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Review

Poplar Short Rotation Coppice Plantations under Mediterranean Conditions: The Case of Spain

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Abstract: Developing a circular bioeconomy based on the sustainable use of biological resources, such as biomass, seems to be the best way of responding to the challenges associated with global change. Among the many sources, short rotation forest crops are an essential instrument for obtaining quality biomass with a predictable periodicity and yield, according to the areas of cultivation. This review aims to provide an overview of available knowledge on short rotation coppice *Populus* spp. plantations under Mediterranean conditions and specifically in Spain, in order to identify not only the status, but also the future prospects, for this type of biomass production. The analysis of available information was conducted by taking into consideration the following aspects: Genetic plant material; plantation design, including densities, rotation lengths and the number of rotations, and mixtures; management activities, including irrigation, fertilization, and weed control; yield prediction; biomass characterization; and finally, an evaluation of the sustainability of the plantation and ecosystem services provided. Despite advances, there is still much to be done if these plantations are to become a commercial reality in some Mediterranean areas. To achieve this aim, different aspects need to be reconsidered, such as irrigation, bearing in mind that water restrictions represent a real threat; the specific adaptation of genetic material to these conditions, in order to obtain a greater efficiency in resource use, as well as a greater resistance to pests and diseases or tolerance to abiotic stresses such as drought and salinity; rationalizing fertilization; quantifying and valuing the ecosystem services; the advance of more reliable predictive models based on ecophysiology; the specific characterization of biomass for its final use (bioenergy/bioproducts); technological improvements in management and harvesting; and finally, improving the critical aspects detected in environmental, energy, and economic analyses to achieve profitable and sustainable plantations under Mediterranean conditions.

Keywords: biomass; *Populus*; SRC (Short Rotation Coppice); short rotation woody crops; sustainability; Mediterranean conditions; management; review

1. Introduction

The challenges associated with climate change, along with the changing paradigm for both economic development and the energy model, have been crystallized into a Green Deal for Europe [1]. In this context, the use, production, and utilization of biomass are undoubtedly some of the main issues, very much related to the need to redirect the linear economy towards a circular bioeconomy based on the use of sustainable biological resources [2]. The Innovation Strategy for Sustainable Growth: A Bioeconomy for Europe [3] and its later revision [4] establish the bioeconomy as the general framework and key factor for achieving green, sustainable growth in Europe. In harmony with the

European strategy, while also taking into account the national possibilities, the Spanish Strategy for the Bioeconomy [5] and the current draft Law on Climate Change and Energy Transition [6] have been published.

Development in this area must take into consideration the potential of natural resources, including biomass. The options of using existing biomass in forests, agricultural residues, or the production of new biomass from crops planted specifically for this purpose are all seen as key to the development of the bioeconomy [3], not only for economic reasons, but also with environmental and social considerations in mind. In Spain, the Strategic Research and Innovation Agenda in relation to biomass has also recently been presented [7]. In this context, biomass is a highly valued resource for both bioenergy production and bioproducts, thus contributing towards addressing the abovementioned global challenges.

There are various sources of forest biomass, which can be differentiated into the following: (i) That derived from forest management activities associated with timber exploitation; (ii) residues resulting from silvicultural operations apart from timber exploitation; (iii) biomass derived from the forestry industry; and lastly, (iv) dedicated forest crops specifically designed for the production of woody biomass.

The first category includes logging residues and small diameter or crooked logs which are used for energy production (pellets, wood chips, or firewood). The first and third categories are the type of biomass mainly used in Spain today. The Spanish Renewable Energy Association (APPA) has repeatedly pointed to the underutilization of wood resources at a national level, as only 41% of the annual wood increment is currently being used, which is notably below the average of 60–70% for Europe [8].

However, if the amount of wood resources has been constantly increasing since the 1960's, what is the point of developing specific forestry crops? Firstly, these crops are seen as being of particular importance in terms of their potential contribution to the efficient diversification of biomass sources [9–11]. Secondly, of all biomass sources, forest crops specifically designed for woody biomass production are those most readily managed in terms of both time and space, with a predictable periodicity and yield. Thirdly, biomass from forest crops can contribute to generating and stabilizing the biomass market.

The aim of this study is to assess the advances made in poplar short rotation coppice (SRC) plantations over recent years, focusing on specific advances in Mediterranean conditions under irrigation (Spain) within the global context and to identify the areas of research where progress still needs to be made. The current state-of-the-art in biomass production from poplar SRC under Mediterranean conditions is addressed, highlighting both the strengths and weaknesses.

Therefore, this paper is structured around the following: (i) A global vision of SRC plantations focusing on poplar as one of the most suitable species in Mediterranean areas; (ii) the state-of-the-art of these plantations at a global level, while focusing on the progress made in Spain; and finally, (iii) conclusions drawn under Mediterranean conditions, with a particular emphasis on the weaknesses identified and the short- and long-term lines of research needed to address them.

2. Short Rotation Forest Crops for the Production of Biomass: The *Populus* Genus

Despite the different dedicated energy crops, the current agenda [7] only considers herbaceous and woody lignocellulosic crops for more diverse uses, which also include bioproducts.

Fast growing species are used in SRC, employing intensive or semi-intensive techniques [12], with coppicing cycles of between 2 and 8 years until stool productivity declines, which normally occurs after 15 years [13,14], depending on the site quality.

Biomass from SRC may become essential as an addition to the biomass provided by forests, contributing towards meeting the demands of European industry and assuring market stability [15]. This is probably linked to the need to find spatiotemporal complementarity in biomass resources, contributing to matching the supply with the demand; this circumstance is already a commercial reality in many parts of the world [16]. The suitability of such biomass is also linked to the intrinsic characteristics of its production and management [17], such as the abundance of improved, highly adaptable genetic material; high rate of successful rooting; good juvenile growth; and its resprouting capacity, among others [18–20]. Other traits associated with its end use are also deemed to be important, such as a low chlorine (Cl) and sulfur (S) content, low ash content, and high lignin content [21–24], among others.

SRC have been found to provide ecosystem services seldom sufficiently quantified and contrasted, such as air cleaning; the control of erosion or flooding in certain areas [25–27]; mitigation of the effects of climate change through carbon fixing in foliar or root biomass fractions [14,28,29]; increases of the biodiversity in agricultural environments [30–33]; and even soil decontamination [34–36], including mining reclamation [37,38]. From a social perspective, woody crops contribute towards the creation of employment in rural areas, given that these crops provide an opportunity to make use of poor, marginal, or surplus agricultural land [39]. Finally, the use of biomass from SRC helps to reduce the pressure on natural forests by providing a raw material much demanded by society and therefore by industry.

Despite this, to achieve sustainability in the implementation of SRC, it is important to consider the impact of land use changes in areas where these plantations compete with agricultural crops for land, as well as aspects related to water consumption in areas with limited water resources. Therefore, it is necessary to define the limitations in order to guarantee the sustainability of these crops [40]. Many of these aspects can probably be dealt with through the use of biotechnology to achieve improvements, or by using circular economy techniques such as wastewater reuse [41–43].

In Spain, the interest in producing biomass from SRC dates back to the mid-80's [44–46], coinciding to a large extent with the crisis in the oil sector. However, it was around 2000 when initiatives to increase sources of renewable energy at a global scale, particularly in Europe, provided the impetus to explore possibilities for the production of biomass as a renewable resource. The climatic, edaphic, and demographic characteristics of some parts of the country are suitable for the cultivation of SRC, with an expected high productivity [47] exceeding that obtained in other European countries. However, because of the Mediterranean climatic conditions, such plantations are only viable with the use of irrigation. In areas with an Atlantic climate, the conditions for SRC are also suitable, with limitations such as the orographic characteristics, which may complicate the intensive silviculture applied in this type of plantation, or the limitations associated with certain species due to soil acidity.

Although many studies have focused on the selection of vegetal material best adapted to given areas of Spain, there is still a long way to go with regards to identifying the interaction between the genotype and the environment, which is a determining factor in the success or failure of SRC.

There are many woody species potentially cultivable for biomass production. In general, they are fast growing broadleaf species with a high re-sprouting capacity.

In Europe, the *Salicaceae* family (*Populus* spp. and *Salix* spp.) presents the greatest developments on an industrial level. Plantations based on species and hybrids of *Populus* are well-established in both central and southern Europe, with examples in Germany [48], the United Kingdom [13], the Czech Republic [49], Bulgaria [50], Serbia [51], Poland [52], and France [53], as well as in Mediterranean regions, mainly Italy [54] and Spain [55]. In northern Europe, where *Salix* spp. has been the predominant species for this purpose, poplar cultivation is beginning to attract interest, with different trials being established to evaluate its potential [56,57].

To a large extent, *Populus* species are at the forefront of biomass production because of the highly efficient breeding programs in different countries, many of which are located in Europe [58]. These programs are favored due to the very broad genetic base with which to work in terms of traits linked to cultivation and wood properties [59,60], but also due to knowledge of the genome sequence [61] and the relatively short breeding cycles. Other factors include a high capacity for vegetative reproduction and their rapid growth rate.

The importance of cultivating *Salicaceae* for biomass production at a global scale is reflected by the abundance of information gathered over the last decade by the International Poplar Commission (statutory body within the FAO), which has specifically covered the subject in one of its working groups [62]. The International Catalogue of Base Materials of *Populus* for obtaining forest reproductive material contains 358 entries, among which several are specifically referenced for biomass production ('Boiano-4', 'Baldo', 'Hunneghem', and 'Raspalje'). Many more are at preliminary stages for inclusion and have been put forward for this use ('AF2', 'AF8', 'A4A', 'Monviso', 'Muur', 'Orion', 'Oudenberg', 'Sirio', and 'Vesten'). Within the framework of the EU-POP project, more than 17 genotypes are currently being characterized as biomass producers in a multi-environment trial in which ten European countries are taking part, including Spain [63].

In addition to the genotypes that have been catalogued (or are in the cataloguing phase) for this purpose, there are others that have been identified for their wood production, but which also seem to possess suitable characteristics for the production of biomass. Figure 1 shows the main genotypes that are being tested or planted for commercial purposes in some European countries.

Figure 1. Some of the main genotypes planted for biomass purposes in each country are represented on a European map.

In Spain, the main species of interest at a commercial or pre-commercial level are those belonging to the genera *Populus* spp. and *Eucalyptus* spp. The cultivation of species and hybrids of *Populus* for industrial wood (veneer) is well-established in many areas of the country [64]. Although poplar production plantations in Spain represent less than 1% of the tree-covered forest area (approximately 100,000 ha), in some provinces, these plantations account for more than 50% of the harvested wood, which is around 40% of the economic value of roundwood cuttings. In the province of Castilla y Leon, for example, poplar is the forest species with the highest economic value [65,66]. However, regarding poplar in SRC, there is only a token presence in Spain, with it occupying around 50 ha at its peak. The potential land at a national level corresponds to irrigated agricultural marginal land for food production with the edaphoclimatic requirements for the species [47]. Currently, the irrigated agricultural land in Spain is 3.8 Mha [67].

The genotypes for planting should be included in the European Catalogue of Base Material for *Populus* reproductive material. There is also a Spanish National Catalogue of Base Material for forest reproductive material of the *Populus* genus in qualified and controlled categories comprising 24 commercial quality genotypes (Table 1). Some of this material, which is well-adapted to the specific Spanish Mediterranean conditions, could also be of interest for biomass production. Most of the genotypes already tested or currently being tested are listed in Figure 1, and include materials from both the European and Spanish lists, as well as some that have not yet been catalogued. The potential of *Populus* is explained to a large degree by the availability of material adapted to existing conditions, along with appropriate knowledge relating to the management of the species in many parts of the country [68,69].

Table 1. Genotypes included in the National Catalogue of Base Materials for the production of forest reproductive materials related to the genus *Populus* L.

Parentage		Section	Genotypes
P. × *canadensis* Mönch	D × N	Aigeiros	'2000 Verde', 'Agathe F' [a], 'E-298' [a], 'Branagesi', 'B-1M', 'Canadá Blanco', 'Dorskamp', 'Flevo', 'Guardi', 'I-214' [b], 'Campeador' [b], 'I-454/40', 'Luisa Avanzo', 'MC', 'Triplo'
P. deltoides W. Bartram ex Marshall	D	Aigeiros	'Lux', 'Viriato'
P. × *generosa* Henry	T × D	Tacamahaca × Aigeiros	'Beaupre', 'Boelare', 'Raspalje', 'Unal', 'USA 49-177'
P. × *generosa* Henry × *P. alba* L.	(T × D) × A	(Tacamahaca × Aigeiros) × Populus	'I-114/69'
P. nigra L.	N	Aigeiros	'Tr 56/75', 'Bordils', 'Lombardo leones'

D is *P. deltoides*; N is *P. nigra*; T is *P. trichocarpa*; A is *P. alba*; [a] 'Agathe F' = 'E-298'; and [b] 'I-214' = 'Campeador'. Order of 24/06/1992, Order APA/544/2003 of 06/032003, Resolution of 07/07/2006 of the Dirección General de Agricultura, and Resolution of 07/11/2011 of the Dirección General de Recursos Agrícolas y Ganaderos.

In relation to *Eucalyptus*, the cultivation of some species and hybrids for the production of biomass has been significant in certain areas of the country, reaching production values of 14.6 Mg ha^{-1} year^{-1} in the case of *Eucalyptus globulus* Labill. and 21.5 Mg ha^{-1} year^{-1} for *Eucalyptus nitens* (Deane and Maiden) Maiden [70] in Atlantic areas without irrigation, whereas the development of similar yields in southern Spain would need irrigation.

Some genotypes of *Eucalyptus* exhibit the additional advantage of presenting an acceptable degree of tolerance to drought conditions [71,72], although the high levels of production are associated with scenarios where droughts do not occur or where irrigation is used. One of the main differences with respect to poplar is that *Eucalyptus* is an evergreen species, so harvested trees include twigs and even leaves, yielding biomass with a high ash content.

Furthermore, trials with other potentially usable species have taken place in recent years, leading to differing results. In this regard, at a Mediterranean scale, there have been experimental trials with *Ulmus pumila* L. [73], *Robinia pseudoacacia* L. [74–77], hybrids of *Salix* spp. [78–81], *Platanus* × *hispanica* Mill. ex Münchh [77], and different cultivars of *Paulownia* spp. [82,83], with the latter displaying severe adaptation problems to the climatic conditions of the Mediterranean area (early frosts and flooding) [84]. Although some of these may be of interest in terms of adding diversity to the area of crop development, perhaps the main limitation of most of these species stems from the fact that there is a lack of improved genetic material, which is necessary for allowing their use in different environments.

3. Lines of Progress: State of the Art

Sustainable improvement in biomass production from poplar SRC crops requires advances to be made in different aspects, which have been summarized in Figure 2. An overall vision of the current situation of each of these aspects is provided in this section.

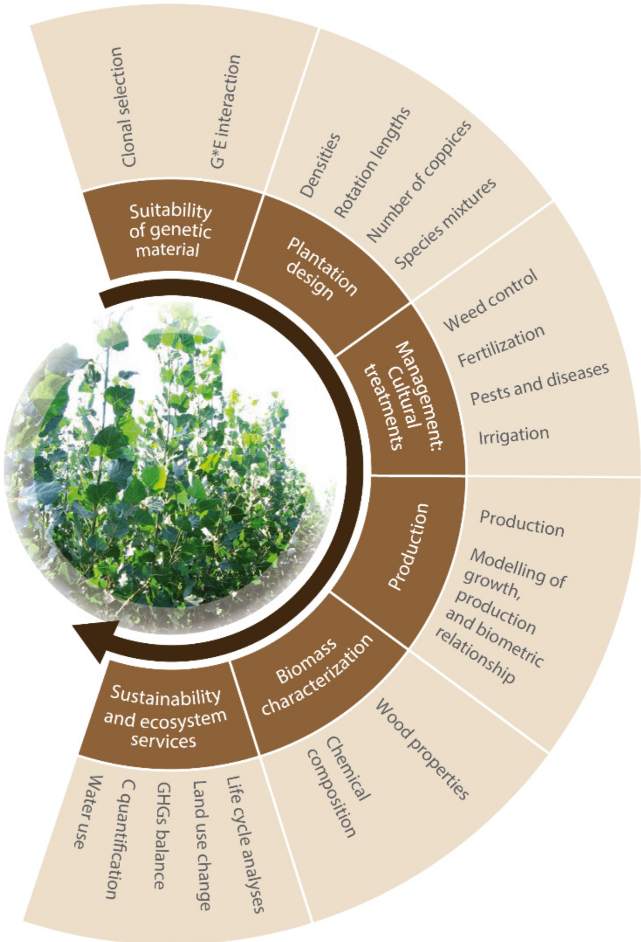

Figure 2. Lines of action for improving short rotation coppice-managed woody crops.

Literature searches for the combination of the terms *Populus* or poplar, and short rotation or energy crop, were conducted using Web of Science (WOS, Core collection of Web of Science), which is one of the main journal databases. There were no restrictions in terms of the year of publication or language. Figure 3 shows the number of documents per country (including only the top 30 countries) found in WOS, totaling 2185 documents. From these searches, documents from Spain were filtered and it was found that some of them were not properly classified in the database. Out of the 112 documents relating to Spain (ranked 10th) found in the WOS, only 83 were included.

In this review, we took into account not only the documents found in this database, but also other scientific publications belonging to Journal Citations Report (JCR) indexed journals, as well as numerous pieces of available gray literature. All this information was identified by tracing back papers cited in the references of the identified studies and reviewing publications by scientists who have worked or are currently working on poplar short rotation in Spain. In any case, given the abundance of existing information and the difficulties associated with the use of diverse terminology, there may be certain literature that we are not aware of, and therefore has not been considered in this review.

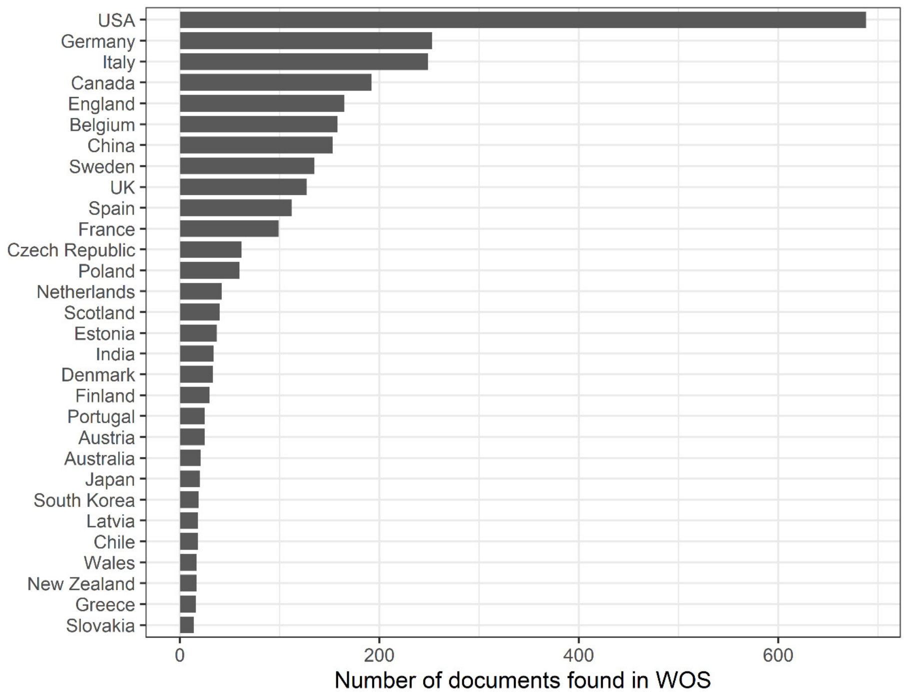

Figure 3. Ranking of the number of publications per country (including only the top 30 countries) found in the Web of Science (WOS) journal database, for the combination of the terms *Populus* or poplar, and short rotation or energy crop, in July 2020.

A classification of all the information available at a national level was performed according to the six categories detailed in Figure 2. This information was also broken down according to the availability of literature, separating the so-called gray literature from that contained in science journals and books (Figure 4). In Spain, biomass characterization and sustainability (mainly energy, economic, and environmental analysis) are the lines of research which have been explored the most based on scientific publications, although, if we include gray bibliography, then the most explored lines are production, modeling, and genetic material. Approximately 50.5% of the information evaluated corresponds to gray literature, 4.5% to books, and the rest to scientific publications (45%).

3.1. Suitability of Genetic Material

Clonal Selection

Poplar is the model tree for genetic studies and is the furthest ahead in terms of biological knowledge and genetic resources [58]. Using the best adapted material when developing plantations helps to ensure the efficient use of site resources and therefore higher levels of production. Phenotypic plasticity refers to the capacity of an organism to alter its characteristics in response to environmental conditions [85]. The genotype by environment interaction (G*E) is evidenced by the instability of phenotypic correlations derived from drastic differences in biomass production found in poplar plantations [86–88].

The G*E interaction makes poplar clonal recommendations more difficult, although it can also provide an opportunity to maximize production in these plantations by matching the most suitable material to specific site conditions. Genotypic stability is understood as the capacity of a cultivar to produce in accordance with the productive potential of each environment, that is, without straying from the behavior expected for the average genotypic value [89]. However, the strategies may differ, and this can be observed in different poplar SRC plantations; these strategies include attempting to find a broad adaptation or optimizing the adaptation to specific site conditions, hence the necessity to characterize the material [90–92]. This characterization not only has an impact on crop management, but also has repercussions for improvement strategies. In Spain, poplar material destined for biomass production has been characterized in recent years through the analysis of this interaction [55,77,93–95].

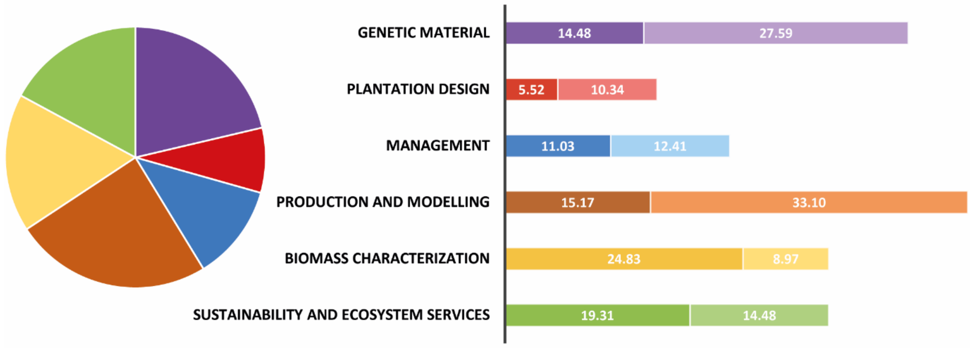

Figure 4. Percentages of Spanish publications in each of the six categories established. The light color corresponds to the gray literature on each subject.

With regards to the biomass, the development of genotypes aimed at achieving increased production, a greater tolerance to pests and diseases, and specific feedstock properties is ongoing through breeding programs in the countries spearheading the research, with the most prominent of these being the USA, Canada, Italy, France, Germany, and Sweden [58].

Traditional approaches based on recurrent selection as a way to increase hybrid vigor [54,96] are now supported by genomics and phenomic techniques which contribute to accelerating these processes [97,98]. For example, tools such as genome editing using Crispr/Cas9 technology [99–101], the development of transgenic plants [102], complete genome association analysis [103], and new phenotypic tools [104], are now leading to important advances in genetic improvement of the *Populus* genus. A relevant review of the progress towards an improved biomass quality and resilience of production using both traditional approaches and new technology is provided by Clifton-Brown et al. [58], specifying the breeding programs in which each of these techniques has been used. New avenues of research have also been opened up through considering epigenetic inheritance, also termed soft inheritance. This relates to inheritable changes to the gene expression induced by environmental changes [105,106].

In Spain, although progress in this line of research is limited by the lack of specific breeding programs, progress has been made in the development and testing of different transformed poplar lines expressing a pine glutamine synthetase (GS) transgene involved in N assimilation [107]; the CsDML gene that induces bud formation needed for the survival of the apical meristem under the harsh conditions of winter [108]; and a gene related to ABI3/VP1 1 (CsRAV1) to increase syllepsis, and consequently biomass production, in commercial elite trees [109,110]. The biomass potential of the different available genotypes has also been tested, with multiple clonal trials involving traditional genotypes [95,111–116], as well as new genotypes specifically selected for biomass [77,117]. The results have revealed hybrids like 'Orion' and 'AF2' as site-specific genotypes, while 'I-214' and 'Monviso' have been demonstrated to adapt well to a wide variety of scenarios. Likewise, the ability of different genotypes to produce biomass in areas degraded by mining is also being tested, with some genotypes, such as 'Raspalje' and 'AF2', displaying acceptable yields [118]. In general, a strong correlation has been identified between the response to environmental variables and the taxonomic background, with the euramerican genotypes such as '2000 Verde' responding better to lower latitudes, higher mean temperatures of the vegetative period, and a lower sandy soil content, unlike interamerican genotypes such as 'Unal' [93].

3.2. Plantation Design

The design of a plantation is also a highly influential factor in stand management and the optimization of production [119]. Many different types of design have been tested in Spain, combining different plantation densities [120], tree distributions [121], and rotation lengths [122]. The possibility of mixing different species or different varieties of the same species has also been put forward as a way to optimize production.

3.2.1. Densities

A broad range of initial stocking rates have been employed to define the optimum plantation density, from 1000 cuttings ha^{-1} up to more than 40,000 cuttings ha^{-1} [123,124]. Even higher densities have been contemplated, albeit less frequently, as in the case of DeBell et al. [125]. In Spain, a wide range of densities in multiple environments have been tested [46,126,127]. In terms of the yield, densities of around 20,000–25,000 cuttings ha^{-1} were the most productive in the first year, but the effect of competition reduced the differences between these and less stocked plantations as rotation approached three years [120]. Other factors, such as the costs associated with the higher densities due to the greater number of cuttings, increased demand for water, and increased consumption of consumables and time required for operations such as irrigation or harvesting [128], along with impediments to mechanization of the plantation, mean that densities in excess of 15,000 cuttings ha^{-1} are not recommended [120].

Furthermore, the position of the stools for a given density is also a matter of debate. Therefore, it is common for trials to include both single-row layouts [78,92] and double rows [13,129]. No significant differences in yield were found between the two layouts [130], although single-row designs tend to facilitate management operations. In Spain, both layouts have been tested [77,131], although a single row is more commonly used.

The density and distribution of stools should be directly linked to the rotation lengths applied, along with the maintenance and harvesting processes, always attempting to keep the production cost per biomass unit obtained as low as possible.

3.2.2. Rotation Lengths and Number of Coppices

The rotation is a factor closely linked to the density, as well as being influenced by the environment. Different rotations have been employed in the management of poplar SRC, from yearly to longer rotations for other productive objectives [132–135]. In recent years, rotations of 2 to 4 years have been the most frequently employed, with the final harvesting age depending on the genotype and site conditions [90,129,136].

In Spain, rotations from 2 to 9 years have been tested [110,117,128,137], although few studies have compared different rotation lengths. Hernández Garasa et al. [138] determined that the maximum volume production occurred between 3 and 4 years, depending on the genotype planted. The suitability of a 3- or 4-year rotation length for different genotypes under poor site conditions was evaluated by Oliveira et al. [139], who noted that biomass production increases in most genotypes from 74% to 166% when the rotation length is extended by 1 year. However, some genotypes, such as 'AF2' and 'Dorskamp', presented no significant differences. These results are consistent with those obtained under average site conditions, where the maximum volume production was not reached with a 3-year rotation length, except in the cases of certain genotypes, such as 'A2A', 'A4A', and 'Lombardo Leones' [140]. Therefore, the rotation length chosen clearly depends on both the genotype and the site conditions, with longer rotation lengths being advisable when the conditions are not optimal. Further studies are needed in order to optimize the rotation length for specific sites, genotypes, and management conditions.

Another question that has sparked controversy is whether or not to coppice after the first establishment year to encourage multiple shoot growth [141,142]. This is a common practice in some countries, such as England [143]. In Spain, the use of management techniques both with or without coppicing after the first establishment year has also been studied [144–146], although no apparent advantage was found with regard to the additional coppice after the first establishment year, either in terms of biomass yield or quality.

Opinions also vary regarding how many times coppicing should take place [129,135], given that the lifecycle is clearly related not only to the rotation length, but also to the genotype and its interaction with the environment and the cultural practices applied, with all of these factors conditioning the useful life of the stool [68]. However, studies such as Štochlová et al. [147] suggest that five or six 3-year rotations are possible, although only one commercial clone—an interspecific hybrid of *P. maximowiczii* Rupr. × *P. trichocarpa* Torr & A. Gray—was capable of biomass productivity compatible with the economic feasibility of cultivation. Therefore, it is important to take into account the factors limiting the duration of SRC crops. In Spain, several studies carried out over three successive rotations of 3 years each point to a decrease in biomass production during the third rotation cycle, suggesting the end of its productive cycle [148,149]. However, not all genotypes show the same behavior, with the genotypes 'I-214' and 'Monviso' presenting the highest yields during the third rotation [150].

3.2.3. Species Mixtures

There has been a sharp rise of interest in mixed forest plantations over recent decades because of the perceived benefits, not only for the environment and ecology, but also, although not always, for the yield, as a result of resource-use efficiency and facilitation. Although applying these designs in SRC plantations has attracted interest, there is still little information about it. Few examples exist of mixed plantations of poplar with other species in SRC. Some are mixtures of *Populus* spp. with *Alnus* spp. [151,152], the euramerican genotype 'AF2' with *Ulmus* spp. and *Platanus* × *hispanica* [153], and *Populus* spp. with *Robinia* spp. [154–156]. The mixture of *Populus alba* L.-*Robinia pseudoacacia* in SRC under Mediterranean conditions showed encouraging results in the first rotation [76], but they were not as promising in the second [157]. A similar design mixing *R. pseudoacacia* with the euramerican genotype 'Dorskamp' in central France demonstrated interspecific competition in the mixture as the preponderant interaction, resulting in higher mortality and lower biomass production than the two monocultures [155]. However, this mixture would appear to be advantageous given the different strategies shown by the two species in terms of the amount of litter and the dynamics of the main nutrients [158]. Therefore, although mixing the species does not increase the biomass yield, it may provide a good strategy for reducing future requirements for nitrogen addition (with the consequent ecological and economic implications), given the differences between the two monocultures in terms of processing the main nutrients [158]. Furthermore, both species—*P. alba* and *R. pseudoacacia*—are considered to be relatively tolerant to possible drought scenarios [111,159].

In any case, the current plantations are only experimental and their implementation on a commercial scale would involve restrictions in the spatial distribution as a result of the complex establishment and the harvesting requirements [76]. These difficulties often lead to mixing the species in lines or groups, thus losing the facilitation effect, although other benefits, such as the reduction of biotic and abiotic damage, landscape effects, and other environmental benefits, are retained.

Apart from mixtures of different species, complementarity is also explored in mixtures of varieties within the same genus [160,161]. Some examples in this regard include plurivarietal plantations of *P.* × *generosa* Henry [162], other hybrid groups of *Populus* [163], and different varieties of *Salix* spp. [164,165], where the aim is to attain a greater tolerance to biotic and abiotic stresses while also increasing productivity.

3.3. Management: Cultural Treatments

There are many aspects of plantation management which have an impact on production.

3.3.1. Control of Competing Vegetation

Competition from weeds in the initial crop establishment stage is one of the main reasons for plantation failure. It is not only competition for water and nutrients, but also for light and space, which is crucial in the establishment stage. Deficits of these requirements can render the plantation unviable [68]. Therefore, weed control is considered a necessary practice, with treatments also being necessary during the first establishment year and after each coppicing. These treatments may involve both chemical and/or mechanical techniques [166–168].

Currently, the application of specific herbicides for poplar cultivation is very limited due to the European regulation on the sustainable use of pesticides and their commercialization (Directive 2009/128/CE of the European parliament; Regulation (CE) n° 1107/2009 of the European parliament). In Spain, only six formulations are registered for use with hardwoods (RD 971/2014), but only one of them is specific for *Populus*.

3.3.2. Fertilization

The use of fertilizer in SRC plantations is a subject which attracts debate. There are many examples where fertilization provides no benefits [59,90,169–171] and others where there are positive effects on production [145,172–177].

The lack of response to fertilization may be due to the fact that soil fertility is optimal or to an inadequate assessment of the limiting nutrients. The high N requirements of poplar [178,179] mean that in locations where the soil is poor in organic matter, it is beneficial to apply fertilizer to increase the yield [180]. However, the excessive use of nitrogen fertilizers as part of conventional practice is increasingly being questioned because of environmental risks [181–183] and the high economic costs. Therefore, the use of alternatives to improve the nutritional status, such as designs with mixed plantations that include nitrogen fixing species [155] or alternative fertilization through the use of sewage sludge or waste water, have gained prominence in recent years [184–186]. Besides not having to use traditional fertilizers, these materials are purified and/or reused and the plantations thus act as phytoremediators [187]. All these alternative fertilization techniques have also been tested in poplar SRC plantations in Spain in recent years, although all in experimental plantations [42,188,189].

In all cases, it is recommended that soil analysis be conducted prior to planting in order to optimize the use, where required, of fertilizers [190].

3.3.3. Control of Pests and Diseases

Newly emerging pests and diseases are one of the main problems facing agriculture in the 21st century due to the presence of extreme climatic conditions [191]. In poplar plantations, this risk has increased sharply as a result of the expansion of monoclonal plantations, with only a small number of different genotypes planted. There has been clear progress made in this area and it continues to be one of the main objectives in the breeding programs of the genus.

Examples of the most serious pests and diseases affecting the leaves are those caused by *Melampsora* spp. (rusts), *Marssonina brunnea* (Ell. et Ev.) Magn., *Phloeomyzus passerinii* Sign. (woolly poplar aphid), *Venturia populina* (Vuill.) Fabr., *Chrysomela populi* L. (red poplar leaf beetle), and *Leucoma salicis* L. (white satin moth), whilst those affecting the stems and trunks are *Mycosphaerella populorum* Peck (stem canker), *Cryptorhynchus lapathi* L. (poplar and willow borer), *Paranthrene tabaniformis* Rott. (dusky clearwing), and *Sesia apiformis* L., among others, although these are not as relevant to the SRC crop [192–197].

In Spain, although phytosanitary problems in SRC crops have not occurred very frequently, the presence of rust has been observed in rust-prone genotypes when grown for timber production. *Chrysomela populi* L. has been detected in plantations in the northern half of the country, as well as *Corythucha ciliata* (Say) in the center of the peninsula, necessitating the timely application of phytosanitary products.

In any case, the sustainability of these plantations depends on the use of genetic material which is tolerant or resistant to these types of stress [68,198], as well as resorting to biological control in the case of certain pests.

3.3.4. Irrigation

Given the marked hygrophilic nature of the *Populus* genus [199], the availability of water in the soil is one of the limiting factors for its cultivation [200]. Due to the Mediterranean climatic conditions, it is necessary to irrigate SRC plantations in Spain during the summer drought season [201–203]. Due to limitations on water use at a global scale [204], the irrigation of SRC crops is viewed with caution in areas where this practice is necessary. This has led to changes in the way irrigation is applied, moving away from flood irrigation towards more efficient systems such as drip irrigation, although much more can still be done to increase the technical efficiency [205].

Water restrictions generally lead to production losses [206,207], although a high variability has been found in response to drought conditions. For this reason, the identification of genotypes with a greater water-use efficiency through different methodological approaches is undoubtedly of interest [208], seeking to combine materials with a high productivity and greater water-use efficiency [209]. This is especially true in the Mediterranean area [77,210–213], although accepting a certain loss of production may be advisable in these scenarios [205].

Highly productive genotypes such as 'AF2' and 'Monviso' have exhibited the greatest water-use efficiency under optimal conditions, although under restrictive water conditions, they have presented a similar water-use efficiency to that of the less productive genotypes. The strategy followed by all of them to improve the intrinsic water-use efficiency seems to be linked to stomatal control, rather than differences in the rate of photosynthesis [205].

In addition to the implications in terms of sustainability, the economic implications must also be taken into account, bearing in mind that irrigation is one of the limiting factors when assessing the profitability of these plantations under Mediterranean conditions. It has been calculated that the costs associated with irrigation, which include the irrigation system, maintenance, and the annual costs of water and electricity, account for 30% of the total costs over a whole cycle of 12 years [214].

The reusing of water from different sources represents a new approach in the context of SRC [187,188], with a solid background in the past [215,216]. In any case, it is necessary to increase the amount of research into the breeding of plants for production under conditions of water scarcity at a global level, especially in regions that suffer from water restrictions.

These alternatives, together with the improvement in irrigation techniques, could provide solutions to ensure that viable production is attained in areas where water use must be minimized, such as in Mediterranean environments.

3.4. Production

Short rotation coppice plantations (SRC) provide a viable alternative for the production of quality lignocellulosic biomass [217]. The biomass produced in SRC is characterized by a predictable periodicity and yield, depending on the area of cultivation. The main challenge with regard to these crops is to achieve a high level of sustainable production while maximizing benefits; that is, combining economic viability with environmental sustainability.

According to a review by Sixto et al. [68] concerning biomass production in this type of plantation using poplar genotypes, a large quantity of literature exists on the different clonal productivity under a range of environments. Table 2 presents some examples of biomass production obtained in different European countries, ranging widely from 1 to 24 Mg dm (dry matter) ha^{-1} year^{-1}, depending on the site characteristics, the genetic material, the design, and the management scheme. Table 3 presents the production obtained in Spain under Mediterranean conditions, ranging widely from 1 to 37 Mg dm ha^{-1} year^{-1}. The largest reported productions appear to be those associated with Mediterranean irrigated environments. Despite this, the average potential production at a national level in Spain is estimated to be around 15.3 Mg dm ha^{-1} year^{-1} for plantations with standard management schemes [47], although there is also high variability, depending on the previously mentioned factors [46,55,77,145,218].

Table 2. Different examples of the biomass yield (Mg dm ha^{-1} year^{-1}) per genotype, age, and rotation in poplar short rotation plantations in Europe (excluding Spain).

Species and Poplar Hybrids	Genotype	Density	Age	Country	Yield (Mg dm ha^{-1} Year^{-1}) by Rotation			Reference
					1st	2nd	3rd	
P. deltoides × *P. trichocarpa*	'IBW2'	10,000	4	Belgium	2.5	1.6		[19,219]
P. nigra	'Wolterson'				8.1	9.7		
P. trichocarpa	'Columbia River'				7.8			
	'Fritzi Pauley'				8.1	8.2		
	'Trichobel'				8.4	8.2		
P. × *canadensis*	'Gibecq'				1.6	3.5		
P. × *generosa*	'Hazendans'				10.8	3		
	'Hoogvorst'				10.1	8.2		
P. deltoides × *P.* × *generosa*	'Grimminge'	8000	2 (In the 3rd rot the age is 3 year)	Belgium	4.3	11.7	8.4	[136] *
P. nigra	'Brandaris'				1.4	7.0	8.7	
P. nigra × *P. maximowiczii*	'Wolterson'				2.7	11.7	14.6	
P. trichocarpa × *P. maximowiczii*	'Bakan'				4.9	14.3	18.1	
	'Skado'				5.7	16.8	20.8	
P. × *canadensis*	'Ellert'				3.3	11.1	19.5	
	'Hees'				6.5	15.5	26.0	
	'Koster'				2.8	9.5	14.1	
	'Muur'				3.9	12.4	17.1	
	'Oudenberg'				3.7	13.4	14.0	
	'Robusta'				2.5	8.1	15.6	
	'Vesten				4.7	12.6	16.1	
P. maximowiczii × *P. trichocarpa*	'NE-42'	2222	3 (2nd rot: 4 year)	Czech Republic	1.0–1.4	9.4–9.8	9.1–11.4	[220]
			3 (2nd rot: 2 year)		8.3	15.4	18.9	

Table 2. *Cont.*

Species and Poplar Hybrids	Genotype	Density	Age	Country	Yield (Mg dm ha^{-1} Year^{-1}) by Rotation			Reference
					1st	2nd	3rd	
P. balsamifera × *P. tremula*	'P-524'	10,000	6	Czech Republic	8.1			[221]
P. maximowiczii × *P. berolinensis*	'P-494'				10.2			
P. nigra	*P. nigra*				2.6			
P. nigra × *P. maximowiczii*	'J-104'				11.9			
	'J-105'				13.9			
P. × *generosa*	'P-473'				9.7			
P. × *generosa*	'Beaupré'	3030	3	France	1.57–11.13			[222]
			4		2.73–12.7			
	'Boelare'		3		1.37–10.53			
			4		2.85–11.6			
	'Hunnegem'		3		12.1			
			4		13.68			
	'Raspalje'		3		2.2			
			4		3.63			
P. × *generosa*	'Beaupré'	8333	8	Germany	6.1			[133] *
	'Rap'				5.8			
P. nigra × *P. maximowiczii*	'Max 1'				3.3			
	'Max 3'				3.5			
	'Max 4'				3			
P. maximowiczii × *P. trichocarpa*	'Androscoggin'				3.3			
	'Hybride 275'				4.2			
P. trichocarpa	'Muhle Larsen'				3.7			
P. maximowiczii × *P. nigra*	'Max 1'	8890	2	Germany	1.0–1.59			[223]
		9250			6.81			
P. maximowiczii × *P. nigra*	'Max 3'	17,778	4	Germany	8.6			[48]
P. maximowiczii × *P. trichocarpa*	'Androscoggin'				10.5			
P. maximowiczii × *P. nigra*	'Max 4'	11,000	2	Germany	5.4–6.3			[224]

Table 2. *Cont.*

Species and Poplar Hybrids	Genotype	Density	Age	Country	Yield (Mg dm ha^{-1} $Year^{-1}$) by Rotation			Reference
					1st	2nd	3rd	
P. deltoides	'Baldo'	5747	2	Italy	4.75			[90]
		10,000			17.5			
	'Dvina'	10,000			11.8			
	'Lambro'	10,000			9.5			
	'Lena'	10,000			14.2			
	'Lux'	5714			7.05			
		8333			4.3			
	'Oglio'	10,000			14.1			
P. × canadensis	'BL-Costanzo'	5714			3.25			
		7142			4.45			
	'Cima'	5714			4.55			
		7142			5.7			
	'I-214'	5747			4.35			
		10,000			8.4			
	'Luisa Avanzo'	5714			5.55			
		7142			6.25			
	'Orion'	5747			4.46			
		10,000			17.0			
P. deltoides	'Lux'	10,000	2	Italy	12.38	6.99	4.99	[225]
			3			7.07	14.53	
P. deltoides	'Lux'	10,000	1	Italy			16.4	[135]
			2		22.5			
			3		24.3			
P. deltoides	'Lux'	5900	2	Italy	3.31–9.33	2.17–18.85		[226]
P. maximowiczii × P. nigra	'AF10'				14.84	20.74		
P. × canadensis	'AF2'				5.66–15.77	7.54–17.01		
	'I-214'				3.63–11.87	4.2–18.44		
	'Sirio'				5.65	8.55		
P. × generosa × P. nigra	'AF6'				5.76–15.04	5.79–17.07		
	'Monviso'				6.79–17.92	9.31–23.55		
P. × generosa × P. trichocarpa	'AF8'				4.75–14.93	5.04–24.05		

Table 2. *Cont.*

Species and Poplar Hybrids	Genotype	Density	Age	Country	Yield (Mg dm ha^{-1} Year^{-1}) by Rotation			Reference
					1st	2nd	3rd	
P. × *canadensis*	'AF2'	6061	2	Italy	16	17	17	[92] *
	'I-214'				11.5	18	13.5	
P. × *generosa* × *P. nigra*	'AF6'				15	17.5	15	
	'Monviso'				17.5	23.5	17.5	
P. × *generosa* × *P. trichocarpa*	'AF8'				15	24	19	
P. maximowiczii × *P. trichocarpa*	'NE-42'	1333	7	Poland	8			[52]
P. trichocarpa × *P. trichocarpa*	'Fritzi Pauley'				8.1			
P. × *canadensis*	'AF2'				4.1			
	'Albelo'				4			
	'Degrosso'				6.8			
	'Koster'				5.6			
	'Polargo'				4.3			
P. × *generosa* × *P. trichocarpa*	'AF8'				2.5			
P. nigra × *P. maximowiczii*	'Max 5'	11,110	3	Poland	7.8			[227]
P. trichocarpa	'Columbia River'	10,000	3	United Kingdom	6.71	6.62		[13]
	'Fritzi Pauley'				8.59	8.24		
	'Trichobel'				9.08	9.59		
P. trichocarpa × *P. balsamifera*	'Balsam Spire'				7.24	7.03		
P. × *canadensis*	'Gaver'				6.58	5.58		
	'Ghoy'				6.45	5.77		
	'Gibecq'				5.7	4.73		
	'Beaupré'				7.34	4.87		
P. × *generosa*	'Boelare'				6.23	4.2		
	'Hazendans'				7.23	7.56		
	'Hoogvorst'				8.84	8.12		
	'Raspalje'				6.69	4.66		
	'Unal'				7.55	5.25		
P. balsamifera × *P. trichocarpa*	'Balsam Spire'	10,000	5	United Kingdom	14.42			[228]
		4444	5		11.20			
		10,000	4		13.98			

* Estimated values from graphs.

Table 3. Different examples of the biomass yield (Mg dm ha^{-1} year^{-1}) per genotype, age, and rotation in poplar short rotation plantations in Spain under Mediterranean conditions.

Species and Poplar Hybrids	Genotype	Density	Age	Location	Yield (Mg dm ha^{-1} Year^{-1}) by Rotation			Reference
					1st	2nd	3rd	
P. × *canadensis*	'AF2'	13,333	3	Aragón	24.72			[229] *
	'Ballottino'				25.08			
	'I-214'				28.64			
P. × *generosa* × *P. nigra*	'Monviso'				26.91			
P. × *canadensis*	'Campeador'	10,000	5	Soria	12.10			[230]
	'Dorskamp'				6.3			
P. × *generosa*	'Boelare'				16.6			
	'Raspalje'				19.8			
P. × *canadensis*	'Campeador'	10,000	6	Soria	9.3			[126,127]
	'I-214'				9.9			
	'Boelare'				12.9			
P. × *generosa*	'Raspalje'	2500			8.0			
		5000			9.2			
		10,000	6 (2nd–3rd:5year)		16.5	17.2	14.8	
		10,000	3		9.8			
		20,000			12.7			
		40,000			15.6			
P. × *canadensis*	'AF2'	8000	7	Lugo	0.84			[231] Without irrigation in a transition zone between Mediterranean and Atlantic climate
	'I-214'				2.96			
P. × *generosa*	'Beaupré'				3.07			
	'Raspalje'				3.1			
	'Unal'				1.97			
P. × *generosa* × *P. nigra*	'AF6'				1.14			
	'Monviso'				0.93			
P. trichocarpa	'Trichocarpa'				3.93			
P. × *canadensis*	'AF2' and 'I-214'	33,333	3	Soria	7–12	2–9.5	1.5–4.5	[145] *
P. × *canadensis*	'I-214'	10,000	3	Asturias	9	11	6	[148] * Without irrigation in mining zone
P. × *canadensis*	'I-214'	37,037	2	Salamanca	12.41	9.99	24.83	[232]

Table 3. *Cont.*

Species and Poplar Hybrids	Genotype	Density	Age	Location	Yield (Mg dm ha^{-1} Year^{-1}) by Rotation 1st	2nd	3rd	Reference
P. × canadensis	'AF2' 'I-214' 'Guardi'	13,333	3	Aragón	15.53 10.3 9.03			[233] *, [234]
P. deltoides	'Viriato'				14			
P. × generosa	'Unal'				9.23			
P. × generosa × P. nigra	'Monviso'				13.13			
P. × canadensis	'I-214'	33,333	2	Spain	15.1			[112]
Populus spp.	4 genotypes	13,333	3	Granada	13.7			[235]
Populus spp.	3 genotypes	19,700	4	Soria	12.0			
Populus spp.	4 genotypes	13,333	3	Zamora	7.7			
Populus spp.	4 genotypes	33,333	3	León	6.9			
Populus spp.	4 genotypes	20,000	3	Navarra	16			
P. nigra	'Lombardo leones'	17,316	3	Soria	9.1	17.1		[236]
P. × canadensis	'A4A' 'A2A' 'I-214' 'Luisa Avanzo' 'MC' '2000 Verde'				20.0 11.8 22.0 17.3 16.8 13.64	12.2 15.3 30.1 27.1 18.4 14.25		
P. deltoindes	'Baldo'	10,000	3	Gerona, Madrid, Soria	8.25–19.07	8.59–29.94		[77,80]
P. × canadensis	'Ballottino' 'I-214' 'Orion' 'Oudenberg'				8.25–15.94 5.45–16.16 12.53–22.65 9.43–14.27	11.45–19.20 11.09–37.27 12.70–34.56 9.66–19.96		
P. × canadensis	'I-214'	6666-33,333	3	Barcelona Gerona Gerona Granada León León León Madrid Navarra Soria Soria Zamora	4.2 5.7 11.6 18.3 4.7 5.8 15.2 13.2 18.5 8.1 14.2 8.2			[47]

Table 3. *Cont.*

Species and Poplar Hybrids	Genotype	Density	Age	Location	Yield (Mg dm ha^{-1} Year^{-1}) by Rotation			Reference
					1st	2nd	3rd	
P. × canadensis	'I-214'	5000	4	Madrid	12.4			[44]
	'Campeador'				10.0			
	'Canada Blanco'				8.4			
	'I-214'		2		10.90			
	'I-214'		3		10.10			
	'I-214'		5		17.30			
	'I-214'	10,000	4		16.9			
P. × canadensis	'AF2'	13,333	3	Granada	17.1			[237]
P. × canadensis	'AF2'	33,333	3	León	16.75			[122]
	'Guardi'				16.14			
	'I-214'				15.14			
	'MC'				15.01			
	'2000 Verde'				10.05			
P. × generosa	'Unal'				11.38			
	'USA 49-177'				15.92			
P. × generosa × P. nigra	'Monviso'				15.16			
	'Pegaso'				7.37			
P. × canadensis	'AF2'	33,333	3	León, Gerona, Madrid, Soria	16.8			[55]
	'Guardi'				12.44			
	'I-214'				12.21			
	'MC'				15.32			
	'2000 Verde'				15.38			
P. × generosa	'Unal'				11.13			
P. × generosa × P. nigra	'Monviso'				14.47			
	'Pegaso'				6.65			
P. deltoides	'Viriato'	13,333	3	Granada	9.55	18.20	12.82	[150]
P. × canadensis	'AF2'				13.47	16.66	13.99	
	'Ballottino'				9.48	16.75	12.27	
	'I-214'				9.11	13.44	15.81	
P. × generosa × P. nigra	'Monviso'				12.29	11.57	13.92	

Table 3. *Cont.*

Species and Poplar Hybrids	Genotype	Density	Age	Location	Yield (Mg dm ha^{-1} $Year^{-1}$) by Rotation 1st	2nd	3rd	Reference
P. × canadensis	'AF2'	20,000	3 (2nd rot: 2 year)	Navarra	15.59			[238]
	'A4A'				23.80	22.12		
	'Guardi'				15.59	6.43		
	'I-214'				23.80	18.51		
	'MC'				11.21	26.51		
	'Triplo'				18.07	32.92		
P. deltoides	'Viriato'				16.68	38.18		
P. × generosa	'Beaupré'				21.29	15.29		
	'Unal'				25.86	12.15		
P. × generosa × P. nigra	'Monviso'				15.41			
	'Pegaso'				13.99			
P. × canadensis	'I-214'	15,000	3 (2nd rot:2 year)	Navarra	18.20	14.46		[239]
		20,000			18.68	18.51		
		25,000			23.36	14.65		
		33,333			18.85	17.13		

* Estimated values from graphs.

Modeling of Growth, Production, and Biometric Relationships in SRC Poplar Plantations

The use of estimation models to predict available biomass is becoming more frequent as research into this type of plantation progresses, not only because of the costs involved in carrying out direct estimates [240], but also due to the greater flexibility and the possibility of extrapolating the results to larger scales when the models are based on a wide range of empirical data.

Allometric models which relate the tree diameter or another easily measurable variable to the biomass are those most commonly used in forest inventories or ecological studies [241,242]. These models have also been employed in SRC plantations to estimate the available biomass [243–245]. These predictions are particularly important when evaluating the economic viability of a crop [47,246]. Apart from the choice of regression model, the assumptions that underlie the regression procedures, and the data transformations used during the procedures [247], we are confronted with a large number of factors which create uncertainty and may affect the final results [248]. Simple equations which are valid for a wide range of conditions and plant material are usually preferred. There are several examples used for poplar SRC plantations [18,30,78,136,171,226,249–253]. The precision of such allometric equations is generally sufficient for stem biomass components [254]. However, other examples of equations exist that include more predictive variables in the models, which can improve the precision of the estimations [11,47,205,255–258]. Although specific genotype-level models provide the greatest precision, in cases where genotype identification is complicated, models for genotypes which are taxonomically close or taxonomic-specific models are often used. However, under Mediterranean conditions at least, Oliveira et al. [252] proves that the genetic origin does not explain the similarities in biomass allometry among genotypes, so these approaches are not always advisable.

Over the last decade, considerable advances have been made with regards to modeling to estimate biomass from SRC poplar plantations. Not only have advances been made in allometric models, but also much effort has been channeled towards modeling other aspects of growth in these plantations, such as the leaf architecture [259], root production [260–262], and the use of process models with this aim [263–267], in addition to other management tools derived from models [47,268–270].

In recent years, considerable progress has been made in the development of specific predictive models for SRC plantations under Mediterranean conditions. Improvements in the model development methodology to achieve more robust biomass predictions have been made [248,271], and the suitability of biomass models for local populations, as well as their performance for different sample sizes, have also been evaluated [253]. Different models have been developed, including a dynamic, whole-stand model for 'I-214' poplar genotype plantations in the northern and central plateau in Spain [272], along with individual tree models and general models for estimating both the above- and below-ground biomass in poplar SRC plantations under Mediterranean conditions [252,262].

Other management tools derived from models, such as maps of possible zones of production [47,273,274], estimations derived from the use of new technologies [270,275,276], and tools such as reference diagrams, which are particularly useful for both planning and managing this type of crop [277], have also been developed in recent years.

3.5. Biomass Characterization

The use of lignocellulosic biomass is not limited to the production of bioenergy. In recent years, a wide range of bioproduct-related options have sprung up, such as biopolymers, bioplastics, and sugar fermentation bioproducts, among others [278–280].

Poplar lignocellulosic biomass is mainly composed of cellulose (42–49%), hemicellulose (16–23%), and lignin (21–29%) [22,233,279]. Its biomass can supply raw material for processes of thermochemical or microbiological conversion. Worthy of note among the former is combustion, either for domestic or agro-industrial applications, but also for industrial cogeneration or co-firing [281,282]. Thermochemical processes also include gasification in downdraft gasifiers or fluidized beds [283], slow pyrolysis for the production of biochar [284], and fast pyrolysis to produce biocrude oil [285]. With regards to the biochemical processes, the conversion to second-generation bioethanol is the most studied process [286–288], although lignocellulosic biomass can also be a source of biobutanol [289,290] and other second-generation biofuels [22,279,291].

In Spain, several studies have addressed the characterization of poplar biomass for thermal use [148,231,292,293] as biofuels [294–297] or for new bioproducts [298,299]. The lower heating value, which is used to calculated the available energy, is usually around 18–20 MJ kg^{-1} in poplar wood on a dry basis [300,301]. Values found in Spain are within a range very similar to those obtained for other European countries, although the characteristics vary, depending on the genotype and the age, ranging from 17.61 to 18.74 MJ kg^{-1} [137,302,303].

The humidity content can be as high as 48–50% at winter harvesting [231,303], but poplar biomass has shown a good ability for air drying [303]. The specific density is known to be low [304–307], thus deriving in low bulk density chips (150–260 kg m^{-3}, [231]), corresponding to low energy densities. Densification to produce pellets is therefore an option.

The ash content, which is negatively related to the energy value and associated with the risk of boiler corrosion [308], varies broadly (1–4%), depending on genotype and site conditions [117,137,231,303]. The fouling and slagging risk derived from ash compositions are known to be very low [308–310]. The presence of nitrogen (N), which is related to NOx emissions, is low (0.5%) in poplar biomass [148,231,311], along with chlorine (Cl, <0.02%) and sulfur (S, <0.04%), which are corrosive [145,312,313].

The combination of a high volatile matter content (much higher than 80%, [137,303,314]), softness of the wood (which is easy to grind), and a low lignin content makes poplar from SRC a promissory feedstock for gasifiers. It can also be used for the generation of bioethanol [287,315].

Lignocellulosic biomass has many other uses in the context of the bioeconomy. For example, cellulose is used in the manufacturing of cosmetics, textiles, and pharmaceutical products, among others [291,297]. Lignin can potentially be used as a raw material in the manufacturing of products with high value added, such as vanillin, biopolymers in petrochemistry, and biopesticides, as well as a material for soil enrichment [291]. Hyd-Poplar lignin could be used for the production of flame-retardant materials [299]. For example, Martín-Sampedro et al. [234] and Ibarra et al. [233] identified the genotype 'Viriato' as being very promising for use in the production of biofuels, as well as in other value-added products, all of which point to the suitability of poplar raw material for different uses in the context of the bioeconomy.

3.6. Sustainability and Ecosystem Services

The importance of the sustainability of crops destined for biomass production has been highlighted when evaluating their future development. During the last decade, the European Commission has carried out different analyses and much effort has been dedicated to defining criteria and indicators of sustainability (EC, Directive 2009/28/EC, 2009; EU Parliament Resolution 2013; Directive 2018/2001/EC; European Parliament 2017). The World Bioenergy Association [40] has drawn up a document which includes 24 voluntary sustainability indicators related to bioenergy in general. This document is particularly important since it represents the only multilateral initiative with a broad consensus among the different governments and international organizations, providing a framework for future policy development. Spain has been part of this association since 2008 through the Institute for Diversification and Energy Saving (IDAE). Despite this consensus, there are many different approaches to tackling these studies, sometimes because of geographical differences, which often leads to approaches that are not always homogeneous. Examples of these initiatives include the analyses conducted by Dallemand et al. [316] and Dimitriou and Rutz [317], among many others.

In any case, the criteria and indicators must be based on scientific evidence and contain specifications for each production model or source of biomass, as these vary considerably. In this regard, there are numerous aspects which need to be addressed, such as life cycle and water cycle analyses, soil quality, and erosion control, among many others [318]. The environmental impacts of establishment, harvesting, and transportation have been considered negligible when the crop is grown on marginal land in central Europe [319]. Sustainability is also necessary from economic and energetic perspectives. With regards to the latter, the adaptation would appear to be favorable. However, this may not be the case with regard to the economic viability given the current prices of biomass and absence of subsidies [320,321]. In Spain, several life cycle analyses including not only environmental, but also energetic and even economic, issues [128,237,322–325] have been carried out in order to identify the most relevant factors for these crops under Mediterranean conditions. These analyses concluded that fertilization, transport, and irrigation are some of the most influential factors [237,288,326,327]. The price of biomass, the price of land rent, harvesting, and irrigation have been identified as the most influential factors from an economic perspective in Mediterranean environments [214,237,328]. The economic viability of poplar SRC under irrigated Mediterranean conditions can be achieved either by ensuring optimum productivity or through an increase in the market prices, associated with more diversified energy use or bioproducts, along with the quantification of ecosystem services, which currently do not have a market price [214]. In addition to this, improvements in clonal selection and irrigation technology, as well as the employment of other irrigation methods, such as making use of reused water, will be essential if these plantations are to be profitable.

A review by Li et al. [329] highlights the necessity to identify sustainable sources of bioenergy. With this purpose in mind, the authors identified poplar crops among the five lignocellulosic crops with the greatest future potential. They compiled and described biomass yield information across a whole range of locations and countries, and concluded that these crops, which only account for 3% of the bioenergy in Europe [330], can be grown under a wide range of climatic conditions, thus allowing direct competition with food crops to be avoided. Moreover, it has been determined that woody crops cultivated in short rotation and herbaceous lignocellulosic crops emit between 40% and 99% less NO_2 than traditional crops and consequently have lower fertilization requirements and a greater N use efficiency. They also sequester carbon in the biomass that remains in the soil (0.44 Mg C ha^{-1} $year^{-1}$) when they are planted on disused agricultural land, although the balance is not positive when they are planted on former pastureland. Other associated ecosystem benefits include an increased biodiversity (phytodiversity and zoological diversity) [32,331], erosion control and soil conservation [332], improvements in the water quality [333], and the role of the crop in phytoremediation [334–336]. In the case of Spain, the potential of the genus in the phytoremediation of soils has been evaluated through examples of the restoration of coal mining areas in northern Spain [131,337,338], or water phytodepuration [42,187,216,339]. Research has also focused on nutrient fluxes, evaluating the role of annual leaf litter in soil fertility throughout the rotation [340]; the quantification of accumulated carbon in both above- and below-ground fractions (reaching values of around 6.5 Mg C ha^{-1} $year^{-1}$ in the above-ground woody biomass, around 1.0 Mg C ha^{-1} $year^{-1}$ in the below-ground biomass [262], and around 2.5 Mg C ha^{-1} $year^{-1}$ in the case of the litter [341]), as well as the economic implications of CO_2 capture [342]. The impact of these forestry crops on the landscape of the agricultural environments where they are grown has not yet been evaluated in our country. Their effects on soil, biodiversity, and its function of mitigating diffuse pollution are examples of aspects that should be considered.

Among the main concerns in Europe in terms of the sustainability of crops destined for biomass production and therefore SRC plantations, are those linked to land use change. According to some studies, the balance of greenhouse gases and C in the soil indicates that bioenergy as a whole plays a role in the mitigation of climate change [343]. However, other studies question this affirmation [330], or point to a minimum cultivation period, beyond which the C balance becomes positive [344–347].

The impact on water resources must also be rigorously assessed [332,348]. In the Mediterranean area, the need for irrigation is perceived as one of the main weaknesses of these plantations. Different options aimed at minimizing or achieving more efficient irrigation in Mediterranean environments have been mentioned in Section 3.3.4. The application of wastewater in poplar plantations not only constitutes an attractive method for producing biomass through the regeneration of wastewater, but also implies a reduction or suspension of fertilizer application [42,187,188]. Hence, this approach not only provides a sustainable way to minimize water use, but also takes advantage of the ability of these plantations as vegetation filters.

Improving the sustainability of SRC crops as contributors to the biomass pool will probably require global decisions that take into account local specifications.

4. Current Status and Future Prospects in Spain

The availability of abandoned agricultural land, the lack of economic alternatives in rural areas, and the possibilities for complementarity afforded by SRC crops in terms of supply along with the ecosystem services associated with their establishment on agriculture land, are factors favoring the implementation of SRC forest crops [349–351]. As with other sources of biomass, it is important to analyse the biomass produced from forest crops and assess its sustainability and the best methods for producing it. However, the positive and negative aspects of this type of biomass production, indeed of biomass production in general, must always be taken into account and there will always be a certain degree of controversy surrounding its viability. Biomass from forest crops in short rotation has attracted a lot of interest in Spain, probably due to the regulations regarding electricity production in 2004 (RD 436/2004) and later in 2007 (RD 661/2007). At that time, many large and medium-sized companies considered establishing forest crops in SRC. However, the amendment to this regulation in 2013 removed the incentives at a time when many aspects associated with the establishment of crops in Mediterranean environments had still not been clarified, the ecosystem services had not been assessed, and the economic viability was far from guaranteed. This situation resulted in a declining interest in the sector, which continues today.

Despite the expected gradual increase in the contribution of renewable energy to the final gross energy consumption, in 2017, Spain was still 2.5% points from its 2020 national target [352]. Of the total contribution of renewable energy, biomass accounts for 13% [353]. With regards to the amount of biomass destined for bioproducts, as far as we know, there are no statistics for the country given that there are only a residual number of biorefineries producing such bioproducts [280]. Therefore, many aspects must still be resolved before the economic viability of renewable biomass resources can be determined. For example, the price of biomass in Spain is lower than in neighboring countries, so part of the biomass is exported. This would appear to be problematic in terms of sustainability. Moreover, no stable, predictable market for biomass exists in Spain.

In relation to biomass from forest crops in short rotation, many advances have been made in Spain over recent years, which have been described in this article. These advances include the following: (i) Increased knowledge of the genetic material in relation to the environment, with a better understanding of the adaptability of genotypes, including their water-use efficiency; (ii) maximizing production based on densities, genotypes, and management practices; (iii) evaluating the sustainability of plantations from different perspectives (environmental, energetic, and economic); (iv) exploring alternative designs, such as mixed plantations; (v) implementing plantations in marginal areas previously used for mining; (vi) quantifying accumulated carbon; (vii) specific predictive models and management tools for SRC plantations under Mediterranean conditions; (viii) physiological and molecular characterization of attributes, mainly those that are relevant to cultivation in marginal zones; (ix) chemical composition and pyrolytic behavior; and (x) the use of biotechnology to develop new materials, which should lead to increased production in the future. The role of these forest crops in water purification has also recently emerged as a matter of interest.

Despite these advances, we still have a long way to go to make SRC plantations a commercial reality in Spain. It is also known that biomass, including dedicated crops, would generate significant economic returns in rural areas [354]. This may be especially relevant in a country like Spain, where a large part of the country suffers from high levels of depopulation, although some aspects that hinder the short-term economic viability have also been identified, such as those previously mentioned regarding land rental, the need for irrigation, and the technological development of harvesting machinery at reasonable local prices. However, other issues need to be addressed in relation to crop management, such as (i) the use of irrigation, which should only be resorted to in areas where it is sustainable, by modernizing the systems, using more water-use efficient plant material or by using recycled water; (ii) the continual updating of genetic material adaptations to the site, testing of new materials, and making use of new technologies (genome editing, linkage maps, etc.), in order to produce material that is resistant to pests and diseases, tolerant to drought or a high salinity, or can adapt more effectively to specific soil and climate conditions; (iii) exploring new plantation designs; although the preliminary results of using mixtures are not particularly encouraging, many different alternatives remain to be explored; and (iv) rationalizing fertilization by evaluating the inputs derived from leaf litter and the exports of nutrients from wood, as well as by using alternative fertilizer inputs, such as those derived from sewage sludge.

Other questions should be explored based on the need to (v) quantify and value ecosystem services in terms of increased biodiversity in the agricultural landscape; carbon accumulation in each of the biomass fractions, both those that are extracted, as well as those that remain in the soil, such as foliar and root biomass; and their additional role in phytoremediation, or (vi) advance predictive modeling for Mediterranean conditions by combining the best features of empirical and process models, the advantages of which have been well-documented. The inclusion of ecophysiological variables enabling the prediction of individual tree-level biometry under different conditions, along with improvements in determining the most important variables, are some of the future objectives of modeling SRC plantations under Mediterranean conditions. In addition, as water restrictions represent a real threat, this factor is also being considered in the development of models that enable the simulation of different climate change scenarios. Regarding (vii) the characterization of biomass, although many studies have already addressed this aspect, a more in-depth knowledge will be required as the final products and their intended uses become more defined. Identifying the requirements of each of the final products will be essential in order to determine the most suitable genotypes for each crop. Given that Spain is a diverse country, it is also necessary (viii) to analyse where and how this biomass is produced at a national scale.

Improving the critical aspects detected in environmental, energetic, and economic analyses is essential for achieving profitable and sustainable plantations under Mediterranean conditions. Biomass produced ad hoc through plantations under SRC systems may be of interest in many areas of the Mediterranean, providing a further option which could contribute to the development of a circular bioeconomy while also generating important environmental services.

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