$ (Spinelli et al. 2008; Guidi et al. 2009; Bergante et al. 2015; Stolarski et al. 2015, 2017; Krzyżaniak et al. 2019). The development of new poplar clones and the improvement of in cultivation techniques have made possible to sustain high biomass yield (Bergante et al. 2010). Poplar cultivation presents also environmental benefits such as the prevention of soil erosion and protection of soil water (Pandey and Srivastava 2010) and the habitat for many species (Walle et al. 2007; Archaux et al. 2010).

Owing to distinct features (fast growth and short rotation) and the dependency on the wood price market, hybrid poplar plantations have experienced large inter-annual fluctuation in the planted area. This calls for a frequent update of information about the geographical distribution and the potential wood supply from these plantations, since the economic value of poplar production largely depends on projections about local wood availability in the near future.

From a methodological perspective, the large-scale statistically sound estimation of fast-growing plantations requires the use of an effective probabilistic sampling scheme. Owing to the large extension of the study area, the scheme should involve more than one sampling phase. In this scenario, Marcelli et al. (2020) suggest the use of a two-phase scheme in which the first phase exploits the first phase of some conventional NFI, as suggested by Corona and Marchetti (2007). In their first phases, NFIs select a large sample of points onto the study area in accordance with a suitable probabilistic scheme. Then, these points can be checked on the basis of aerial information and those plantations spotted by at least one point are selected. Subsequently, in the second phase, a stratified sample of the plantations selected in the first phase is achieved and these plantations are visited on the ground. In this way, plantation surveys can benefit of the relatively intensive sampling usually performed in the first phases of NFIs. Moreover, taking fixed the first-phase sample of plantations selected by the NFI scheme, the second-phase sampling can allow to update information on a short time.

Regarding the first phase of sampling, spatially balanced schemes are usually adopted in the first phase of NFIs to ensure a uniform sampling coverage over the survey area (e.g., Tomppo et al. 2010). For the first phase of plantation surveys, Marcelli et al. (2020) suggest exploiting those NFIs adopting tessellation stratified sampling (TSS), a scheme that is becoming increasingly popular: actually, both the Italian and the USDA Forest Services are currently adopting TSS in the first phase of their NFIs (Fattorini et al. 2006; Tomppo et al. 2010). TSS is based on covering the survey area by means of regular polygons of equal size, each of them containing at least a portion of the area and then randomly selecting one point in each polygon (Fig. 1).

The statistical properties of TSS and its superiority with respect to other schemes usually adopted for allocating first-phase points on a large-scale study area have been investigated by Barabesi and Franceschi (2011) and Barabesi et al. (2012). Moreover, the statistical appealing of second-phase strategies subsequent to TSS has been theoretically proven by Fattorini et al. (2017). In this sense, the sampling strategy proposed by Marcelli et al. (2020) is equipped by a substantial theoretical background. In the same paper, performance of the proposal has been empirically checked by means of a simulation study carried out on a set of artificial populations of poplar plantations, providing satisfactory results in terms of precision.

In this paper, we applied the proposal by Marcelli et al. (2020) for assessing the state of hybrid poplar plantations in Northern Italy. In the first phase, we exploited the TSS scheme adopted in the IUTI (from the Italian acronym of 'Inventario dell'Uso delle Terre d'Italia') permanent national land-use pure-panel survey (Corona et al. 2012). In the second phase, plantations selected in the first phase were partitioned by the five administrative regions of Northern
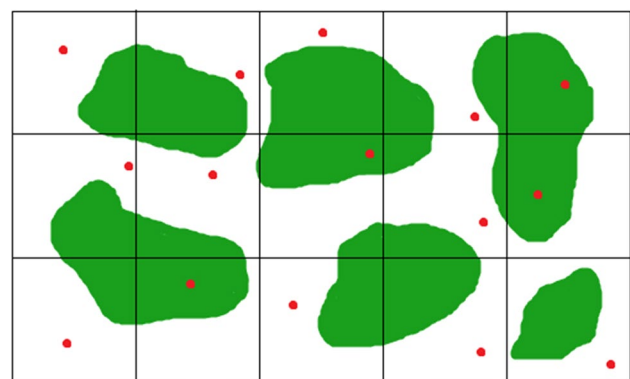
Fig. 1 Example of plantations sampled by TSS in the first phase. Green areas represent tree plantations, and red points represent sample points. Plantations selected in the first phase are those spotted by at least one point

Italy and a sample of them was selected by means of stratified sampling with proportional allocation.

Materials and methods

The survey here reported refers to the assessment of hybrid poplar plantations in Padan plain (Northern Italy) where poplar cultivation is mainly concentrated, targeted to plywood productions, with plantation density ranging from 200 to 300 trees ha^{-1} and rotations around 10–12 years. It provides high-quality wood material and represents a major source of timber for the national industry.

Survey area

The survey area is constituted by five administrative regions across the Padan plain: Piedmont, Lombardy, Emilia-Romagna, Veneto and Friuli-Venezia Giulia (Fig. 2) and extends approximately 650 km (400 miles) in an east–west direction running from the Western Alps to the Adriatic Sea, spreading over about 100,000 square kilometers.

First-phase sampling

In the first phase, we exploited the TSS scheme adopted in the IUTI permanent national land-use pure-panel survey performed by the Italian Ministry of Environment and Protection of Land and Sea (for details, see Corona et al. 2012). The scheme was based on a grid of semi-kilometer quadrats covering the whole Italian territory and as many sampling points randomly selected within each quadrat. Sampling points lying within the five administrative regions of the survey area were photo-interpreted by high-resolution airborne imagery (digital orthoimages with geometric resolution ≤ 50 cm) supported by Google Earth images and tools

(i.e., Google Street View). This phase envisaged checking about 390,000 sampling points. The hybrid poplar plantations spotted by at least one sampling point (Table 1) were selected and mapped. Based on the definitions by FAO/FRA (2000) and IUTI (Corona et al. 2012), we only considered those hybrid poplar plantations having a minimum area of 5000 m^2 with at least one side longer than 20 meters and composed at least by 3 rows. Canopy cover and the corresponding age class (determined by the level of canopy cover, according to Lapietra et al. 1994) were assessed on the orthoimages.

Second-phase sampling

In the second phase, plantations selected in the first phase were partitioned into strata coinciding with the five administrative regions. Then, within each of the strata a subset equal to 3% of the plantations selected in the first phase were drawn by means of simple random sampling without replacement (Table 1).

The plantations selected in the second phase were visited on the ground, recording information such as year of plantation, clone type and tree spacing. Year of the plantations

Table 1 First- and second-phase sample sizes by administrative regions

Region	First-phase sample sizes	Second-phase sample sizes
Piedmont	499	21
Lombardy	794	16
Veneto	106	5
Friuli-Venezia Giulia	149	8
Emilia-Romagna	188	7
Total	1736	57

Fig. 2 Survey area: the Padan plain in Northern Italy with boundaries of the five administrative regions evidenced in red

was assessed by Google Earth images of different years and checked also by tree cores (No errors have been detected by the field survey carried out in the second phase with respect to the age classes of the selected plantations as assigned in the first phase according to their level of canopy cover.) Each tree in the selected plantations was enumerated, and diameter at breast height and tree height was recorded. We then reckoned the total wood volume of second-phase plantations as the sum of volumes of single trees that, in turn, were determined by means of allometric equations developed by Chiarabaglio and Coaloa (2002). The mean annual increment in wood volume was calculated for each plantation dividing the total wood volume by the age of the plantation. Finally, a digital terrain model at 20 m resolution was used to create slope, exposure and altitude classes for further elaborations.

Estimation

Any theoretical detail about estimation formulas is given in Marcelli et al. (2020). Regarding the two-phase estimation, it is worth noting that Marcelli et al. (2020) adopt a two-phase version of a one-phase estimator of population totals originally proposed in Baffetta et al. (2011) for surveying woodlot and tree rows at large scale. The estimator avoids the cumbersome quantification of the sizes of the portions of the selected plantations lying in adjacent quadrats and is suitable when the sizes of units to be sampled are small compared with the size of quadrats, in such a way that units are likely to lie within a unique quadrat. Apart from the pedagogical representation of Fig. 1, fast-growing tree plantations within agricultural farms in the survey area are smaller than 25 ha (on average, plantation size is 6 ha) and rarely straddle quadrat boundaries.

In the first phase of sampling, we estimated the total area $|P|$ covered by plantations by means of

$$\left|\hat{P}\right| = |Q|r(P)$$

where $|Q|$ is the size of the study area, R is the number of first-phase points, $R(P)$ is the number of first-phase points falling within plantations, and $r(P) = R(P)/R$ is the fraction of first-phase points falling within plantations. We estimated the sampling variance by means of

$$\hat{V}^2\left(|\hat{P}|\right) = \frac{|Q|^2}{R-1} r(P)[1 - R(P)]$$

We distinguished poplar plantations in accordance with some criteria (e.g., clone type) and achieved separate estimates of the plantation areas for the subpopulations (usually referred to as domains). We estimated the plantation surface $|P_k|$ in the kth domain by means of

$$\left|\hat{P}_k\right| = |Q|r(P_k)$$

where $R(P_k)$ is the number of sample points falling within plantations of the kth domain and $r(P_k) = R(P_k)/R$ is the corresponding fraction. We estimated the sampling variance by means of

$$\hat{V}^2\left(\left|\hat{P}_k\right|\right) = \frac{|Q|^2}{R-1} r(P_k)\left[1 - r(P_k)\right]$$

In the second phase of sampling, we estimated the total T_Y of any interest attribute Y by means of

$$\hat{T}_{(2)y} = \frac{|Q|}{R} \sum_{l=1}^{L} \frac{n_l}{m_l} \sum_{j \in w_l} \frac{y_j}{\left|a_j\right|}$$

where L is the number of strata partitioning the plantations selected in the first phase, n_l is the size of the stratum l, W_l is the sample of plantations selected from stratum l in the second phase, m_l is the size of W_l, $\left|a_j\right|$ is the size of the plantation j, and y_j is the value of the attribute for the same plantation recorded on the ground in the second phase. We estimated the sampling variance by means of

$$\hat{V}^2\left(\hat{T}_{(2)y}\right) = \frac{1}{R(R-1)} \left\{ |Q|^2 \sum_{l=1}^{L} \frac{n_l}{m_l} \sum_{j \in W_l} \frac{y_j^2}{|a_j|^2} - R\hat{T}_{(2)y}^2 \right\}$$
$$+ \frac{|Q|^2}{R^2} \sum_{l=1}^{L} n_l(n_l - m_l)\frac{S_l^2}{m_l}$$

where $t_j = y_j/\left|a_j\right|$,

$$S_l^2 = \frac{1}{m_l - 1} \sum_{j \in W_l} \left(t_j - \bar{t}_l\right)^2$$

and

$$\bar{t}_l = \frac{1}{m_l} \sum_{j \in W_l} t_j$$

Regarding the estimate of the plantation surface $|P_k|$ in the kth domain, if the domain cannot be determined by photointerpretation but it can only be recorded in the field, we cannot use the first-phase estimator $\left|\hat{P}_k\right|$. In these cases, we adopted the two-phase estimator

$$\left|\hat{P}_{(2)k}\right| = \frac{|Q|}{R} \sum_{l=1}^{L} \frac{n_l}{m_l} m_{lk}$$

Table 2 Estimated area (expressed in hectares) of hybrid poplar plantations by administrative regions (percent standard error, SE %, is reported in brackets)

Region	Area (SE %)
Piedmont	12,475 (4.5%)
Lombardy	19,850 (3.5%)
Veneto	2650 (9.7%)
Friuli-Venezia Giulia	3725 (8.2%)
Emilia-Romagna	4700 (7.3%)
Total	43,400 (2.4%)

where m_{lk} is the number of the plantations belonging to the domain k that were selected in the second phase from stratum l. We estimated the sampling variance by means of

$$\hat{V}^2\left(\left|\hat{P}_{(2)k}\right|\right) = \frac{|Q|^2}{R^2} \sum_{l=1}^{L} n_l(n_l - m_l) \frac{\bar{y}_{lk}(1 - \bar{y}_{lk})}{m_l - 1}$$
$$+ \frac{\left|\hat{P}_{(2)k}\right|\left(|Q| - \left|\hat{P}_{(2)k}\right|\right)}{R - 1}$$

where $\bar{y}_{lk} = m_{lk}/m_l$.

Finally, we estimated the relative standard error of any estimator by dividing the square roof of the variance estimate by the value of resulting estimate.

Results

The first-phase sampling procedure allowed to estimate the area of hybrid poplar plantations in the considered five administrative regions across the Padan plain equal to 43,400 ha, with a relative standard error equal to 2.4% (Table 2).

Except for Piedmont, in which hybrid poplar cultivation is spread even in hilly areas (mainly between 300 and 600 m asl), most of the hybrid poplar plantations are concentrated in flat areas (below 300 m asl). About 98% of the hybrid poplar plantations is estimated to grow at lower slopes ($<5\%$), with more variability observed in Piedmont. Most hybrid poplar plantations grow in territorial zones under nature conservation or environmental restrictions (about 45% of the plantation area is estimated to fall within such zones.)

Table 3 illustrates the estimated area of hybrid poplar plantations according to the canopy cover and age: considering the conventional rotation of 10–12 years, over half of the poplar plantations proves to be near the technical maturity (i.e., ≥ 7 years).

Tables 4, 5 and 6 summarize the results of the second-phase sampling, where hybrid poplar attributes have been measured in the field. Overall, tree spacing is predominantly equal or greater than 36 m² (over 80%; Table 4). The clone 'I-214' (*Populus x euramericana* (Dode) Guiner) is the most used in cultivation: it contributes to about 77% of the total poplar planted area (Table 5), and it is mainly represented in

Table 3 Estimated area of hybrid poplar plantations according to the canopy cover and age classes by administrative regions

Region	I class (1 year)		II class (2–3 years)		III class (4–6 years)		IV class (≥ 7 years)	
	Area (ha)	S.E. (%)	Area (ha)	S.E. (ha)	Area (%)	S.E. (%)	Area (ha)	S.E. (%)
Piedmont	700	18.9	1050	15.4	2400	10.2	8325	5.5
Lombardy	2200	10.7	1950	11.3	6050	6.4	9650	5.1
Veneto	250	31.6	325	27.7	350	26.7	1725	12.0
Friuli-Venezia Giulia	475	22.9	500	22.4	500	22.4	2250	10.5
Emilia-Romagna	425	24.3	725	18.6	1.250	14.1	2300	10.4
Total	4050	7.9	4550	7.4	10,550	4.9	24,250	3.2

Table 4 Estimated area of hybrid poplar plantations according to tree spacing by administrative regions

Region	Tree spacing $<6\times6$ m (ha)	S.E. (%)	Tree spacing $=6\times6$ m (ha)	S.E. (%)	Tree spacing $>6\times6$ m (ha)	S.E. (%)
Piedmont	594.1	100	6534.5	21.8	5346.4	26.2
Lombardy	2481.3	68.4	12,406.3	20.3	4962.5	44.8
Veneto	0.0	–	2650.0	9.7	0.0	–
Friuli-Venezia Giulia	2328.1	30.3	1396.9	49.3	0.0	–
Emilia-Romagna	671.4	100	2014.3	47.6	2014.2	47.6
Total	6074.9	33.6	25,002.0	12.5	12,323.1	22.7

Table 5 Estimated area of hybrid poplar plantations according to the clone type ('I-214'; other clones) by administrative regions

Region	'I-214' clone (ha)	S.E. (%)	Other clones (ha)	S.E. (%)
Piedmont	11,286.9	8.5	1188.1	69.0
Lombardy	14,887.5	15.3	4962.5	44.8
Veneto	1060.0	61.7	1590.0	41.8
Friuli-Venezia Giulia	2328.1	30.3	1396.9	49.3
Emilia-Romagna	4028.6	18.2	671.4	100
Total	33,591.1	8.2	9808.9	27.0

Table 6 Main wood production of hybrid poplar plantations by administrative regions

Region	All plantations				'I-214' Plantations			
	Wood volume (m^3)	S.E. (%)	Annual increment in wood volume (m^3 $year^{-1}$)	S.E. (%)	Wood volume (m^3)	S.E. (%)	Annual increment in wood volume (m^3 $year^{-1}$)	S.E. (%)
Piedmont	1,763,739.6	19.0	202,507.2	11.5	1,315,001.9	16.8	172,812.2	12.2
Lombardy	3,124,747.5	18.9	354,837.0	10.4	2,326,066.0	16.9	278,464.1	12.5
Veneto	274,595.9	38.3	27,680.2	32.7	100,323.5	89.0	12,202.9	78.2
Friuli-Venezia Giulia	616,336.5	21.7	62,913.8	16.2	390,233.1	32.4	45,037.8	25.9
Emilia-Romagna	319,018.4	44.4	46,516.3	31.2	250,023.9	55.7	35,017.2	38.3
Total	6,098,437.9	11.7	694,454.5	6.9	4,381,648.4	11.3	543,534.2	8.4

older plantations (54% of the 'I-214' clone plantation area and 43% of the total plantation area).

Piedmont and Lombardy regions show the largest wood production, while Veneto shows the smallest. As expected, the productivity of hybrid poplar plantations is distinctively high: considering the plantations near the technical maturity, the annual increment in wood volume is about 700,000 m^3 $year^{-1}$.

The achieved results evidence the importance of poplar cultivation in Italy as a significant component of the national timber industry and stress its critical role in sustainable development strategies under a green economy perspective. The classification of poplar trees in age classes shows an uneven distribution of the areas invested annually compared to the typical rotation of 10–12 years; in particular, there is a concentration of hybrid poplar plantations close to commercial maturity, but, at the same time, the estimates of number of plantations of the first age class (1 year old) most likely indicate the beginning of a new cycle of poplar plantation expansion. From this evidence, it is possible to hypothesize that, starting from 2020, there will be a progressive reduction in the poplar wood available, due to the decrease in new plantations established in the last years, and then, there will be a new increase after 2023: if the current levels of annually planted area are confirmed in the next years, starting from 2027, at least 4000 hectares per year will be available for cutting, with about 1 million cubic meters of wood for industrial use.

Final remarks

Forest tree monitoring and assessment are rapidly evolving as new information needs arise and new techniques and tools become available. However, the exploitation of the latter, as well as their implementation within operative management processes, should be evidence-based (Corona 2018). Under this perspective, we have applied the two-phase sampling strategy developed by Marcelli et al. (2020) in order to provide a large-scale assessment of hybrid poplar plantations in Northern Italy, where most of the national forest tree crops within agricultural farms are concentrated.

From a practical point of view, a large survey area as Northern Italy (over 46,000 square kilometers) makes a complete investigation of the forest tree crops prohibitive. On the other hand, we completed the first-phase work on airborne imagery in about 60 days/man and the second-phase work in the field in about 15 days/man: such figures, compared with the estimated uncertainty below 3% for the estimation of the area covered by hybrid poplar plantations and below 12% for the estimation of their wood volume, represent a reasonable compromise between available resources and survey efficiency. As assessed during the survey, both the interpretation of remotely sensed imagery and fieldwork prove to be easier than in conventional forest inventory. Forest tree crops recognition within farmland by the high-resolution imagery is straightforward, while the accessibility of

the plantation is simple, and field measurements easy. In this sense, the adopted sampling strategy is proven fully feasible to be implemented and replicated, with reduced costs when exploiting freely available remotely sensed data like Google Earth images.

On the whole, the sampling strategy can allow to update information on a short time; it has the advantage of being rapid and simple to be carried out, being particularly suited for fast-growing plantations, which rapidly alternate on agricultural lands, making conventional 5–10 years periodic inventory information temporally obsolete.

The produced information on the extent and characteristics of forest tree crops is of primary importance for developing long-term and large-scale strategies for supporting fast-growing forest tree cropping as well as the timber industry. The necessity of producing reliable estimates among countries allows obtaining harmonized and comparable information (Corona 2016; Fardusi et al. 2017). This can support the development of the sector in view of the forthcoming rural development policy: for instance, considering the importance of the aspects related to the environmental sustainability of hybrid poplar plantations in this application, it may be useful to favor there the supply possibilities on the nursery market of clone varieties with greater environmental sustainability compared to the clone 'I-214,' much appreciated by the plywood industry but susceptible to numerous biotic adversities and therefore subject to a relatively intense chemical phytoiatric protection.

References

Alam MB, Shahi C, Pulkki R (2014) Economic impact of enhanced forest inventory information and merchandizing yards in the forest product industry supply chain. Socio Econ Plan Sci 48:189–197. https://doi.org/10.1016/j.seps.2014.06.002

Archaux F, Chevalier R, Berthelot A (2010) Towards practices favourable to plant diversity in hybrid poplar plantations. Forest Ecol Manag 259(12):2410–2417. https://doi.org/10.1016/j.foreco.2010.03.017

Baffetta F, Fattorini L, Corona P (2011) Estimation of small woodlot and tree row attributes in large scale forest inventories. Environ Ecol Stat 18:146–167. https://doi.org/10.1007/s10651-009-0125-0

Barabesi L, Franceschi S (2011) Sampling properties of spatial total estimators under tessellation stratified designs. Environmetrics 22:271–278. https://doi.org/10.1002/env.1046

Barabesi L, Franceschi S, Marcheselli M (2012) Properties of design-based estimation under stratified spatial sampling with application

to canopy coverage estimation. Ann App Stat 4:210–228. https://doi.org/10.1214/11-AOAS509

Barontini M, Scarfone A, Spinelli R, Gallucci F, Santangelo E, Acampora A, Jirjis R, Civitarese V, Pari L (2014) Storage dynamics and fuel quality of poplar chips. Biomass Bioenerg 62:17–25. https://doi.org/10.1016/j.biombioe.2014.01.022

Bergante S, Facciotto G, Minotta G (2010) Identification of the main site factors and management intensity affecting the establishment of short-rotation-coppices (SRC) in Northern Italy through stepwise regression analysis. Cent Eur J Biol 5:522–530. https://doi.org/10.2478/s11535-010-0028-y

Bergante S, Zenone T, Facciotto G (2015). Short rotation forestry for energy production in italy: environmental aspects and new perspectives of use in biofuel industry. In: Bhardwaj AK, Zenone T, Chen J (eds) Sustainable Biofuels. An Ecological Assessment of the Future Energy. pp 137–153

Cardias Williams F, Thomas T (2006) Some key issues concerning current poplar production and future marketing in the United Kingdom. New Forest 31:343–359. https://doi.org/10.1007/s11056-005-8197-7

Casella E, Ceulemans R (2002) Spatial distribution of leaf morphological and physiological characteristics in relation to local radiation regime within the canopies of 3-year-old *Populus* clones in coppice culture. Tree Physiol 22:1277–1288. https://doi.org/10.1093/treephys/22.18.1277

Chiarabaglio PM, Coaloa D (2002) Valutazione qualitativa e quantitativa del pioppeto maturo in piedi. L'Informatore Agrario 41:25–27 **In Italian**

Corona P (2016) Consolidating new paradigms in large-scale monitoring and assessment of forest ecosystems. Environ Res 144:8–14. https://doi.org/10.1016/j.envres.2015.10.017

Corona P (2018) Communicating facts, findings and thinking to support evidence-based strategies and decisions. Ann Silv Res 42:1–2. https://doi.org/10.12899/asr-1617

Corona P, Marchetti M (2007) Outlining multi-purpose forest inventories to assess the ecosystem approach in forestry. Plant Biosyst 2:243–251. https://doi.org/10.1080/11263500701401836

Corona P, Barbati A, Tomao A, Bertani R, Valentini R, Marchetti M, Perugini L (2012) Land use inventory as framework for environmental accounting: an application in Italy. iForest 5(4):204–209. https://doi.org/10.3832/ifor0625-005

Dillen SY, Rood SB, Ceulemans R (2010). Growth and physiology. In: Jansson S, Bhalerao R, Groover A (eds) Genetics and Genomics of *Populus* (Plant Genetics and Genomics: Crops and Models), vol. 8. Springer, New York, USA, pp 39–63. https://doi.org/10.1007/978-1-4419-1541-2_3

EUROSTAT (2019). Renewable energy statistics. Statistics explained. 14 pp. https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics. Accessed 12 February 2019

FAO (2015) Global Forest Resources Assessment 2015. Food and Agriculture Organization of United Nations, Rome

FAO/FRA (2000). Global forest resources assessment 2000. Main Report. FAO Forestry Paper 140, Rome, Italy

Fardusi MJ, Chianucci F, Barbati A (2017) Concept to practice of geospatial-information tools to assist forest management and planning under precision forestry framework: a review. Ann Silv Res 41(1):3–14. https://doi.org/10.12899/asr-1354

Fattorini L, Marcheselli M, Pisani C (2006) A three-phase sampling strategy for large-scale multiresource forest inventories. J Agric Biol Environ Stat 11:1–21. https://doi.org/10.1198/108571106X96871

Fattorini L, Marcheselli M, Pisani C, Pratelli L (2017) Design-based asymptotics for two-phase sampling strategies in environmental surveys. Biometrika 104:195–205. https://doi.org/10.1093/biomet/asw062

Groot A, Cortini F, Wulder MA (2015) Crown-fibre attribute relationships for enhanced forest inventory: progress and prospects. Forest Chron 91(3):266–279. https://doi.org/10.5558/tfc2015-048

Guidi W, Tozzini C, Bonari E (2009) Estimation of chemical traits in poplar short-rotation coppice at stand level. Biomass Bioenerg 33(12):1703–1709. https://doi.org/10.1016/j.biombioe.2009.09.004

Johansson T, Karačić A (2011) Increment and biomass in hybrid poplar and some practical implications. Biomass Bioenerg 35(5):1925–1934. https://doi.org/10.1016/j.biombioe.2011.01.040

Krzyżaniak M, Stolarski MJ, Warmiński N (2019) Life cycle assessment of poplar production: environmental impact of different soil enrichment methods. J Clean Prod 206:785–796. https://doi.org/10.1016/j.jclepro.2018.09.180

Lapietra G, Coaloa D, Chiarabaglio PM (1994) Rapporto annuale sulla pioppicoltura 1993. Cellulosa e Carta 45:2–8 **In Italian**

Marcelli A, Mattioli W, Puletti N, Chianucci F, Gianelle D, Grotti M, Chirici G, D'Amico G, Francini S, Travaglini D, Fattorini L, Corona P (2020). Large-scale two-phase estimation of wood production by poplar plantations exploiting Sentinel-2 data as auxiliary information. Silva Fenn 54(1) article id 10247. https://doi.org/10.14214/sf.10247

Pandey A, Srivastava RK (2010) Role of dendropower in wastewater treatment and sustaining economy. J Clean Prod 18(10–11):1113–1117. https://doi.org/10.1016/j.jclepro.2010.02.026

Pointailler JY, Ceulemans R, Guittet J, Mau F (1997) Linear and non-linear functions of volume index to estimate woody biomass in high density young poplar stands. Ann For Sci 54(4):335–345. https://doi.org/10.1051/forest:19970402

Spinelli R, Nati C, Magagnotti N (2008) Harvesting Short-Rotation Poplar plantations for biomass production. Croat J For Eng 29(2):129–139

Stolarski MJ, Krzyżaniak M, Szczukowski S, Tworkowski J, Załuski D, Bieniek A, Gołaszewski J (2015) Effect of increased soil fertility on the yield and energy value of short-rotation woody crops. Bioenerg Res 8(3):1136–1147. https://doi.org/10.1007/s12155-014-9567-9

Stolarski MJ, Olba-Zięty E, Rosenqvist H, Krzyżaniak M (2017) Economic efficiency of willow, poplar and black locust production using different soil amendments. Biomass Bioenerg 106:74–82. https://doi.org/10.1016/j.biombioe.2017.08.019

Tomppo E, Gschwantner T, Lawrence M, McRoberts RE (eds) (2010) National forest inventories: Pathways for common reporting. Springer, New York

Walle IV, Van Camp N, Van de Casteele L, Verheyen K, Lemeur R (2007) Short-rotation forestry of birch, maple, poplar and willow in Flanders (Belgium) I—biomass production after 4 years of tree growth. Biomass Bioenerg 31(5):267–275. https://doi.org/10.1016/j.biombioe.2007.01.019

Wulder MA, Bater CW, Coops NC, Hilker T, White JC (2008) The role of LiDAR in sustainable forest management. Forest Chron 84(6):807–826. https://doi.org/10.5558/tfc84807-6