B4EST

Adaptive BREEDING for productive, sustainable and resilient FORESTs under climate change

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Layman's report on benefits, costs and risks related use of improved poplar clones FRM in alluvial regions of central and southern Europe

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1 Summary

The changing climate is an important driver of change in forests. It can increase forest vulnerability to damage and disease occurrence and intensity, reduce forest health and productivity, and cause economic losses. Depending on the region, it can also have positive effects, such as increasing renewable biomass growth due to longer growing seasons and increased temperature when water access is not limited.

This report considers the benefits and possible risks deriving from the use of improved poplar clones in alluvial regions of central and southern Europe, where the largest poplar cultivated areas are located for a total area of about 900,000 hectares. By adopting new improved breeding strategies and fostering the use of new Forest Reproductive Material (FRM) more tolerant to increasing biotic and abiotic stresses, it is already and will be possible to remedy to the critical issues for poplar cultivation deriving from the changed eco-physiological conditions as a result of climate change.

The cultivation of improved poplar clones combining faster growth and good technological characteristics requires lower input (especially regarding water and nutrients), and therefore lower production costs, and allows the achievement of objectives of greater environmental sustainability both in monoclonal plantations and in mixed plantations with higher level of genetic diversity.

Other aspects highlighted concern the ecosystem services that these sustainable plantations can provide with benefits both for growers but also for all the society, as the uptake of air, water and soil pollutants and the conservation of the environment and landscape for future generations.

2 Tree breeding and deployment of FRM to meet challenges of European forestry

Climate change, caused mainly by anthropogenic greenhouse gas emissions, is disrupting our ecosystems (Mooney et al. 2009): species are decreasing, terrestrial systems have been converted by human activities, fresh water are one of the most altered ecosystems, extreme climatic events cause damages to humans; fast growing trees species (FGT, including poplar) can contribute to the mitigation of these impacts thanks to a continuous adaptation of plant performances and poplar cultivations to these challenges. In case of poplar cultivation, increase of international mobility that caused the introduction of exotic pests and diseases with high impacts on poplar populations add to the effects of climate change which can promote the emergence and expansion of known pests and diseases.

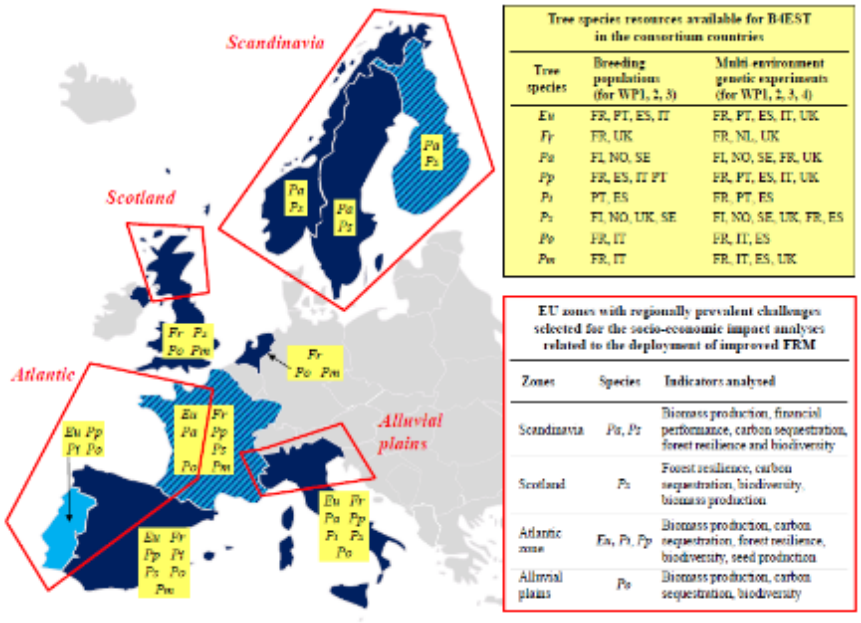
Climate change affecting air temperature, solar radiation, rainfall and carbon dioxide are the most important factors for forest plantation productivity. Carbon sink capacity is related to growing rate; therefore, FGT species plantations can sequester a great amount of carbon from the atmosphere, working as a climate mitigation tool also in relation to greenhouse gas emission due to natural forest degradation and deforestation, that account for approximately 18% of global carbon emissions (Sobola et al. 2015). Among the forest mitigation strategies, the product substitution involves the use of wood fuel instead of fossil fuels for energy: FGT plantations managed as Short Rotation Coppice are able to produce a large amount of biomass for energy, helping to reduce forest exploitation. Other interesting example are wooden

houses, where FGT (also poplar) can substitute other material less sustainable (Green & Taggart 2020).

So the changing climate is an important driver of change in forests. It can also have positive effects, offering opportunities for growing trees in previously suboptimal regions.

The strategic goal of B4EST is to increase forest survival, health, resilience and productivity under climate change and natural disturbances, while maintaining genetic diversity and key ecological functions and fostering a competitive EU bio-based economy. B4EST has provided forest tree breeders, forest owners, managers and policy makers with: 1) better scientific knowledge of adaptation profiles to increase sustainable forest productivity, and added value of raw materials for economically important tree species, 2) new and flexible adaptive tree breeding strategies and tools, 3) decision-support tools for the choice and use of Forest Reproductive Material (FRM) for balancing production, resilience and genetic diversity, 4) robust management and transfer recommendations for FRM deployment at stand and landscape levels, 5) policy recommendations to adapt European forest production systems to the challenges posed by climate change and natural disturbances, and to meet societal demands set to sustainable and multifunctional utilization of forest resources.

Benefits, costs, and risks related to the deployment of improved FRM in Europe have been assessed by carrying out analyses indicating the impacts of revised deployment strategies in four different regions of Europe (Figure 1) focusing on regionally prevalent challenges. The four different regions differ for growth conditions, tree species, structure of forests, operational environment of forestry, and expected biotic risks and other impacts of environmental change.



Tree species resources available for B4EST in the consortium countries

Tree species	Breeding populations (for WP1, 2, 3)	Multi environment genetic experiments (for WP1, 2, 3, 4)
Eu	FR, PT, ES, IT	FR, PT, ES, IT, UK
Fy	FR, UK	FR, NL, UK
Pa	FI, NO, SE	FI, NO, SE, FR, UK
Pp	FR, ES, IT PT	FR, PT, ES, IT, UK
Pi	PT, ES	FR, PT, ES
Ps	FI, NO, UK, SE	FI, NO, SE, UK, FR, ES
Po	FR, IT	FR, IT, ES
Pm	FR, IT	FR, IT, ES, UK

EU zones with regionally prevalent challenges selected for the socio-economic impact analyses related to the deployment of improved FRM

Zones	Species	Indicators analysed
Scandinavia	*Ps, Pt*	Biomass production, financial performance, carbon sequestration, forest resilience and biodiversity
Scotland	*Ps*	Forest resilience, carbon sequestration, biodiversity, biomass production
Atlantic zone	*Eu, Pi, Pp*	Biomass production, carbon sequestration, forest resilience, biodiversity, seed production
Alluvial plains	*Po*	Biomass production, carbon sequestration, biodiversity

Figure 1: deployment of improved FRM in four different regions of Europe.

This report presents the main results regarding poplar cultivation in alluvial plains of Central and southern Europe, a very active economic sector in forest and wood bioeconomy with specificities in comparison to other main forest tree species: duration of the rotation, location

of production, cultivation techniques, wood value chain. Poplar cultivation is based on improved FRM, continuously put on the market with the objectives to guarantee wood supplies for the poplar processing industry (wood security) thanks to adjusted adaptation to climate change and biotic risks and development of sustainable production systems (low impact cultivation techniques).

3 Context and regional prevalent challenges

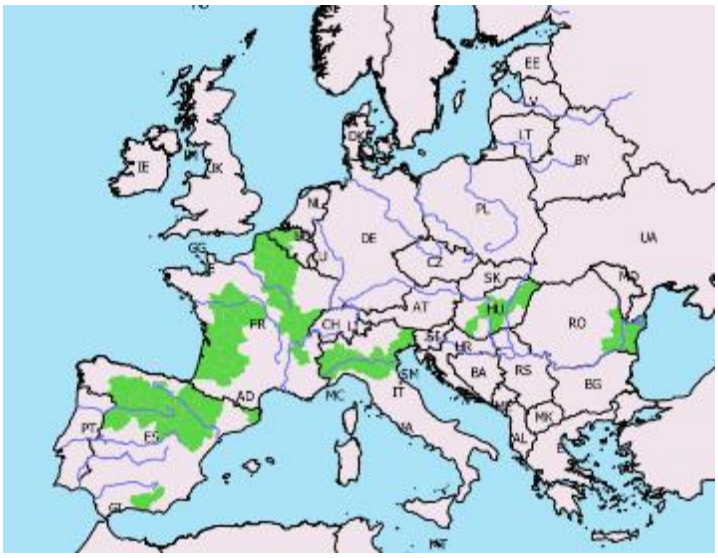


Figure 2: ***Location of intensive poplar cultivation in Europe***

In figure 2 in green are highlighted the main poplar cultivation areas in Europe. The alluvial plains of Spain, France, Italy, Hungary and Romany are the most important. Poplars are cultivated in the plains along rivers where they found site conditions favorable with good water availability. Different to other countries, in Italy poplar cultivation is located on agricultural land, in rotation with crops, mainly cereals.

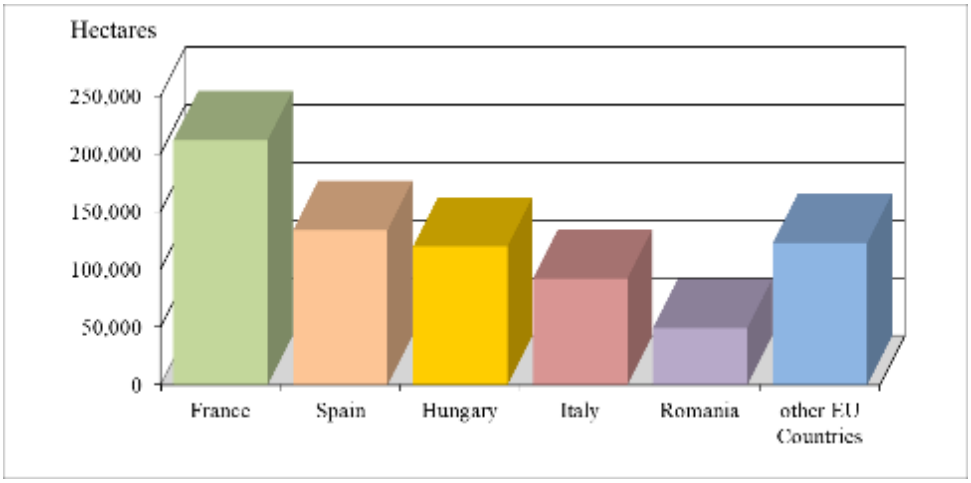


Figure 3: ***Total hectares of poplar plantation in EU (2016)***

Poplar cultivation in EU amount to 900,000 hectares (FAO 2016). France is the most important country for poplar production with more than 200,000 hectares. Spain and Hungary follow with values above 100,000 hectares and then Italy with about 92,000 hectares. Other

countries (Belgium, Serbia, Germany, Croatia, Switzerland, Sweden, Moldova, Bulgaria, United Kingdom, Slovenia) have an area of 123,500 hectares.

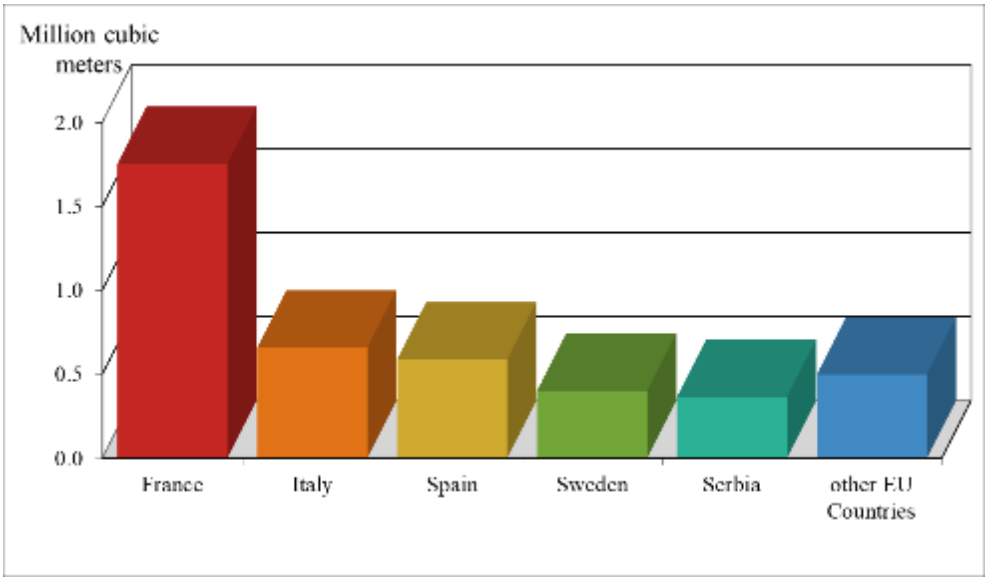


Figure 4: ***Production of poplar wood in cubic meters in EU (2016)***

As far as the production of wood assortments is concerned, France is still the most important country with approximately 1.7 million cubic metres of round wood equivalent, followed by Italy and Spain with just over 0.5 million cubic metres, Sweden (0.4 million) and Serbia (0.36 million cubic meters). All other EU Countries produce about 5.0 million cubic metres of round wood equivalent.

In Italy specialized poplar plantations are mainly dedicated to the production of veneer logs; rotations generally range from 8 to 10 years in the lowlands to up to 15 years in the foothills, while plantations specialized for production of logs for panels and packaging and pulp have rotations of 4 to 6 years. Planting and cultivation techniques obviously differ, as do the varietal choices, based on the wood properties required by end users.

Italian poplar cultivation is widely linked to the use of *P.* ×*canadensis* clone 'I-214', which has ideal wood characteristics for the manufacture of plywood panels (light weight, white colour) but presents challenges owing to its susceptibility to biotic threats (woolly aphid, rusts, *Marssonina* leaf spot). The preference of the Italian industrial sector for the quality of the wood produced by clone 'I-214' has significantly influenced the choice of FRM, limiting the dissemination of new clones and favouring widespread monoclonal plantations. On the other hand, the availability of clones offering greater environmental sustainability (in Italian "Maggiore Sostenibilità Ambientale", thus referred to as MSA clones) characterized by better resistance to the main biotic adversities, makes it possible to develop semi-extensive cultivation models that, by minimizing cultural practices and pest controls, allow a more eco-sustainable poplar cultivation (Table 1). The wood peeling process of these clones is similar to that of 'I-214' even if the different wood characteristics may require the industry to adapt their processing methods (for example, by separating logs of various clones in the yard and semi-finished products in the warehouse, differentiating drying regimes, etc.).

Table 1. List of 25 poplar elite clones referred as MSA clones (Greater Environmental Sustainability) in the Italian register of Base Materials and performances regarding resistance main pests and diseases in Italy.

	CLONE	SPRING LEAF AND SHOOT BLIGHT	LEAF RUSTS	MARSSONINA LEAF SPOT	WOOLLY APHID	GENETIC ORIGIN
	I-214	*****	***	**	**	*Populus ×canadensis*
1	AF8	*****	****	*****	****	*Populus ×generosa × Populus trichocarpa*
2	ALERAMO	****	*****	*****	****	*Populus ×canadensis*
3	BRENTA	*****	***	*****	*****	*Populus ×canadensis*
4	DIVA	****	*****	*****	*****	*Populus ×canadensis*
5	DVINA	*****	****	*****	****	*Populus deltoides*
6	ERIDANO	*****	*****	*****	*****	*Populus deltoides × Populus maximowiczii*
7	HARVARD	*****	****	*****	****	*Populus deltoides*
8	KOSTER	*****	****	***	*****	*Populus ×canadensis*
9	LAMBRO	*****	***	*****	*****	*Populus ×canadensis*
10	LENA	*****	****	*****	****	*Populus deltoides*
11	LUX	*****	****	*****	*****	*Populus deltoides*
12	MELLA	*****	***	*****	****	*Populus ×canadensis*
13	MOLETO	****	*****	*****	*****	*Populus ×canadensis*
14	MOMBELLO	****	****	*****	*****	*Populus ×canadensis*
15	MONCALVO	****	*****	*****	*****	*Populus ×canadensis*
16	OGLIO	****	*****	*****	*****	*Populus deltoides*
17	ONDA	*****	****	*****	****	*Populus deltoides*
18	SAN MARTINO	*****	****	****	****	*Populus ×canadensis*
19	SENNA	****	*****	****	*****	*Populus ×canadensis*
20	SILE	****	*****	*****	*****	*Populus deltoides × Populus ciliata*
21	SOLIGO	*****	*****	*****	****	*Populus ×canadensis*
22	STURA	****	*****	*****	*****	*Populus ×canadensis*
23	TARO	*****	****	*****	*****	*Populus ×canadensis × Populus ×generosa*
24	TUCANO	****	*****	*****	*****	*Populus ×canadensis*
25	VILLAFRANCA	*****	*****	*****	*****	*Populus alba*

LEGEND

*	highly susceptible
**	susceptible
***	tolerant
****	resistant

In other Mediterranean Countries, like Spain the situation is similar in many aspects although it differs in others. The rotation length in plantations for veneer, logs or boards production is between 12 and 15 years. Clone ‘I-214’ continues to be the most widely planted also in Spain, although companies make great efforts to encourage the diversity of genetic material and incorporate new clones that are more tolerant to diseases and ensure higher yields. Some clones such as ‘Diva’, ‘Tucano’, ‘Aleramo’, ‘AF8’, ‘AF13’, ’Raspalje’, and ‘N277’ are obtaining interesting results in several experimental poplar plantations. For biomass production, rotations are between 2 and 4 years, although at present they are not carried out commercially.

In France poplar growth is generally carried out between 15 and 23 years depending on the quality of the soil and the local climate, which depend on the geographical area. The varieties currently used in France are diversified to consider the quality of the soil, the climate and the future uses of the wood. While 'Koster' has been the most widely planted variety for several years, many other varieties commercialized for 8 to more than 20 years, are also currently widely planted, such as 'Diva', 'Tucano', 'I45/51', 'Vesten', 'Trichobel', 'Rona', 'Polargo', 'AF8' and 'Dano'. These 10 varieties represent 75% of the plantings in the 2019-2020 season. Poplar wood is mainly used for plywood (32%) and light wood packaging (37%) while the remaining 31% is used for sawn timber.

4 B4est: benefits, costs and risks related to the use of improved poplar clones.

Specialized poplar cultivation offers excellent production in numerous countries all over the world, representing a highly significant share of annual industrial timber harvesting. At the same time, poplar cultivation contributes significantly to the carbon sequestration (through accumulation in above and below-ground tree biomass and increase in the stock of organic matter in the soil when tree plantations replace traditional intensive agricultural crops) and allows a lower use of plant protection products in comparison with traditional agriculture. Poplar plantations have a positive carbon balance also because poplar wood replaces other materials more energy-intensive to produce (for example, concrete and iron) (Chiarabaglio & Giorcelli 2016) when used as a raw material in the production of durable products, and as biomass for energy production.

The intensification of international exchanges of reproductive materials has contributed in many countries to the development of interspecific hybridisation programmes of between key species (*P. deltoides, P. trichocarpa, P. maximowiczii, P. nigra, P. tremula, P. tremuloides*). Hybrid vigor has been one of the main characteristics considered in poplar breeding since times and their high productivity is generally related to a longer vegetation period, compared with the parental species (Yu et al. 2001). Moreover, hybrid clones have usually been found to be more adaptive over a range of environments than clones of pure species.

In recent decades the research on hybrid poplar clones has received a strong impulse on fast growing genotypes, more efficient in water and nutrient use, resistant or tolerant to pests and diseases (Rennenberg et al. 2010, Polle et al. 2013) but also highly appreciated wood qualities.

The intensification of cultural practices adopted in monoclonal stands together with the narrow genetic basis of the cultivated clones deployed in a given area have been the predisposing factor for outbreaks of several biotic risks: bacterial cancer (*Xanthomonas campestris*), poplar rusts (*Melampsora spp*.) and woolly Poplar Aphid (*Phloeomyzus passerinii*). The risks of monoclonal poplar plantations can be mitigated by a combination of actions : shorter rotations, continuous efforts regarding resistance and tolerance to several pests and diseases combined with a clonal diversification at different scales (stand, regional area, among time). In plantation it is extremely important to maintain a considerable genetic variability using select clones with a diversified genetic background confirmed with an hicreased knowledge of genetic relatedness between commercialized clones.

In this scenario the breeding activity and clonal selection of new genotypes is aimed mainly at clones reaching these different challenges, multiperformance and genetic diversity. Compared to the traditional clones released in 90's, current figures presented in different European breeding programmes let expect continuous genetic gains regarding growth

performance (up to +15% in volume production in favourable conditions). New and flexible adaptive tree breeding strategies and tools have been proposed in frame of B4EST. Their deployment will accelerate access to new genotypes of high adaptive and economic value.

As fast-growing tree species, poplars are able to absorb high amounts of CO_2 and to sequester carbon in wood used for durable products with a long lifetime (plywood for furniture, etc.). It has been calculated that a traditional poplar stand of 278 trees per hectare can sequester up to 25 t ha^{-1} y^{-1} of CO_2 (Chiarabaglio et al. 2014) and that there is additionally a positive carbon storage in the soil, comparing agricultural annual crops and poplar plantations (Zhang et al. 2020). In addition, a future increase in atmospheric CO_2, linked to the greenhouse effect, has been predicted to positively affect the growth and carbon storage of poplars (Gielen et al. 2005). Therefore, new improved clones represent excellent candidate materials to store CO_2 in wood and soil in a changing climate with less water availability and warmer temperatures due to greater water use efficiency compared with traditional clones (Marchi et al. 2022). In addition, innovative and sustainable cultivation techniques would allow the optimization of wastewater use derived from urban or agricultural activities (Dimitriou & Aronsson 2011) or the innovative cultural models of agroforestry that allow irrigation application simultaneously for forest and food-feed crops.

In this light, the availability of adequate communication and knowledge dissemination tools for this sector is important. This Layman's report represents a contribution in this direction, integrating the various technical and management aspects in an organic framework in line with a modern vision of ecological and economic sustainability. The concepts, views and contents presented here can also serve as a direct stimulus for further operational advancements. For this purpose, for example, it may be appropriate to set the goal of a zero-chemical poplar plantation (zero herbicides, zero fungicides, zero insecticides, zero synthetic fertilizers, etc.), at least in a long-term vision.

It is therefore hoped that this report can serve as an effective reference, support and stimulus for growers, professional technicians, industrialists, public officials, researchers and policymakers, in the knowledge that the poplar value chain can represent one of the most dynamic sectors of the green economy on a global scale.

In B4EST project, activities in WP5 evaluate impacts of deployment of an extended FRM portfolio on wood and biomass production, supply of benefits (wood, non-wood products, carbon sequestration, biodiversity), and resilience. In alluvial regions of Southern Europe (Italy, France and Spain) where intensive production areas of poplar are located, benefits and risks of improved FRM and new associated management scenarios are evaluated for different objectives (plywood production, biomass for bioenergy, phytoremediation on marginal lands). The effect of using improved FRM for wood and biomass production and the cost-efficiency of different forest management systems to reach ecosystem resilience in poplar plantations have also been investigated in WP4 and WP5 of B4EST project.

Figure 5: ***Poplar intensive plantation in Italy***

5 Ecosystem services provided by poplar cultivation under climate change

According to the Millennium Ecosystem Assessment (2005), there are four categories of ecosystem services: 1) provisioning, the goods or products obtained from ecosystems, e.g. wood for industry; 2) regulating, the benefits obtained from an ecosystem's control of natural processes, e.g. flood regulation and reduced soil erosion, reduces impact compared to agricultural crops, filtering of contaminants in soil and groundwater nutrients and other pollutants, reduction of greenhouse gases; 3) supporting, the natural processes that maintain other services, e.g. creation of buffer zones between wooded and agricultural lands, constitution of elements of the ecological network; 4) cultural, the nonmaterial benefits obtained from ecosystems, e.g. conservation of the rural landscape, conservation of biodiversity, public use for recreation as walking, cycling, horse riding.

5.1 Provisioning services

Poplar is a fast-growing tree species, and the plantations produce in about 10 years 150 – 200 cubic meters of wood for the industry (average of 15 to 20 m^3/ha/year). Specialized plantations are particularly relevant in the production of wood-based panels, i.e. plywood, veneer, fiber-board and particle-board; only a small amount of wood is used for energy purposes. The high quality and quantity of wood from intensive plantations reduces pressure on natural forests.

Figure 6: ***Pile of poplar logs ready for veneer***

5.2 Regulating services

5.2.1 Flooding and soil erosion

Investigations have been carried out to study the effects of natural forests and poplar plantations in floodplain areas to reduce soil erosion and allow water regulation during flood events. After the occurrence of floods in the Po valley (Italy) in 1994 and 2000, poplar plantations and other tree crops contained soil erosion and hydrogeological instability as much as natural forest. (Chiarabaglio et al. 2014 a).

Figure 7: ***Poplar root system during flood events allows to reduce soil erosion and to regulate flooding***

5.2.2 Reduces impact compared to agricultural crops

An ecological study of the environmental impact of poplar cultivation as compared to the impact caused by a typical crop (corn) in rotation with poplar was carried out, using as a control the ecological parameters of natural forests present on the same sites. The study was carried out considering two different cultivation models: the “traditional model”, characterized by intensive cultivation and frequent phytosanitary treatments, and a “controlled model” (considering, for poplar, the improved FRM), with little use of phytosanitary products and low-

impact cultivation practices. The quantities of nitrogen fertilization for both corn and poplar in the two cultivation models are reported in the table 2.

Nitrogen units per hectare per year	product	corn		poplar	
		traditional	disciplinated	traditional	Impr. FRM
Fertilization pre-sawn	15-15-15	105	60	-	-
Fertilization	urea	207	140	179	124
Total Nitrogen		**312**	**200**	**179**	**124**
Removal		140	140	163	163
Not used		**172**	**60**	**16**	**-39**

Table 2. ***Nitrogen units per hectare and per year for corn and for poplar in traditional and innovative (low impact) plantations***

The “corn traditional model” shows a surplus of 172 units of nitrogen not used by the crop, while the “corn controlled model” has 60 units; on the other hand poplar stands have a very low surplus of nitrogen in the “traditional model” and no surplus with the “Improved FRM” (probably the deficit is covered by the organization of the poplar leaves fallen to the ground at the end of each growing season) (Chiarabaglio et al. 2014 b).

In order to assess the environmental impact of the phytosanitary treatments an index has been applied: the Impact Index by Bonari et al. (1999) is the sum of the ratio between the lethal dose 50 and the treatment dose of the phytosanitary products.

Corn		Poplar	
traditional	disciplinated	traditional	improv. FRM
38160	12970	15258	4437

Table 3. ***Impact index for phytosanitary treatments in traditional and innovative (low impact) plantations***

The highest impact index recorded is that of “traditional corn” (Impact index = 38.160) while the lowest is that of “Improved FRM” (Impact index = 4437). The second is that of “traditional poplar” (Impact index = 15258: < 50% traditional corn) and the third is that of “disciplinated corn” (Impact index = 12970) (Chiarabaglio et al. 2014 b).

The effect of poplar plantations on biodiversity can be explored through the study of vegetation and birds’ composition or the presence of insects, for example carabid species.

Generally, fast-growing tree (FGT) species, such as poplar, may be beneficial for biodiversity as they produce a high amount of dead wood useful for a wide range of organisms (Jastrzebska, 2020) and the bark structure creates microhabitat structures important for biodiversity. In a French inventory of poplar plantations of various ages and locations, species richness, Shannon index and equitability index of ground beetles were higher than those of the compared broad-leaved forests and cereal fields. High species diversity was found in all of the three components measured: ground beetles, birds and vegetation (Berthelot et al. 2005).

Elek et al. 2010 reported that poplar plantations do not reduce the diversity of carabids but it has not increased either compared to grasslands and forests. Also, Allegro and Sciaky (2003)

reports as in older poplar plantations, carabid species tend to be the same ones found in natural forests.

For biodiversity studies, it can also be used the Biological Soil Quality Index (BSQI), which represents an evaluation of the community of soil arthropods present in the top 10 cm of the soil (Parisi et al., 2005; Çakır, 2019). These invertebrates are particularly sensitive to soil quality and therefore to human activities (Andrews et al. 2002, Parisi et al., 2005).

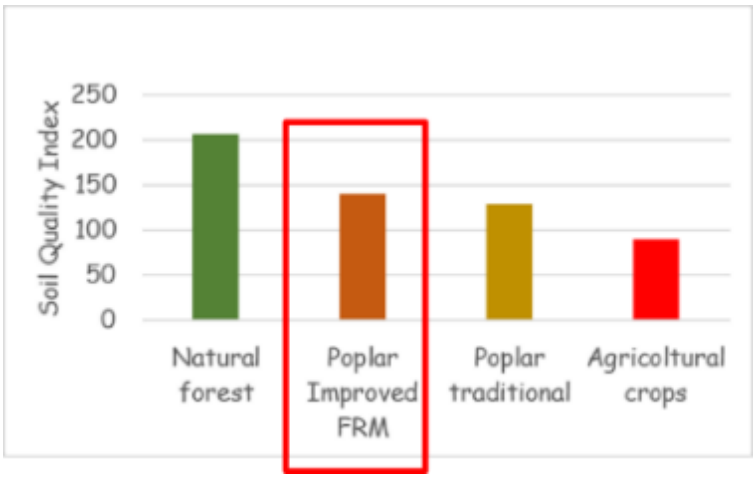


Figure 8: ***Soil Quality Index for poplar traditional and with improved FRM plantation compared with natural forest and agricultural crops***

The poplar stands with Improved FRM have a higher BSQI than crops (corn and wheat) but lower if compared to natural forest. The lower values of the index are due to both cultivation practices (mechanical operations and chemicals) and to the lack of ground cover in the first months for crops and for young poplars having negative effects on soil fauna (Chiarabaglio et al. 2014 b).

5.2.3 Filters the solutions circulating in the soil (nutrients and other substances)

Poplar have been recognized as a promising approach for the decontamination of polluted soils because of their rapid growth, extensive root system and above all high-water uptakes. Many experiences have been conducted on different types of contaminants: heavy metal, polycyclic aromatic hydrocarbons, hydrocarbons and nitrogen (Giordano et al. 2021).

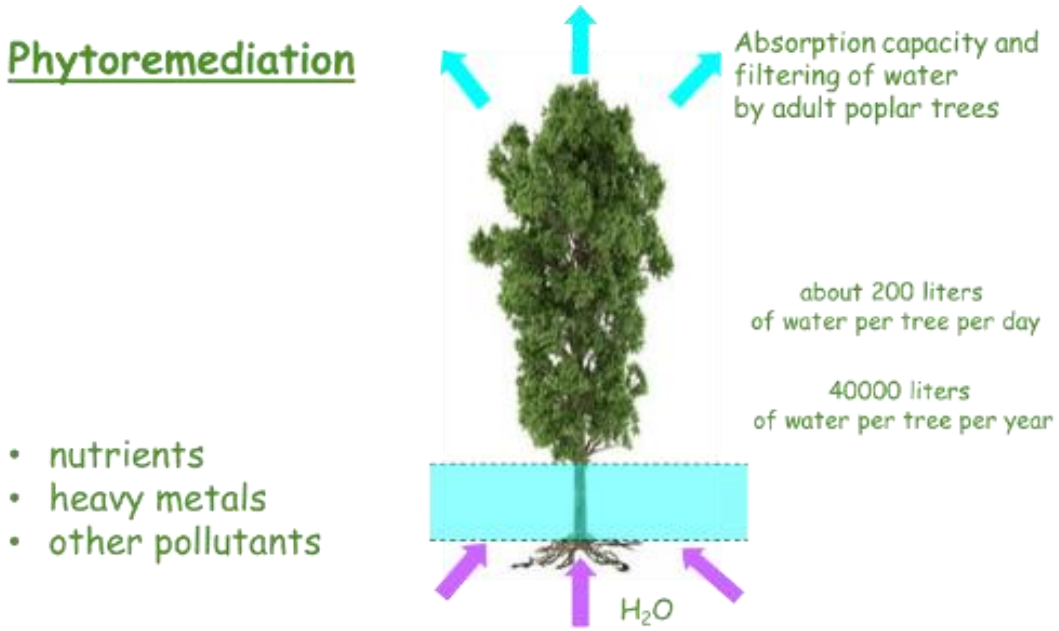


Figure 9. ***Poplar plantations can be used for phytoremediation activities***

In the frame of the Project "DENDROCLEAN: trees to clean up contaminated soils" (grant number CSTO160891), the response to some major heavy metal contaminants of different poplar (*Populus* spp.) and willow (*Salix* spp.) clones cultivated in hydroponic systems was tested by investigating their tolerance, phytoextraction potential and pattern of heavy metal accumulation between green and ligneous organs. Treated clones did not show substantial phytotoxic effects; the phytoextraction efficiency and the accumulation patterns displayed high variability depending on the heavy metal. Although heavy metals can be efficiently sequestered by leaves, some clones achieved good performances in the absorption at stem level.

The use of plants for phytoremediation is appealing, on condition that the species selected for this purpose are endowed with good performances in retaining the target heavy metal contaminants, and with a resistance to the heavy metal contaminants themselves. In fact, if the pollutant addressed by the phytoremediation strategy can determine phytotoxic effects on the plant species used, the efficiency of the whole process may be heavily compromised. For this reason, one of the main goals of this study was the assessment of poplars and willows resistance to Zn and Pb contamination. By monitoring the health status of each plant along the whole duration of the experiment, no symptoms related to the onset phytotoxicity were observed (Figure 10). Although the experiment lasted for only two months, the results of the chemical analysis pointed out that a massive accumulation has occurred, and similar experiments have shown that symptoms can arise in a short span of time (Di Baccio et al., 2003; Dos Santos Utmazian et al., 2007 and references therein). However, Lingua et al. (2012) demonstrated the long-term responses to the heavy metal stress in the protein expression patterns of poplar plants.

Figure 10. ***Absence of symptoms related to phytotoxicity associated with treatments with Zn and Pb solutions on poplar (left panel) and willow (right panel) clones***.

5.2.4 Fix CO_2 in the wood (and temporary in the soil)

With rising concern about the climatic consequences of greenhouse-gas emissions, worldwide efforts are being made to augment carbon sequestration and reduce CO_2 emissions. Now, the global emission of CO_2 from soils is recognized as one of the largest contributors to global carbon fluxes, and small changes in the magnitude of soil respiration could have momentous effects on the CO_2 concentration in the atmosphere (Schlesinger and Andrews, 2000). Deforestation and conversion of natural ecosystems to agricultural ones constitutes major sources of the increasing atmospheric CO_2 concentration (Lal, 2004). When soils are disturbed through cultivation, their soil organic-matter content declines because of the change in the decomposition conditions, soil aeration, destruction of soil aggregates, and moisture content leading to greater rates of soil respiration. Improved management and alternative land use for agricultural soils could potentially bolster the role of soils as a CO_2 sink. In this regard Cantamessa et al. 2022 reports, through the Life Cycle Assessment (LCA), that soil fertilization using compost allowed the reduction of CO_2 emissions values compared to conventional poplar management carried out with inorganic fertilization sink.

Life Cycle Assessment (LCA) is a holistic methodology that aims to analyse products, processes, or services from an environmental perspective (ISO 14040, 2006). This analysis is carried out through the Life Cycle Inventory Analysis (ISO 14041:1999) in which, for each cultivation phase, all the raw material, energy and emissions related to cultural inputs were identified and evaluated. LCI is aimed at Analysis of Impacts (LCIA, ISO 14042:2000), for example utilizing the IPCC 100 method comparing the CO_2 equivalents (CO_2 eq.) total emissions. The functional unit (FU) is fundamental for normalising all LCA data. In LCA studies of agricultural production systems, the FU is usually the area (m^2). In poplar cultivations, the most environmentally impactful management practices in terms of CO_2 emissions are the fertilization, irrigation and soil preparation, especially if the cultivated clone is the ‘I-214’.

For the cultivation of this clone, currently the most widespread and required by industry, total emissions in Italy and Europe, from the stool bed to the poplar stand, are 7.347 kg CO_2 eq. per hectare. In this regard, the cultivation of MSA clones allows to avoid a quote of CO_2 emissions up to about 9%, corresponding to approximatively 300 kg CO_2 per ha in ten years (Chiarabaglio et al. 2020).

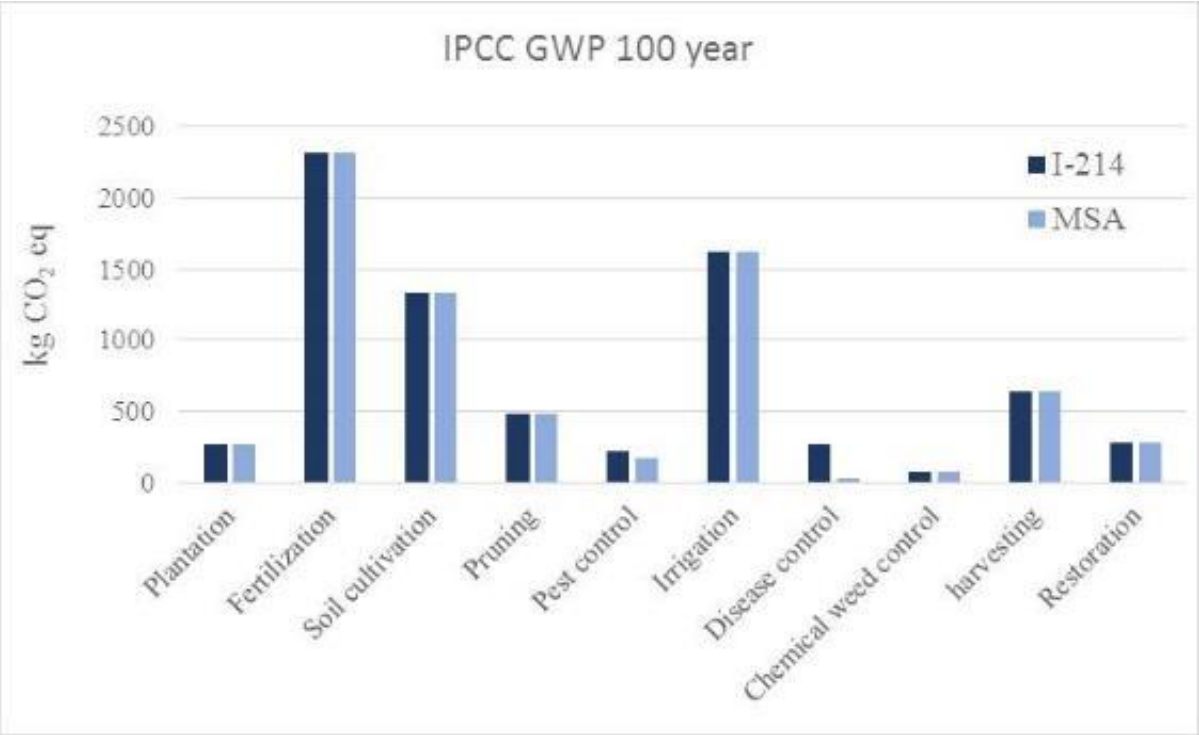


Figure 11: CO_2 equivalent emissions for 'I-214' and MSA (IMP) cultivation divided by cultural inputs. Total emissions of the whole cultivation cycle (stoolbed + nursery + poplar stand).

On the other hand, if CO_2 eq. is normalised to production (m^3), the emissions per unit of volume are significantly lower for MSA clones: 36.6 kg CO2 eq. m^{-3} of MSA, compared with 47.5 CO2 eq. m^{-3} of 'I-214' saving about 23 % of CO_2 eq. This reduction is possible because MSA clones are characterised by a 25% higher growth rate than 'I-214' clones (Chiarabaglio et al. 2020).

The carbon cycle of terrestrial ecosystems plays a key role in regulating CO_2 concentration in the atmosphere. Enhancing carbon storage in terrestrial ecosystems will be a key factor in the maintenance of this balance since soils play a central role in the global carbon cycle and constitute a large carbon reservoir, 3 times larger than the atmospheric-carbon pool. Poplar plantations contribute to remove from the atmosphere some of the carbon (which in the form of carbon dioxide is among the causes of the greenhouses effect) by storing it in long-lived products for furnishing and construction; therefore, can contribute to the pursuit of important objectives for society, such as climate change mitigation and environmental improvement. Acquired knowledge suggests that the carbon footprint of poplar cultivation is more than positive thanks to poplars' high capacity to absorb CO_2 and accumulate it in wood (up to 25 t ha^{-1} $year^{-1}$).

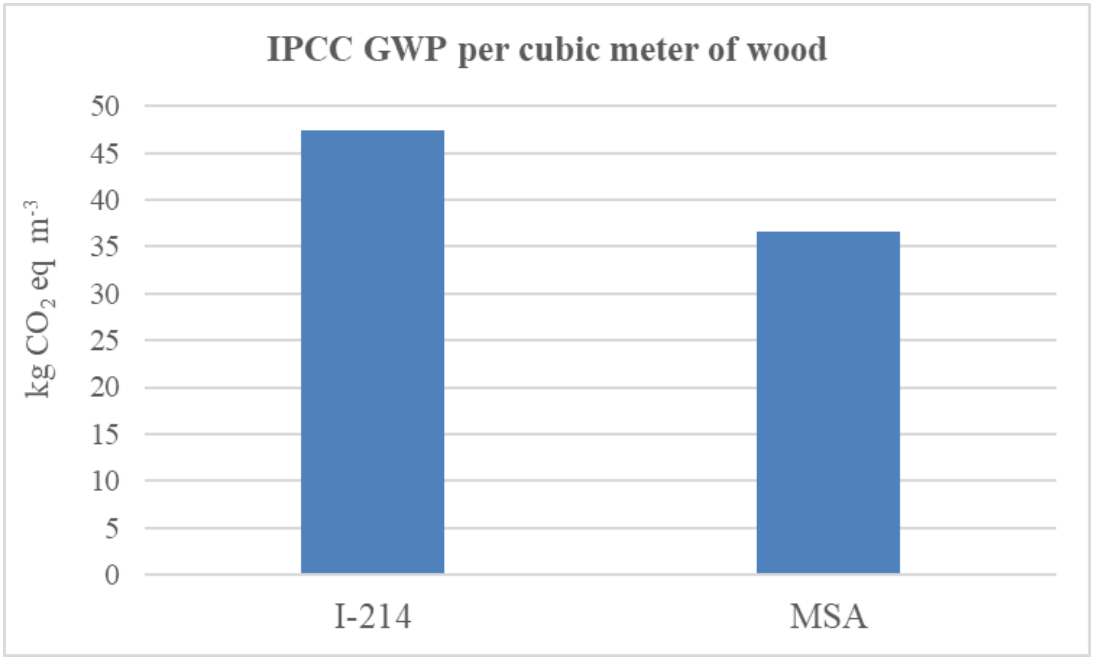


Figure 12: CO2 equivalent emissions for the production on 1 m3 of 'I-214' and MSA clones (IMP). Total emissions of the whole cultivation cycle (stool bed + nursery + poplar stand).

Poplar production, including industrial material and biomass for energy, can contribute to reduce emissions of climate-altering greenhouse gases and the exploitation of forests. The long duration of the plantations on agricultural land, with lower soil disturbance, results in an increase of organic content and fertility of the soil in comparison with annual agricultural crops. The storage of carbon in poplar wood has a long-life cycle thanks to the use of this wood in furniture and other products that can be further recycled (Chiarabaglio et al. 2020).

Afforestation of agricultural soils can help comply with the Kyoto protocol (Article 3.3) by increasing carbon sequestration. There is mounting interest in planting tree crops on agricultural land as an energy feedstock (Hansen, 1993). Carbon sequestration resulting from incremental forest management, afforestation, and reforestation are eligible for receiving carbon credits from the Kyoto protocol (UNFCC, 1998). Organic-carbon sequestration in poplar-plantation plots is high, reducing CO_2 in the atmosphere and thereby lowering the use of fossil fuels, and adds an appreciable amount of C to the soil, helping to mitigate climate change.

The duration of sequestration can be separated into two components: flow duration and stock duration. Flow duration represents the time period of active sequestration, or the time in which annual changes in soil organic carbon occur. Stock duration represents the time period following active sequestration and can be defined as the period of passive sequestration, or the time in which organic carbon remains sequestered. Therefore, poplar plantations allow a long-term carbon sequestration (Sierra et al. 2013)

5.3 Supporting services

5.3.1 Represent transition zones between “natural land” (river, forest) and agricultural areas.

Poplar cultivation is carried out mainly along rivers, on highly environmentally sensitive land and the cultivation practices carried out by farmers may constitute elements of negative impact. However, in riparian and protected areas, a sustainable cultivation model is still possible using the new FRM that include clones offering greater environmental sustainability (“Maggiore Sostenibilità Ambientale” in Italian, thus referred to as “MSA” clones) characterized by better resistance to the main biotic adversities (brown spot *Marssonina brunnea* (Ell. Et Ev.) P. Magn., rust *Melampsora* spp., spring leaf and shot blight *Venturia populina* (Vuill.) Fabric. and wooly poplar aphid *Phloeomyzus passerinii* Sign- see Table 1). In this way it is possible to develop semi-extensive cultivation models including those based on agroforestry systems or with mixed plantations that, by minimizing cultural and pest-control treatments, allow more environmentally sustainable poplar cultivation (Chiarabaglio et al. 2016). In France, increasing demand exists for multiclonal mixtures of *P. nigra* clones native from different alluvial basins, registered in the national register; mixtures groups about 30 individual clones selected to cover both known molecular diversity in the natural provenance and phenotypic variability for several traits (phenology, growth pattern, branching habit).

5.3.2 Forms parts of the ecological network

Cultivated poplars diversify the agroforestry environment, form part of the ecological network in the often monotonous and relatively low-biodiversity landscape of agricultural areas, create niches with conditions favorable for the survival of animal and plant organisms, and can serve as windbreaks (Corona et al. 2018).

Figure 13. ***Poplar plantations represent an important part of the ecological network especially in intensively cultivated agricultural areas***

5.4 Cultural services: maintenance of the rural landscape and conservation of biodiversity

Poplar plantations are characteristic of the rural landscape of many lowland and floodplain areas. The natural affinity of the Salicaceae for riparian and floodplain areas the most recent technical standards and procedures for an environmentally sustainable cultivation of poplar, suggest that poplar cultivation can have a positive impact on biodiversity with respect to other agricultural crops (Corona et al. 2018).

6 Innovation through new poplar FRM

A systematic and balanced breeding approach where long-term and short-term breeding is in progress since the Eighties at CREA - Research Centre for Forestry and Wood. This program was launched to select *Populus deltoides* × *Populus nigra* hybrids since in the F1 hybrid (*P. xcanadensis*) useful traits of both species are combined together: namely fast growth, wood quality, resistance to pathogen and pest of economic importance as the American species and good rooting ability and resistance to Poplar Mosaic virus as *P. nigra*.

As regards the long-term strategy, a recurrent 'semi-reciprocal' selection program within large synthetic populations of *Populus deltoides* and *Populus nigra* was set up with the focus of maintaining and creating genetic variation for future generations. All the individuals included in the base populations have been progeny tested for General Combining Ability. A first cycle of intra-specific and inter-specific crossings allowed to create two sub-populations of both species and to evaluate *P. deltoides* females and *P. nigra* males respectively. A second cycle of intra-specific crossings – according to a multiple breeding population scheme, where each population is subdivided for the traits of interest - will give rise to two improved populations of the parental species characterized by a greater frequency of genes useful to improve cultivar performance and resistance to pest and diseases.

Short-term breeding is focused on reaching economic goals by crossing parents with good production characteristics and tolerance to adversity from which to select the best commercial varieties within the progenies. The most promising genetic materials obtained in the initial stages of the 'semi-reciprocal' selection program within the inter-specific crossings (*P. deltoides* × *P. nigra*) have been initiated to the selective process and evaluated in multi-sites nurseries and in plantations established on Italian sites characterized by diversified pedo-climatic conditions. New hybrids selected and tested for production of veneers for plywood panels and other clones to be used in short rotation coppice for biomass and particle board production have been released. These clones, registered in Italy, have recently been included in the list of improved poplar clones (IMP) or MSA clones (MSA "*Maggiore Sostenibilità Ambientale*" - Higher Environmental Sustainability clones), and will allow a more 'sustainable' cultivation (Chiarabaglio et al., 2020) as an alternative to the traditional poplar clones obtained in the 60s and 70s on the basis of first selection (FGN) within genetic materials collected from free pollination and evaluated for the performance of the phenotype.Trial activities also conducted in different pedo-climatic conditions, has allowed to confirm their good level of environmental adaptability, tolerance/resistance to the main poplar adversities.

As reported also in the deliverable D 4.6 dedicated to spatial modelling and evaluation of reaction norms, phenotypic plasticity of hybrid clones grown in Italy (both 'traditional-old' clones grouped in FGN clones and new improved clones grouped in IMP clone category) has been predicted thanks to performances collected on multisite experiments and the use of reaction norm model (Fréjaville et al. 2019) and ΔTrait-SDM model(Benito Garzón et al. 2019).

Between 1980 and 2021, 49 poplar clones have been widely tested in Italy with traditional cultivation model. These clones were clustered in two groups (FGN and IMP clones) and single-group reaction norms were calculated to predict the potential productivity across time and space. The most important results about the future potential scenario (2026-2055 = 2040s) of poplar growth in Italy are reported (Marchi et al. 2022) considering two possible variants (numbers 01 and 21 of UKCP18 scenarios RCP2.6 and RCP8.5) calculated by 'ClimateDT' (https://ibbr.cnr.it//climate-dt/).

The Universal Reaction Norms (URN) developed show the possible effects of a changing climate on poplar clone cultivation in Italy (expected Diameter at Breast Height- DBH at ten years). To show the ecological potential of poplar clones across time and space, the spatial predictions across the whole of Italy were generated removing the irrigation effect. For the current climate (1991-2020 normal period) the analysis accurately located the "productive core" of poplar cultivation in Italy in the North and across the Po valley for both groups of clones (Fig.14). This region is where most poplar plantations are located and where timber is harvested. However, additional areas were highlighted in the North-West and parts of Central and Southern Italy. The area predicted by the FGN and IMP models were in agreement showing the same spatial pattern, and predicted that IMP clones were (on average) more productive than FGN clones (Fig. 15).

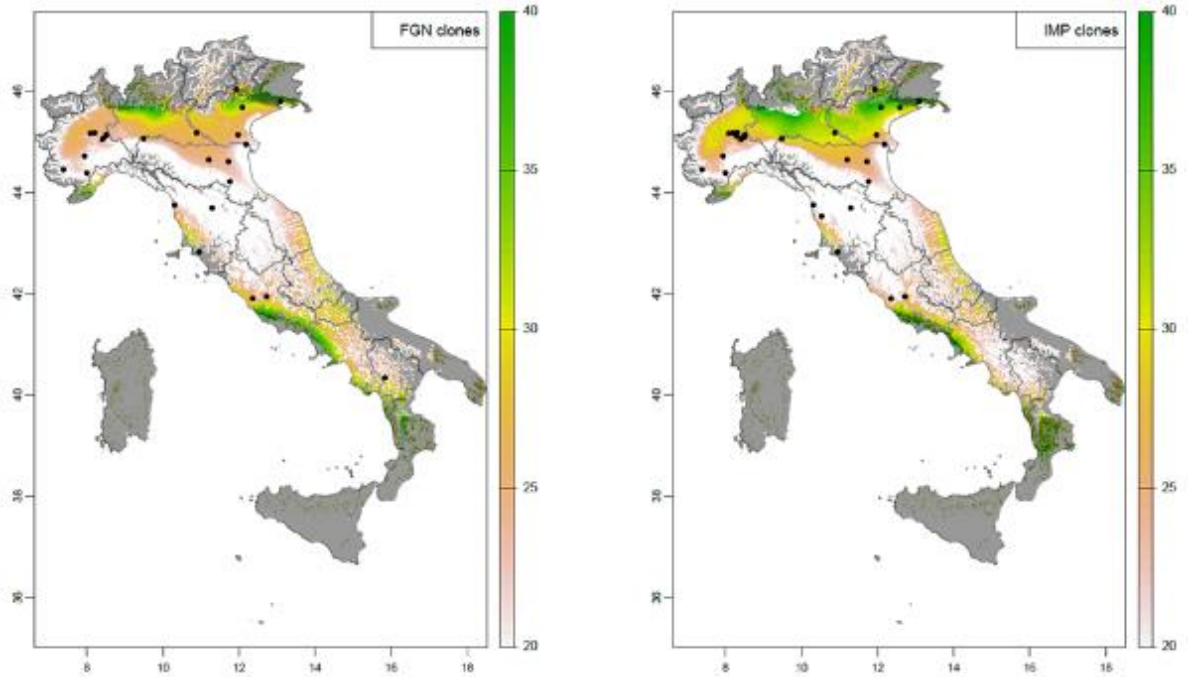


Figure 14 – Expected DBH in cm at age 10 without irrigation under the current 30-years normal climate (1991-2020). FGN = clones not improved for disease resistance are represented on the left; improved clones (IMP) on the right. (*The experimental sites used for modelling the group are shown as black dots and the statistical extrapolation outside the ecological domain is shown as shaded area).*

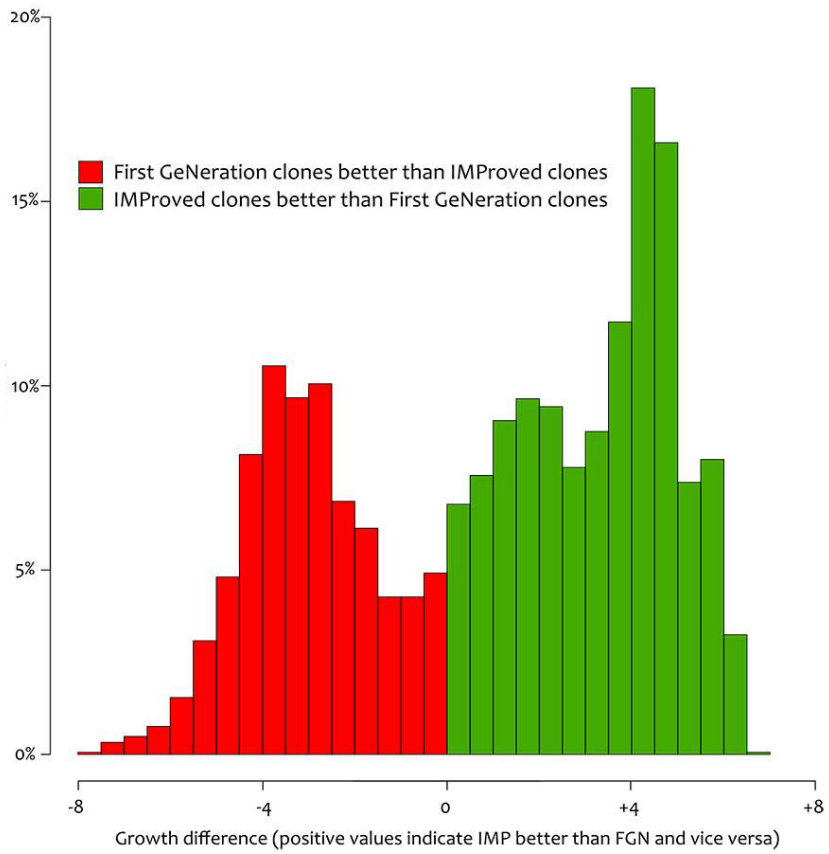


Figure 15 – Predicted 10-year DBH difference (in cm) between FGN and IMP clones across the whole Italy. Positive values indicate that IMP clones are more productive than FGN clones and vice versa. (*Values expresses the delta of DBH in centimetres).*

Also, the average growth in volume of the improved clones (IMP) was always higher than the traditional ones (FGN), with variations from 10 to 26% depending on the clone and the environmental conditions of growth (Facciotto et. al 2016).

Figure 16 shows the average productivity obtained in three different plantations in the Po Valley, ranging from 215 to 270 m^3/ha for some improved clones (IMP) compared to those of three traditional clones (FGN) which resulted variable from 176 to 212 m^3 ha^{-1}.

The resistance to biotic stress that IMP clones achieve marks them as an important candidate source of FRM for poplar cultivation in the future. Adding to the traditional and widely cultivated clones such as 'I-214', here included into the FGN group (genotypes of first generation, not improved for disease resistance), new clones selected in recent years show a predicted growth rate comparable with 'I-214' and better in places.

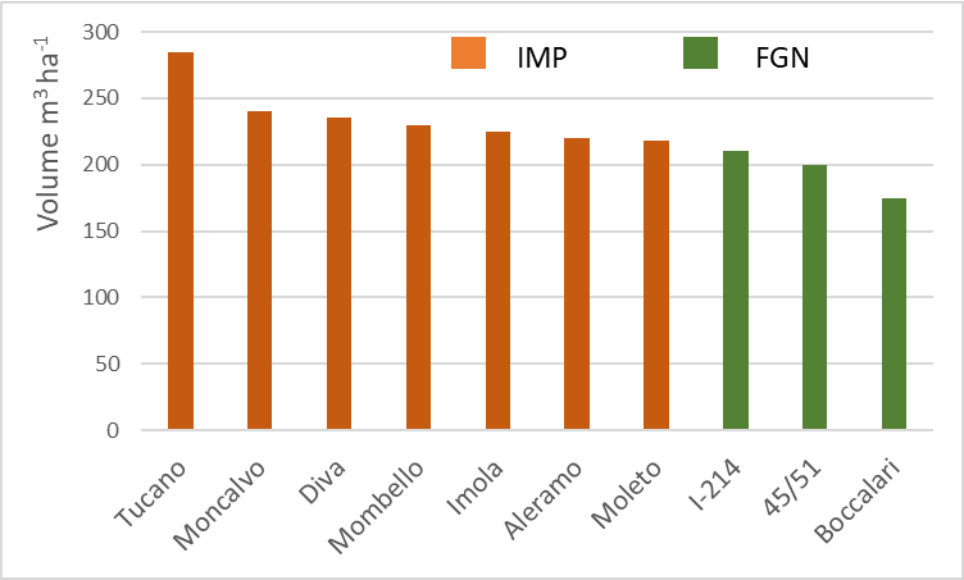


Figure 16 – Average productivity (m^3 ha^{-1}) obtained in three different plantations in Po Valley, between FGN (blue) and IMP(green) poplar clones.

Figure 17 – Experimental plantations in Po Valley using FGN and IMP clones.

While projections across RCPs and time-slices were almost in agreement with the expectations of a decrease in land suitability for poplar cultivation which was delayed for the RCP2.6 scenario compared to the RCP8.5 scenario, a regular trend across time (i.e., 2030s-2040s-2050s) in both RCPs due to a warmer and drier climate was forecast, with a very large difference between variants. Currently this difference was much larger than that observed between RCPs or between time slices, as reported in Fig. 18 where the difference between the two variants in the 2040s for RCP8.5 is proposed.

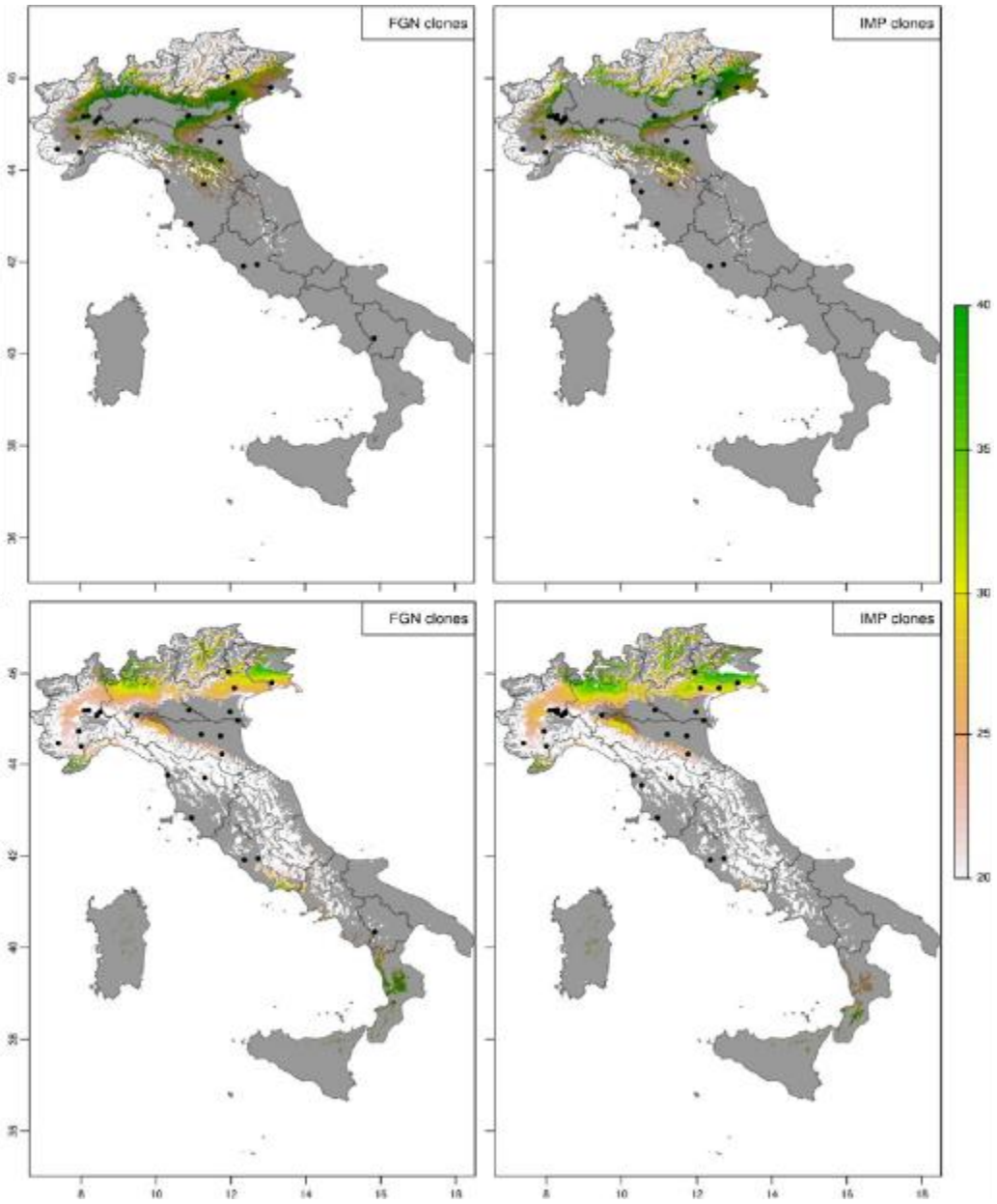


Figure 18 – Predicted DBH in cm at age 10 for the two groups in 2040s under RCP8.5 using the variant01 (up) and variant21 (down). The experimental sites used for modelling the group are shown as black dots and the statistical extrapolation outside the ecological domain is shown as shaded area.

The cultivation of improved poplar clones requires lower cultural input, and then lower production costs; this results in a better environmental sustainability, also remarked in Deliverable D 4.3, D 4.6 and D 4.9 and in a good economical sustainability. The higher wood density and the high production give interesting technological characteristics for different uses.

Operation	Irrigated plantations			Not irrigated plantations		
	I-214	Improved FRM	*difference*	I-214	Improved FRM	*difference*
	€/ha	€/ha	%	€/ha	€/ha	%
Site preparation	275	275		275	275	
Fertitisation	375	375		375	375	
Mark. dig and planting	615	615		615	615	
Seedings	1,251	1,251		1,251	1,251	
Planting	**2,516**	**2,516**		**2,516**	**2,516**	
Disk harrowing/Weeding	1,085	1,085		1,085	1,085	
Irrigation	2,336	2,336		291	291	
Disease control	1,143	0		1,143	0	
Pest control	797	623		797	623	
Pruning	587	720		587	720	
Fertitisation	447	447		447	447	
Coltural operations	**6,395**	**5,211**	*-19*	**4,350**	**3,166**	*-27*
TOTAL	**8,911**	**7,727**	*-13*	**6,866**	**5,682**	*-17*

Table 4. ***Cultural costs for the cultivation model of traditional and improved poplar clones***

The data reported here refer to the cultural costs of two different cultivation models based on the use of only the traditional clone ‘I-214’ or on the use of new FRM clones, resistant to the main poplar adversities. The greater susceptibility of clone ‘I-214’ to some pest and diseases (*Marssonina*, *Melampsora* and poplar aphid) compared to the new FRM clones requires greater phytosanitary treatments with higher cultivation costs for ‘I-214’ plantations. On the contrary cost for pruning are higher with the new FRM clones because their crown architecture (Coaloa et al. 2016).

In order to increase the genetic diversity in plantation, planting model based on clonal mixture or a mosaic of monoclonal plots with a group of different clones was already proposed in the past (Heybroek 1982) to reduce epidemiological risks, using improved clones with a diversified genetic background.

So, the adoption in Europe of a more sustainable cultivation models based on clonal mixture or a mosaic of monoclonal plots with a group of different improved clones (IMP) with greater environmental sustainability, allows to pursue the strategic objectives set out in the European Rural Development Plan.

7 Wood good for uses in building sector

The improved FRM is very interesting for structural application (Figure 19). The high density of the wood represents an opportunity to develop and increasingly employ of poplar wood in engineered products and in buildings. A new structural innovation, eco-sustainability construction was made using poplar wood and plywood obtained from it (Castro et al. 2014).

Figure 19 – Eco-sustainability construction made using poplar wood from new clones.

8 Conclusion

The results obtained with the B4EST project made it possible to pursue strategic objectives in terms of knowledge and innovation transfer regarding poplar breeding and poplar cultivation to the European forestry sector. New and flexible adaptive tree breeding strategies and tools have been proposed as well as tree genotypes of high productivity and economic value.

While some new problems of a biotic (new insects and diseases) and abiotic (drought and severe storms) threats lately have affected the growth and production of poplar wood in alluvial regions of central and southern Europe, a renewed interest in wood plantations outside the forest, has been detected and widely perceived with a greater attention towards sustainable management practices also in view of the increase in prices of phytosanitary products, based on the use of new improved poplar clones, more productive and resilient to climate change.

Monoclonal or mixed poplar plantations will be able to guarantee wood security to better respond to the increased need for timber and wood products but also for other ecosystem services they can provide such as carbon sequestration, soils, and water phytodepuration, flood regulation, creation of buffer zones and conservation of the biodiversity and rural landscape for greater social well-being.

9 Co-operation within B4EST and dissemination

9.1 Co-operation between other WP´s of B4EST project

The indications given in this document summarize some of the results achieved in the different WPs of B4EST project, thanks to the network of relationships and knowledge put in place between the researchers, also highlighted in more detail in several deliverables. Starting from the assessment of the main biotic and abiotic problems deriving from climate change,

new breeding strategies for poplar have been adopted; phenotyping analysis and the genetic characteristics of the germplasm available for the traits of greatest economic and physiological interest were addressed in WP 1 and WP2. In addition to breeding guidelines, genomic analyses were developed in WP3 using segregating populations of different poplar genotypes, with regard to some important characters related to resistance to pest and diseases such as woolly poplar aphid and rusts. Improved genetic materials (FRM) have been evaluated for adaptability and productivity in different environments by adopting conventional practices or cultural models with greater environmental sustainability, in order to provide correct information to the various stakeholders, as remarked also in D 4.3, D 4.6 and D 4.9.

Regarding stakeholder expressions collected in B4EST survey (WP5 – DL5.1), specific attention has been given to two categories of stake holders (farmers and timber industry):

- Poplar farmers express an interest in improved FRM for the economic aspects (reduction of cultural costs due to lower pest and diseases treatments), faster growing (more wood in less time) and clear environmental benefits (lower cultivation inputs, higher environmental sustainability). On the other hand, they show some perplexity in the diffusion of improved FRM because of the greater difficulty in selling their wood on the plywood market driven by very known old FRM. To encourage the use of the new FRM clones, technical and information meetings with the main stakeholders were organized as part of B4EST.

- ***Figure 20 - Dissemination activity to illustrate the behavior of improved poplar clones grown with different culture models***

Poplar growers are aware of the potential of linking increased production to carbon sequestration and environmental benefits: they would like to receive an economic accreditation for these assets.

The timber industry is in favour of improved FRMs and an increase in poplar cultivation areas in order to have more raw material that can also be certified by sustainable forest management systems. The lack of knowledge about the workability of wood is actually a

limitation to spread of new FRM and right remuneration. Evaluation tests and dissemination days on the technological wood characteristics of the different FRM clones compared to the traditional 'I-214' clone was carried out at two different plywood manufacturers, as part of the activities supported by the B4EST project.

Figure 21 - Dissemination activity to illustrate the technological characteristics of the wood obtained from the improved poplar clones

The demand for wood-based products has increased in the last period and this has produced an increase in demand that is currently not balanced by supply (poplar wood productions).

The wood industry, as poplar growers, would like to have an economic accreditation for the use of certificated wood (environmental sustainability) and for the storage of Carbon in products (i.e. furniture and other products) with long life cycle and that can be further recycled.

Poplar plantations create opportunities to achieve carbon neutrality for companies that can no longer reduce their emissions and need to offset them.

9.2 Dissemination

9.2.1 Regional stakeholder events

The results of activities developed under WP4 and WP5 and presented in this deliverable have been the subject of presentations at Poplar Producer Associations (API and AsProLegno), regional forestry technicians (Piemonte, Lombardia, Veneto and Friuli Venezia Giulia), nursery and wood processing workers at various meetings to update on the results of ongoing research.

9.2.2 Planned dissemination activities in the future

In the future, dissemination events will be organized among poplar growers and other stakeholders to inform them of the results obtained in the B4EST project.

10 Partners involved in the work

CREA : Pier Mario Chiarabaglio, Giuseppe Nervo, Sara Bergante, Lorenzo Vietto, Laura Rosso

CSIC-INIA : Sven Mutke, Nerea de Oliveira, Hortensia Sixto

INRAE (Project coordinator): Catherine Bastien

SkogForsk (WP4 Leader) : Mats Berlin

LUKE (WP5 leader and task leader): Hynynen Jari, Ahtikoski Anssi and Simone Bianchi

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