Quantifying the Potential of Hybrid Poplar Plantation Expansion: An Application of Land Suitability Using an Expert-Based Fuzzy Logic Approach

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Abstract

The current demand for wood products is growing globally. Hybrid poplars are fast growing trees and it is beneficial to expand their cultivation area. Digital mapping techniques based on land suitability assessment can effectively support land use decision-making processes in this perspective. The aim of this study was to develop a model to produce land suitability maps to determine the potential production area of hybrid poplar (*Populus ×canadensis* Moench) in Italy. The evaluation was based on a fuzzy logic procedure to generate a raster map with a pixel resolution of 250 m over the country. The modelling approach is planning-oriented: the objective was to predict, on a national scale, the suitability of the land for poplar cultivation by taking into account environmental factors for which geodatabases with adequate and comparable spatial resolution are available. Georeferenced databases of experimental poplar plantations were used as calibration dataset. The assessment identified approximately 2 million hectares of land suitable and highly suitable for hybrid poplar cultivation in Italy. These areas are mainly located in northern Italy (around 36% of the territory) and, to a lesser extent, in central Italy (around 19%) and in southern Italy and the islands (less than 3%). The modelling approach adopted can be easily replicated in other geographical areas or at finer scales, provided that appropriate data are available.

Keywords: multicriteria analysis, digital soil mapping, fast growing plantations, wood production, Italy

1. Introduction

The genus *Populus* includes many species, some of which are intensively cultivated through different genotypes (clones) selected for their rapid growth, good stem shape, wood quality and resistance to diseases. Poplar wood is an important raw material with several uses such as plywood, packaging (crates, pallets and others), pulp for paper, lumber and construction products, as well as for energy purposes (production of cellulosic biofuel and bio-ethanol). Poplars are also a strategic resource for soil conservation and phytoremediation (Bergante et al. 2015). In addition, soil organic carbon is sequestered more effectively after the conversion from intensively grown agricultural crops to more extensive crops such as poplar plantations (Gupta et al. 2009).

Among European countries, the largest surface of poplar plantations is found in France, Hungary and Spain while in Italy the current consistency is around 43,000 hectares, mainly concentrated (94%) in the northern regions along the Po valley (Corona et al. 2020). In this area, selected poplar hybrids (mainly clones of *P. ×canadensis* and *P. deltoides)* are able to express their significant potential, with average yields of 20-22 $m^3ha^{-1}y^{-1}$ under conventional rotations of 9-11 years for the production of plywood and packaging (Corona et al. 2020, Marchi et al. 2022).The most widespread clone is the hybrid of *P. ×canadensis* named 'I-214' due to the lightness of its wood and the environmental adaptability. Nevertheless, new clones are periodically placed on the market, such as the new HES (High Environmental Sustainability) ones characterized by fast growth and high resistance to diseases and to the woolly aphid (*Phloemyzus passerini*).

Hybrid poplar cultivation is influenced, or limited, by factors related to both environmental conditions, such as climate and soil, and management practices, such as tillage and irrigation. Hybrid poplar plantations are most productive on well aerated alluvial deep soils with sufficient moisture and nutrients (Baker and Broadfoot 1979). In temperate regions, such as the Po Valley, average annual rainfall of 700-800 mm, with at least 350-400 mm during the growing season (March to October), is sufficient for growth, although artificial irrigation can ensure significant yield improvement.

The demand for poplar wood by the Italian industries exceeds two million m^3 y^{-1}, but national production does not reach half of this figure: the deficit, which leads to significant imports of round- and semifinished wood, should be filled with an increase in planted areas up to around 115,000 hectares (AA.VV. 2014). Consequently, both for industry and for energy and the environment, there is currently a strong interest in assessing the suitability for poplar cultivation in areas other than the Po valley, in particularly in central and southern Italy. There are already some small areas in such territories cultivated with hybrid poplar, thanks to suitable environmental conditions and the presence of local specialized supply chains, dedicated above all to packaging. Other areas of these territories could turn out to be potentially favourable for poplar cultivation: with the support of experimental activities (common garden trials) and advanced mapping techniques, it is possible to effectively identify the suitability of the land for poplar plantations in these areas, considering the main factors affecting their establishment and growth.

There are two main applications of spatial ecological modelling to predict the potential performance of tree species and provenances over time and space and to select land suitable for a specific use: species distribution modelling techniques (Pecchi et al. 2019) and statistical models performed on data from common garden experiments able to express the genotype by environment interaction (Benito-Garzon et al. 2019, Hallingback et al. 2021, Marchi et al. 2022). However, other methods such as fuzzy-logic functions are also used as a reasonable way to generate spatial maps of land suitability based on knowledge of the ecological requirements of a target species (Zhang et al. 2018). When experimental networks are missing or available only in a limited ecological range, i.e. covering only a subset of the entire potential ecological niche, expert-based methods are the way to extend prediction beyond the investigated domain. In this framework, digital soil mapping (DSM) and digital soil assessment (DSA) have developed rapidly in recent years with the increased availability of soil data and increased CPU processing power. DSA translates DSM outputs into risk-based spatial decision aids (e.g. McBratney et al. 2012, Searle et al. 2021) by answering questions about agricultural potential: this procedure can ensure that appropriate land is allocated to appropriate uses. Regarding the cultivation of hybrid poplar clones in Italy, the lack of data in southern regions, islands and marginal areas in other regions has been recognized as a critical problem for spatial modelling (Marchi et al. 2022). Most of the databases from experimental networks were compiled using hybrid poplar plantations established in productive areas, as close as possible to species optimum. However, some experiences have shown that hybrid poplar clones are able to grow well even in some environments of central-southern Italy (Paris et al. 2018). In the light of these evidence, sound modelling of the hybrid poplar cultivation potential in Italy is appropriate, with particular attention to these regions. The starting point of the work was the evaluation of the general criteria and the Boolean models to identify the suitability with respect to the site pedological factors for the cultivation of hybrid poplars; a first model was developed by Scotti et al. (2010) considering prior knowledge on the physiology of hybrid poplars, acquired thanks to experiments conducted in many countries and summarized in Table 1. The evaluation scheme assumes that the cultivation also takes place on land not-irrigated and that the local climate is not a limiting factor. In Boolean modelling the soil suitability class is determined by the most limiting factor, according to Liebig's law of minimum. This approach has been adopted by FAO (1976), which states that crop yield is determined by the plant nutrient in the lowest supply (e.g. see Roy et al. 2006).

To this end, a fuzzy-logic approach was developed here to provide a national land suitability map for this type of crop.

2. Materials and methods

Spatial multi-criteria decision analysis techniques based on a fuzzy logic and integrated in geographic information systems were used to generate land suitability (LS) raster maps for the territory of Italy (Fig. 1) considering the most cultivated hybrid poplar specie (*P. ×canadensis* Moench) plantations with a spatial resolution of 250 m. Map scale and raster resolution are determined by matching with the resolution of existing data. Eight ecophysiographic drivers were considered, covering both climatic and soil factors, based on literature, empirical evidence and data available for the whole of Italy.

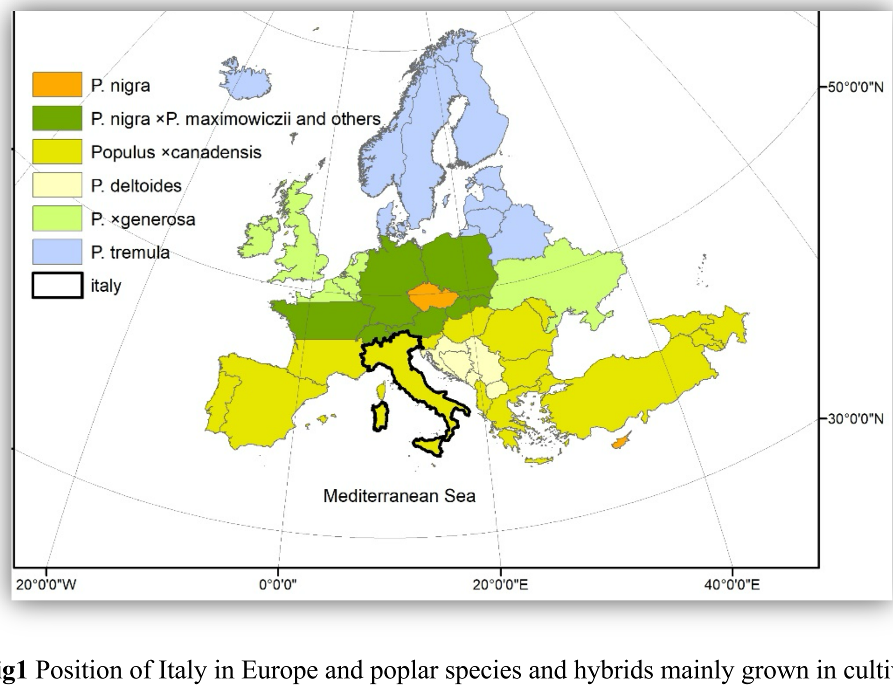

Fig1 Position of Italy in Europe and poplar species and hybrids mainly grown in cultivation by geographic areas.

2.1 Environmental drivers for LS modelling

Three climatic variables were considered: i) annual mean temperature (MAT); ii) mean total annual precipitation (MAP); iii) sum of rainfall between March and October (PMO), indicated as growing season for poplars. The climatic parameters were obtained as the average of the last normal climatic period available (1991-2020) and downloaded from ClimateDT (https://www.ibbr.cnr.it/climate-dt/), a free-of-charge tool capable of providing historic climatic data and future scenarios on a global scale (Marchi et al. 2020). Climate data were retrieved according to Marchi et al. (2022).

Regarding the pedological variables, the starting point of the assessment is the definition of the soil requirements, previously indicated by Scotti (Scotti et al., 2010) and reported in matching table 1. Concerning the soil texture, clay soils are more likely to have drainage problems, which can also occur on sandy soils when the water table is too close to the soil surface. Fine-textured soils may have sufficient aeration and good drainage so they are indicated as a category without limitations. Conversely, sandy soil (sand content higher than 85%) with very rapid drainage are considered less favourable for poplar growth (Stanturf et al. 2001, Van Oosten 2006, Frison 1992). Poplars have a wide tolerance for pH conditions (from 4.0 to 8.0); cultivation on soils with an extremely acid reaction (pH <=4.5) is already excluded by climatic criteria in Italy, while critical nutritional problems occur on strongly alkaline calcareous soils (Colt et al. 1997); iron chlorosis causes leaves to turn yellow to yellow-green between the leaf veins, usually causing the veins to turn darker green.

Table 1

Crispy level of soil limitations for hybrid poplar cultivation in Italy (from Scotti et al. 2010). Variable importance degree: *** high importance, ** medium importance; * little importance. Soil texture (USDA) S = Sandy, LS = Loamy Sand, SL = Sandy Loam.

Soil factors	Importance	Intensity of limitations		
		Absent or very low	Moderate	severe
Soil texture (USDA)	***	Coarse = S, LS, SL	Moderately fine to fine	-
Rooting depth	**	>=50	-	<50
Oxygen availability	***	Good or moderate	Imperfect	Low to very low
Reaction pH	*	5.5 - 8.5	4.5 - 5.5	<4.5 and >8.5
Water deficit risk	*	Absent to moderate	-	High to very high
Water table depth (March-October)	**	100 - 250 cm	50 -100 cm 250 - 500 cm	< 50 cm >500 cm

Salinity EC 1:5 mS/cm (Ece = saturated soil extract)	***	<=0.15 (~ 2.3 ECe)	0.15 - 0.4	>0.4 (~ 4.2 ECe)
Active carbonates%	***	<=6	6-10	>10
Duration (mean) of the floods	**	<=1 month	>1 month	-

Some Authors (e.g. Rüger et al. 2005) underline that the autonomous water supply of some plants derives from groundwater if present within about 250 cm of depth; the depth of the aquifer, on the other hand, is not available on a national scale in Italy: for this reason it has not been included here among the factors subject to evaluation.
The soil and morphometric drivers exploited here for the LS assessment of hybrid poplar plantations were: i) soil depth (SDP); ii) active carbonates (ACR); iii) pH in water (pH); iv) soil salinity (aka electrical conductivity) (SAL); v) soil texture and soil drainage, fused into a single layer (STX) that takes into account the soil structure as a whole; vi) slope (SLO). The national raster maps of such soil properties have been extracted from the soil database developed at the Soil Cartography Laboratory of the Council for Agricultural Research and Economics (CREA), accessible at https://zenodo.org/search?page=1&size=20&q=CRSA_CREA-AA_Firenze (Costantini et al. 2013). The soil salinity map, created by adopting the procedure proposed by the Global Soil Partnership, is accessible at https://www.fao.org/global-soil-partnership/gsasmap/en/ (Ungaro et al. 2022).

2.2. LS modelling strategy

Membership fuzzy functions were developed for each environmental driver and the contribution to the overall suitability was defined by assigning equal importance weight to each factor. The single-driver LS maps were overlayed to obtain an overall LS value for each cell as the average of the single-driver values. To this end, all spatial data were resampled into raster layers with a geometric resolution of 250 m, i.e. each pixel equals 6.25 hectares.
The Corine Land Cover (CLC) classes whose conversion to poplar plantations is impossible or unlikely (i.e., rocky outcrops, water, forests, urban settlements, highly profitable agricultural crops such as vineyards) were set as constraints of the analysis. Therefore, the LS classes have been assigned only to the pixels falling within CLC polygons of the following farmland classes: non irrigated arable land (CLC code = 211); pastures (CLC code = 231); annual crops associated with permanent crops (CLC code = 241); complex cultivation patterns (CLC code = 242); agro-forestry areas (CLC code = 244). Given the management intensity of poplar plantations, even farmland areas included within areas officially designated for nature conservation (national and regional natural parks, Natura 2000 sites, etc.) were excluded from the evaluation of the LS.
According to the classification scheme proposed by Corona et al. (2008), adapted from FAO (1976), membership functions were assigned to each factor for each of four linguistic variables: (i) high suitable land (fuzzy value = 0.90-1.00); (ii) suitable land with some limitations (fuzzy value = 0.70-0.89); (iii) marginally or low suitable land with strict limitations (fuzzy value = 0.20-0.69); (iv) unsuitable land (fuzzy value < 0.20). Pixels with LS values outside the range reported by the fuzzy membership functions for hybrid poplar plantations were considered unsuitable.

2.3 Membership functions

The fuzzy MAT membership was modelled at the pixel level by the Gaussian function:

$$LS = e^{\left(-\frac{(MAT-\mu)^2}{\sigma^2}\right)}$$

where *LS* is the predicted LS value, *MAT* is the pixel's value and μ and σ are the mean (i.e. the MAT value where LS is 1), and the standard deviation, respectively.

For all other factors (except STX) a logistic function was adopted:

$$LS = \frac{L}{1 + e^{k\times(x-x_0)}}$$

where the three coefficients represent the maximum value of the logistic curve (*L*, set to 1), the slope of the curve (k) and the midpoint of the curve (x_0).

A classification matrix has been developed for STX (see § 3.1). All the computation was done in R programming language using the 'stats' and 'terra' packages

2.4 Calibration of fuzzy membership functions

Poplar cultivation data collected by the research center for Forestry and Wood of CREA (CREA-FL) over forty years were used to calibrate the fuzzy membership functions (CREA-FL soil database in Fig1). The extracted dataset consists of 880 observation points coming from different national projects. For each record, pedoclimatic characteristics and growth performance are recorded; about 700 records refer to highly productive plantations, especially in the northern regions, while the other 180 are representative of marginal areas, i.e. they refer to plantations intentionally established on marginal land characterized e.g. from acidic, saline or shallow calcareous soils (Frison and Facciotto 1992). Another dataset was also available, with climatic data only, consisting of 2,155 geo-referenced records of poplar plantations from various research project such as Monipoplar, Bioenerlegno (https://drive.google.com/open?id=1TCCeXAN02hFab2CTJ1vkf3qrTVnDKx55), Precisionpop (https://precisionpop.net/prodotti/), Poplar for Farmers (https://zenodo.org/record/7612569), Faesi, and Suscace (Pari L.et. al 2011).

The parameters of the fuzzy membership functions, initially fixed on the basis of literature review, were iteratively adjusted so that predicted *LS* values matched as closely as possible the actual production performance reported by the plantation records of both datasets mentioned above. The workflow of the procedure is illustrated in Figure 1.

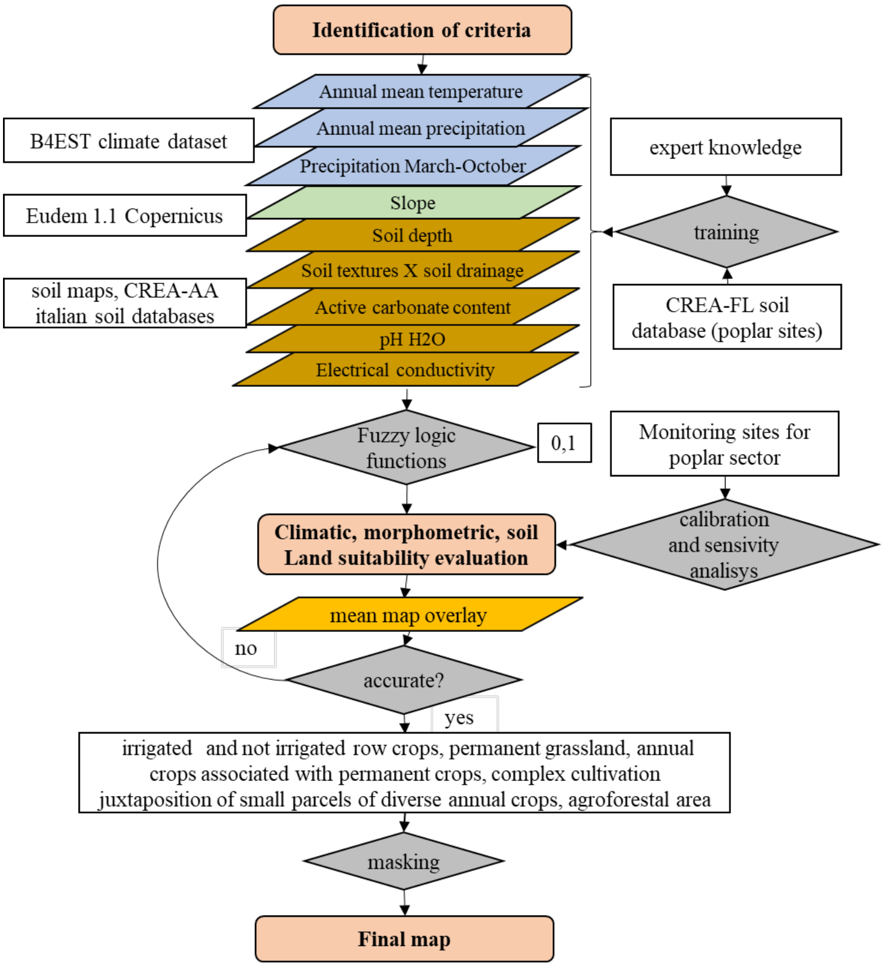

Fig2 Operational flow of the procedure adopted for the attribution of land suitability with respect to hybrid poplar plantation.

3. Results

3.1. Membership assignment

The optimised fuzzy membership functions are shown in Figure 3.

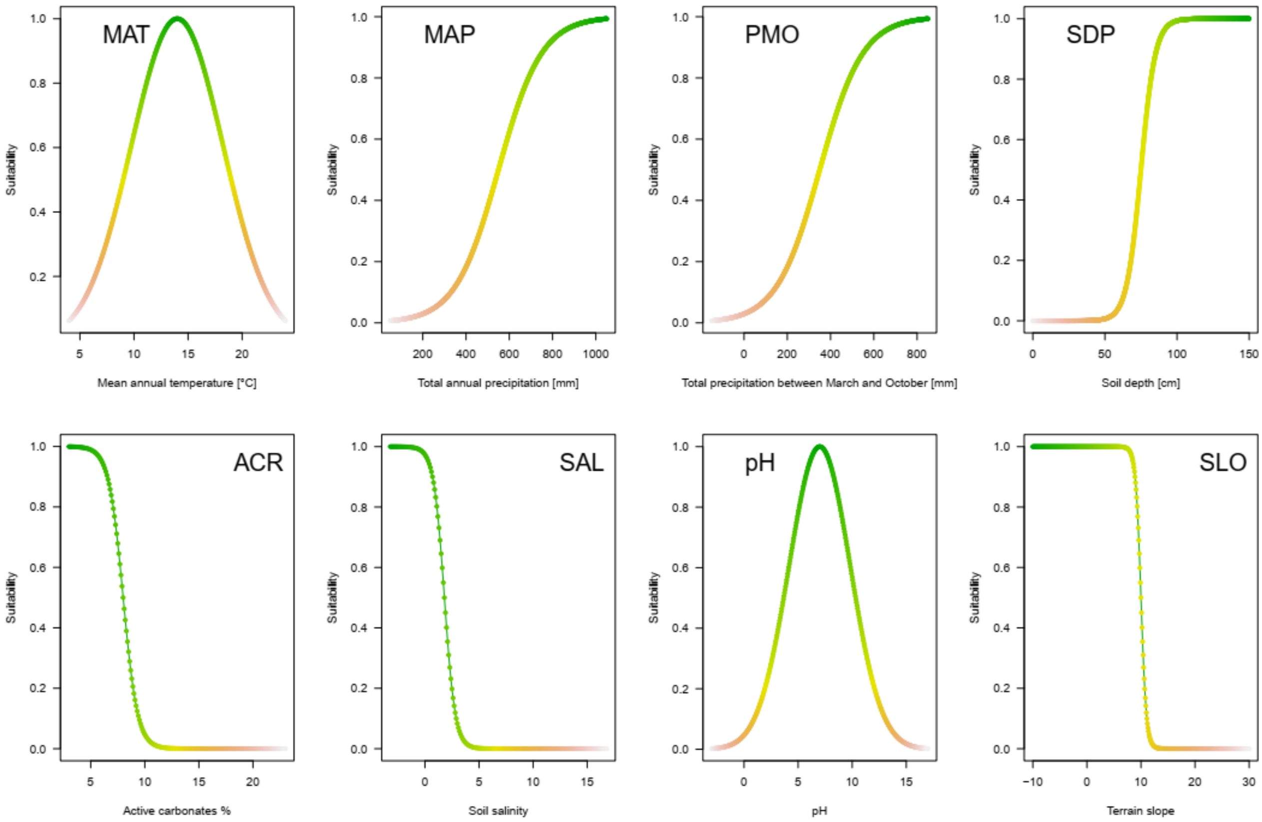

Fig3 Optimised single-parameter fuzzy membership functions for land suitability of poplar plantations in Italy

Each function was optimized starting from experimental experience and from literature data. Particularly, poplars need high light intensity, warm temperatures and sufficient soil moisture during the growing season (Dickmann and Kuzovkina, 2014). Excessively cold temperatures for long periods cause extensive damage during the dormant season, and the amount and timing of rainfall should be considered to ensure adequate water availability during the establishment stage of the plantation. We applied these considerations to set the MAT function at 14°C as the average value and at 5°C as the standard deviation: this expresses the ability of poplar to cope with a large seasonal variation of MAT, where the suitable areas are those characterized by MAT between 11.5°C and 16.5°C. Regarding water availability and rainfall, the requirements for almost all *Populus spp.* and the entire *Salicaceae* family in general is rather high: this is particularly true as regards the amount of rainfall available during the growing season and, overall, between March and October (vegetative season); consequently, optimisation of MAP and PMO yielded a steep function with a growth rate of -0.01 and a midpoint of the curve of 550 mm per year for MAP and 400 mm per year for PMO; land highly suitable for hybrid poplar cultivation are those with MAP equal to or greater than 830 mm and PMO equal to or greater than 690 mm.

SDP is the depth to which the parent material is altered by pedological processes and if the parent material is not hard rock, roots may extend beyond soil weathered horizons; on the other hand the rooting depth can be less in the presence of cemented or strongly compacted horizons and again due to an excess of coarse fragments; thus, rooting depth is more closely related to soil water holding capacity than soil depth. According to Schuette et al. (2009), poplar roots need more oxygen than most other tree species and the youngest trees are the most vulnerable to low oxygen availability: 30% clay in the soil is the maximum allowed to avoid poor drainage, low oxygen availability and a physical barrier to root development. Here the fuzzy membership function for SDP resulted as a sigmoid curve with midpoint at 75 cm, and highly suitable soils with SDP deeper than 90 cm. The membership function of active carbonates (ACR) was found to be an inverse sigmoid with midpoint at 8% and with a high risk of lime chlorosis (Frison and Facciotto 1992) for values >10%. An inverse sigmoid membership function was also found for salt concentration (SAL), with an intermediate value (LS=0.5) corresponding to an ECe value of 1.8 dS/m and impossible survival of trees for ECe values equal or greater than 3.6 dS/m. Slopes greater than 30% inhibit operability for the establishment of poplar plantations and their tending and harvesting: this threshold was used to generate a simple binary layer (0 or 1) for this parameter.

Finally, according with Rogers et al. (2016), soil texture and drainage interact to influence soil suitability for poplar where the texture is represented by the relative proportions of clay, silt and sand (less than 2 mm in diameter) constituting the mineral (inorganic) fraction of soil; after the calibration process on the available records of poplar plantations, a classification with 12 soil classes was generated, according to standard triangle of United States Department of Agriculture: the resulting matrix between soil texture and drainage classes generating the SXT layer is reported in Table 2.

Table 2

Contingency table between 12 USDA soil texture classes and soil drainage classes. Drainage class: ED: overdrained; SED: a little excessively drained; WD: well drained; MWD: moderately well drained; SPD: a little poorly drained; PD-VPD: poorly drained and very poorly drained (for more details, see: Soil survey manual; Soil Science Division Staff 2017). Texture classes (Soil Science Division Staff 2017): sand (S), loamy sand (LS), sandy loam (SL), loam, (L), silt loam (SiL), silt (Si), clay loam (CL), sandy clay loam (SCL), silty clay loam (SiCL), clay (C), silty clay (SiC), sandy clay (SC). For more details, see: Soil survey manual. Handbook n.18 (Soil Science Division Staff., 2017).

		Drainage classes					
		ED	SED	WD	MWD	SPD	PD-VPD
Texture classes	C	0.1	0.1	0	0	0	0
	SiC	0.2	0.2	0.2	0.1	0	0
	SiCL	0.4	0.5	0.4	0.3	0.1	0
	SC	0.5	0.6	0.5	0.4	0.2	0
	SCL	0.6	0.8	0.8	0.6	0.2	0
	CL	0.6	0.7	0.8	0.6	0.1	0
	Si	0.3	0.4	0.2	0.1	0	0
	SiL	0.5	0.8	0.7	0.5	0	0
	L	0.7	0.9	0.9	0.8	0.2	0
	S	0.5	0.6	0.7	0.8	0.3	0
	LS	0.6	0.8	0.9	1	0.2	0
	SL	0.8	1	1	0.9	0.1	0

3.2 LS for hybrid poplar plantations

The results of LS evaluation are shown in Figures 4 and 5. As expected, the best growing conditions for hybrid poplar plantations are in well-drained bottomlands. However, good growth performances can be achieved under a relatively wide range of environmental conditions. Throughout Italy, the developed model identifies around 145,000 hectares of highly suitable land (fuzzy value= 0.90-1) and around 1,926,500 hectares of suitable land (fuzzy values= 0.70-0.89) for the cultivation of hybrid poplar plantations.

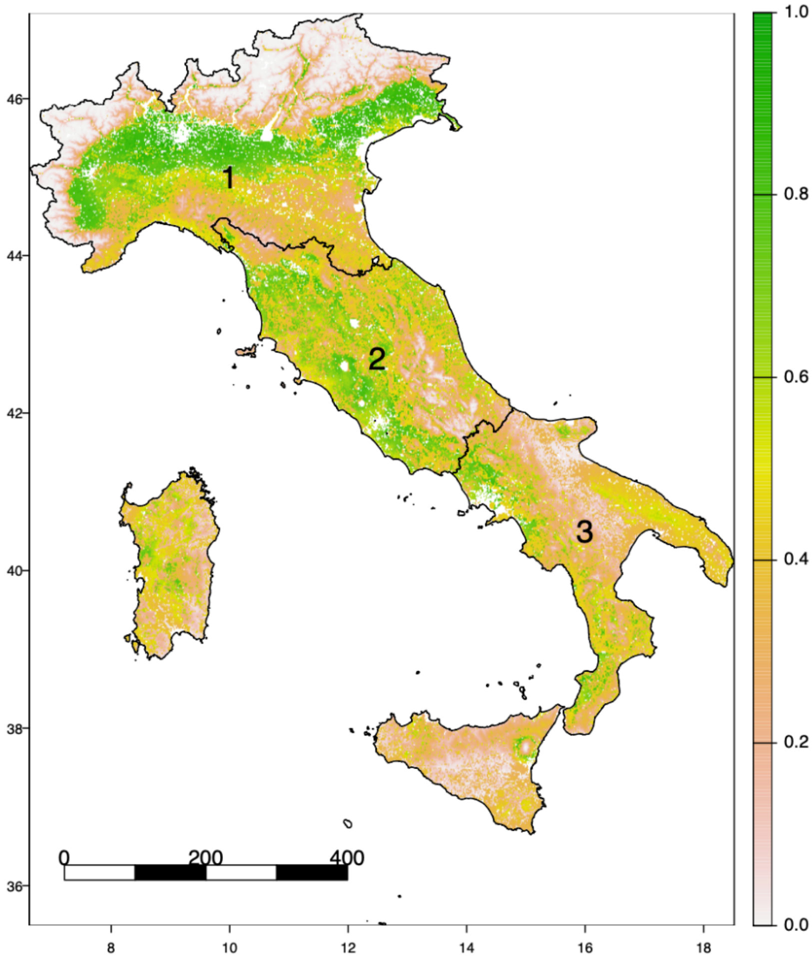

Fig4 LS map for *P. ×canadensis* plantations. The colors indicate the suitability for poplar cultivation between zero (not suitable) and 1 (fully suitable), and the three macro-regions for North (1), Center (2) and South with islands (3) are also shown. The axes indicate latitude and longitude.

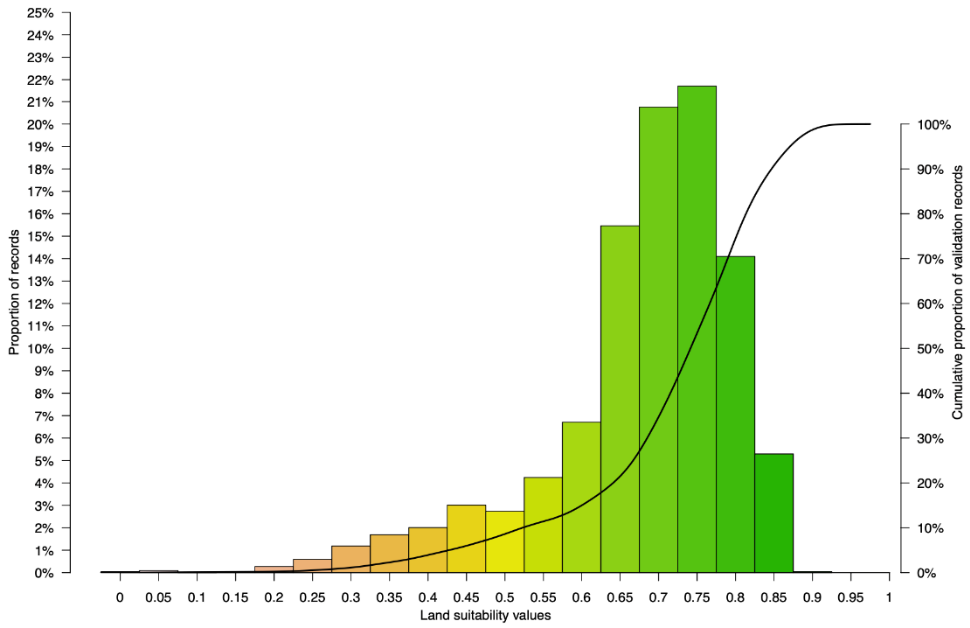

Fig5 Proportion of calibration records (see § 2.5) within each LS class (green bars correspond to suitable and highly suitable values). The first y-axis (left) shows the proportion of validation records falling within each LS class (bars) while the second y-axis (right) is related to the black lune and expresses the cumulative proportion of validation records captured when cumulating the number of records in each bar

In northern Italy 33.6% of the territory proves to be suitable and 2.3% high suitable for hybrid poplar cultivation. About half a million hectares can be recovered from Less Favoured Areas (LFAs), i.e. agricultural land, other than mountain areas, unprofitable for the main intensive agricultural crops (Costantini et al. 2019). The suitability for hybrid poplar plantations is concentrated in the alluvial plain of the Lombardy Region, followed by Piedmont and Friuli. The relatively low suitability in the area of the province of Mantova, known instead as an important district for wood production by poplar plantations, is due to the fact that the irrigation contribution, which is not considered in our evaluation, is very significant in that district. In general, the Po valley, due to the soil characteristics and to the water availability, is currently the main production area of poplar wood in Italy: however, this cultivation currently covers just 40,000 hectares and our study shows that there is a great potential for further expansion.

In central Italy, the orography together with soil characteristics represents the main limiting factor: the LS assessment suggests that 17.7 % of the territory is suitable and 1.4% is high suitable for hybrid poplar cultivation. The administrative regions with the greatest potential are Tuscany, Latium and Campania. Distinctively, there are suitable areas of considerable size north and west of Rome in Latium, where volcanic soils predominate; experimental studies have demonstrated the profitability of poplar coppices in central Italy, provided that the soils are well drained such as those on volcanic deposits (Paris et al. 2018). It is likely that about 157,000 hectares from LFAs could be recovered for expanding such plantations in these regions.

In southern Italy and on the islands the climate is the main limiting factor for cultivation of poplar plantations, due to warm temperatures associated with relatively low water availability. However, the synergy of some environmental factors can make fast growth of poplar possible and with adequate precautions (e.g. the choice of suitable clones) can guarantee profitable wood production in some areas. The LS assessment suggests that 2.4% of study area is suitable and 0.4% is high suitable for hybrid poplar cultivation; around 35,000 hectares can be reclaimed from LFAs. Although the expansion potential may seem relatively limited throughout southern Italy and the islands, significantly large areas can be identified in which to effectively develop local poplar supply chains, such as e.g. in northern part of the Campania region, and supported by the possibility of irrigation.

3.3. Sensitivity analysis

A sensitivity analysis was performed with respect to each environmental driver. The full-layer LS values and the LS extracted on the calibration records (see § 2.5) were also used in the Kolmogorov-Smirnov test. This procedure was repeated for all eight predictors and the *p* values' variability was used to evaluate the most influential/sensitive. We evaluated how the LS map can be affected when any single parameter is changed. The variability of LS values is shown in Fig.6. Overall, soil texture and soil salinity were found to be the most sensitive while active carbonates and the mean annual precipitation were the most stable (Fig. 5).

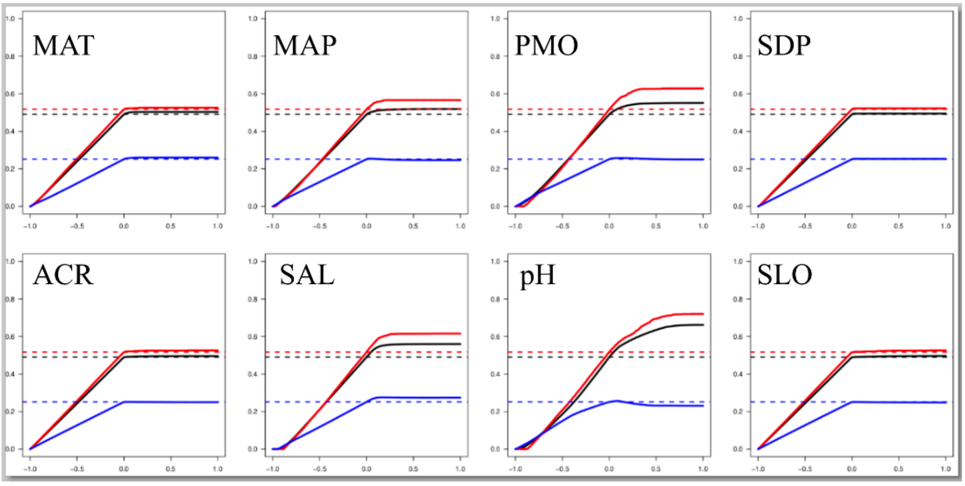

Fig6 Effects of sensitivity analysis of considered factors with respect to LS across the calibration dataset. The three lines represent the mean (black), median (red) and the standard deviation (blue) of LS values when the predictors are manually changed the sensitivity analysis.

4. Discussion

A fine-scale, wall-to-wall LS map has been produced to operationalize current knowledge from the literature and empirical evidence to support effective choices by land use planners and farmers with respect to the potential to foster hybrid poplar plantations in Italy (Fig. 4).

Boolean modelling has been criticized for its simplicity, due to sharply delineated features with inherent loss of information (Joss et al. 2008). An alternative approach could be Analytic Hierarchy Process (AHP) which is a multicriteria decision making that help modeler to select the importance of each criterion, but on the other hand, AHP cannot capture the subjectivity or fuzziness of the criteria. This led us to consider the fuzzy logic approach as a means to deal with ambiguity and uncertainty to generate realistic continuous classifications. Therefore, a set of fuzzy logic criteria based on expert knowledge was used here.

In our approach, in our approach we have not considered cultural variables; the growth-limiting effect of some factors can be overcome through crop inputs, e.g. water availability (through irrigation) and drainage capacity (through soil management); however, other environmental limitations are difficult to overcome, such as e.g. salinity or slope steepness. As mentioned, considering the availability of water, the possibility of irrigating at a relatively low costs, at least within developed irrigation districts, could have a decisive influence on the extension of the areas identified here as suitable.

Furthermore, high suitability does not imply the direct possibility of hybrid poplar cultivation for industry purposes, as socio-economic factors influence, and have historically influenced, the land use choices. When in a territory there are areas already characterized by the presence of poplar plantations, it is conceivable to improve the local wood supply chain by the expansion of the plantations. Conversely, the presence of limited and isolated areas with high LS for poplar cultivation is only an indication of potential that may be difficult to achieve.

The map here developed (Fig. 4) provides an indication of the suitability based on selected environmental factors for which spatial information is available throughout the national territory. Its exploitation has some limitations, as the interactions between factors have not been considered, the influence of which on the performance of hybrid poplar plantations is still largely uncertain, as well as those environmental factors for which spatial information is not available throughout the national territory (e.g., the presence of water table). Furthermore, the LS evaluation carried out involves uncertainties related to the quality of input data (e.g. the soil texture map is characterized by an overall accuracy of just 67%). Finally, only the average behaviour of the *P. ×canadensis* genotype group was taken into account and The methodologies described and their application procedures shall be exported in the unaltered state in *Populus ×canadensis* growing areas as shown in fig1. The methodology can be also suitable for specific genotypes and others specie even considering that significant ecophysiological differences between hybrid clones can be appreciated with respect to the environmental factors here considered.

5. Conclusions

Land suitability can be seen as a bridging step linking land resource assessment to decision-making. The inherent conflicts and the complex network of ecological constraints affecting spatial planning require a flexible support tool capable of incorporating multiple evaluation criteria. Land suitability provides transparent indications to decision-makers on land uses that can be sustainably promoted in the territory under consideration, allowing different areas to be classified according to their degree of suitability for a specific land use. The resulting map provides efficient negotiation support, when addressing issues of sustainable development and economic competitiveness, in an evidence-based framework (Corona 2018).

The modelling approach adopted here is deliberately empirical and planning-oriented. The methodological protocol, based on information for which geodatabases of adequate and comparable spatial resolution are available at national level in Italy, can be easily replicated to other forest tree species (Sallustio et al. 2022) and in other geographical areas or at finer scales, provided that appropriate data are available. The fuzzy approach adopted provides a solid alternative to hard classification methodologies, being such relationships intrinsically characterized by gradual transitions rather than sharp boundaries. For

Considering the growing interest in wood production on agricultural land and the growing demand for poplar wood from national wood-based industries, the results of this study highlight that in Italy there is a significant amount of land available for the expansion of hybrid poplar plantations: suitable and highly suitable land represent, in fact, around 7% of the national territory (or 2,071,500 hectares). The LS digital maps can be used directly by agricultural services and rural planning decision makers to delineate the areas where to promote such plantations. However, it should be reiterated that, unlike the districts of northern Italy, most of the farms in central and southern Italy and the islands are currently not adequately organized and equipped for poplar cultivation, so the expansion of this type of cultivation could be recommended with distinctive regard to the most suitable large districts identified here, where to develop a robust supply chain with the initial support of public incentives.

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