Energy Plantations

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Abstract Energy plantations have been gaining importance in the supply of biomass for energy purposes, due to their high yield in short timeframes. These forest systems also enable to reduce the pressure in other forest systems to provide biomass for energy, in particular those under protection and conservation status. This chapter reviews the state of the art of energy plantations and their yields. It addresses the selection of species, density, rotation, harvest cycles, site selection, management practices, harvesting, biomass yields, and their estimation. Overall, there is a wide set of species and management options that can be used in energy plantations. Similarly, there is a large variability in yields, that vary between and within species, due to site, density, rotation, harvest cycles, and management. Though there are many studies, further research is needed on yield optimisation, rotation length, harvest cycles, management practices, and harvesting.

Keywords Species · Clones · Regime · Site · Management · Yield

1 Introduction

Wood is considered one of the most important raw materials as it satisfies several human needs, among which is energy [1]. In the last decades, energy plantations have been gaining importance as a source of energy because of the energy crises, the concerns about the reduction of greenhouse gas emissions, the dependency on fossil fuels, the increase of carbon sequestration, and to release the pressure on other forests systems [1–8]. These forest systems date back to ancient times, but management practices have been improved to increase their yield [1, 9–11]. Their

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importance was recognised by the International Union of Forest Research Organizations (IUFRO; http://www.iufro.org) through the creation of the research group 1.03.00–Short-rotation forestry.

Dickmann [1] identifies several terms for forest energy plantations: short-rotation woody crops (SRWC), short-rotation forestry (SRF), short-rotation coppice (SRC), short-rotation intensive culture, intensive culture of forest crops, intensive plantation culture, biomass plantation culture, bioenergy plantation culture, biofuels feedstock production system, energy forestry, short-rotation fiber production system, mini-rotation forestry, silage sycamore, wood grass. The most frequently used terms are short-rotation woody crops (SRWC), short-rotation forestry (SRF), and short-rotation coppice (SRC). As no standard term has been defined in this chapter the term energy plantations will be used.

The goals of this review are to provide insights into energy plantations from the selection of species or clones to harvest and yields. This chapter is divided in two sections. One that analyses the energy plantations, including the selection of species, initial density, rotation, harvest cycles, site selection, management practices, and harvesting (Sect. 2), and another that evaluates biomass yields (Sect. 3).

2 Forest Energy Plantations

Forest energy plantations are forest systems whose main goal, frequently the only one, is producing biomass for energy, and have specific spatial and temporal features [6, 12]. The plantations are composed of very fast or fast growing tree species, many times improved hybrids. These stands have frequently very high densities (from 1000 to more than 300,000 stems·ha^{-1}), in coppice systems most of the times, with very short or short rotations (1–12 years), cutting cycles of 10 to 30 years, managed in clearcutting systems, where all aerial biomass is removed in each harvest, and are intensively managed. Their establishment and management (Fig. 1) include site selection, control of spontaneous vegetation, selection of planting techniques, fertilisation, control of pathogens, and irrigation [1, 13–24]. Planting design and management are frequently adapted to a fully mechanised system [25–27].

Biomass from forest energy plantations, when compared to other renewable energy sources, has several advantages: biomass is relatively easy to transport and store [28]; it has different uses, such as heating, electricity or biofuels [3, 28–30]; it is available worldwide [3, 13, 31, 32]; in a specific location its quantity can be increased through anticipated harvest in times of shortage or high prices of other fuels [28] or reduced through delayed harvest when its market price is low or other fuels have low prices [33]; it allows decentralisation of the energy systems [3, 28]; and it is suitable in regions with biomass availability and low population density [28, 34].

Forest energy plantations are considered economically viable when compared to other forest and agricultural productions at the management unit level. These forest systems have low risk and high economic viability. Its harvest flexibility (anticipated

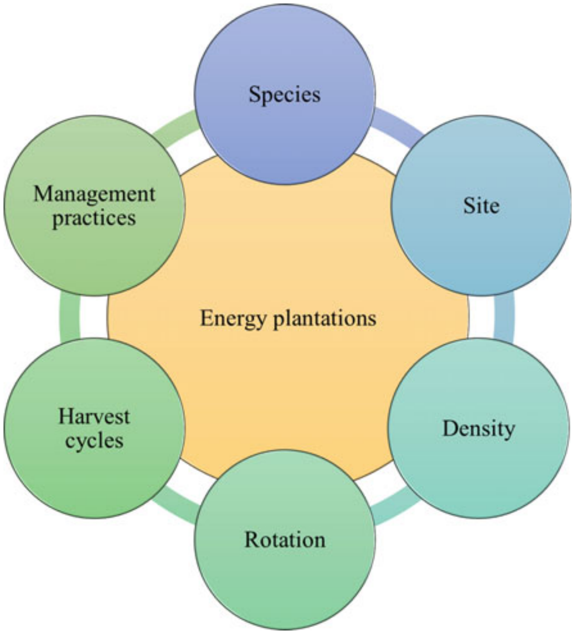


Fig. 1 Factors influencing the establishment and management of energy plantations

or delayed) promotes the reduction of risks, especially if included in agricultural crops portfolios; and it also provides ecosystem services without adding costs, especially in areas of intensive agriculture [2, 4, 5, 7, 35–37]. However, energy plantations can pose a risk when established in areas suited for agriculture, and therefore, it is recognised that they should be settled in set aside agricultural lands or marginal lands [3, 6, 12, 13, 31–33, 38], enabling simultaneously rural development and environmental benefits [1, 2, 12, 39, 40]. These plantations can also be settled for phytoremediation purposes, *i.e.*, using trees in energy plantation systems to remediate contaminated sites while using the biomass for energy [26, 41–45]. Forest energy plantations are well represented, for example, in Canada [46], China [47], United States of America [48, 49], and Europe, northern and central, and to a lesser extent in the southern [13, 31, 32].

Selection of the Species

The selection of tree species for energy plantations encompasses a set of requirements that should be fulfilled [50–53]: biomass should have high specific energy and quality as fuel, high biomass production in dry weight, good resprouting ability, fast juvenile growth, narrow crowns or large size leaves in the upper crown, adaptability to a wide range of sites, and resistance to biotic and abiotic disturbances (Fig. 2a). Ideally, the species should have [3]: maximum possible production in dry matter per stand area

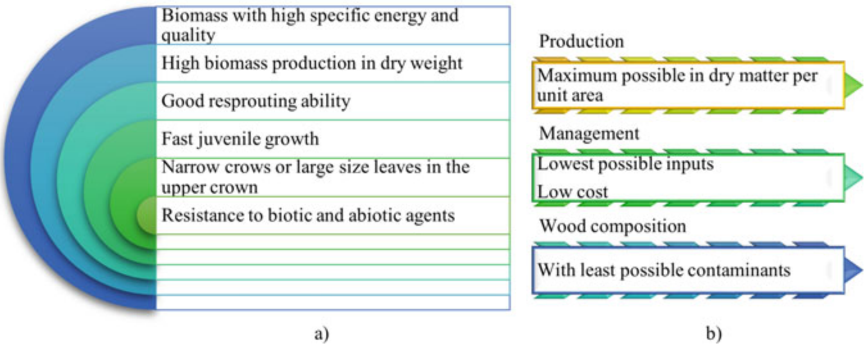


Fig. 2 Species requirements for energy plantations **a** and ideal features for management and high yields **b**

unit, production with low energy input (including nutrient requirements), low cost, and wood composition with the least possible contaminants (Fig. 2b).

These requirements can be satisfied by a large set of species, characterised by a fast initial growth which enables them to outcompete other species for the available growing space. From the many species that can be used for energy plantations some of the referred in literature are presented in Table 1.

Due to their characteristics, *i.e.*, fast or very fast growth, wide genetic base, easy propagation, short improvement cycles, easy vegetative reproduction, and ability to resprout, the aforementioned species are adapted to several climatic and soil conditions. They have also the ability to improve soil quality and to have high productions [51–53, 101]. In European Union countries three *genera* are considered to have the largest potential for energy plantations, namely *Populus* spp., *Salix* spp., and *Eucalyptus* spp. [51–53, 101].

In energy plantations, hybrids are frequently used to improve several tree species traits such as survival rate, biomass productivity, resprouting ability, adaptation to a variety of environmental conditions, and resistance to pathogens. The hybrids can be developed through genetic improvement [26, 98] and/or biotechnology [102]. For example, clones of *Populus* spp. and *Salix* spp. can differ in what regards survival rate, growth, and woody properties due to site quality and/or planting density [103] or not [104]. Relevant are also the relations genotype-environment (e.g., [86, 105]).

Density, Rotation, and Harvest Cycles

In energy plantations *density* and *rotation* length are strictly linked as the main goal is to achieve the highest possible biomass production in the shortest possible time (e.g., [26, 56, 89, 106]). Sixto et al. [6] refer to three principles that are associated with the design and management of forest energy plantations: (a) *Law of final constant yield* that states that biomass yield increases with the increase of density up to an

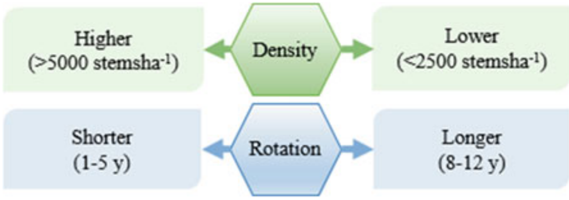
Table 1 Forest species used in energy plantations

Genus/Specie	References
Acacia spp.	[54, 55]
Acer pseudoplatanus	[56–59]
Ailanthus spp.	[55]
Alnus spp	[60–67],
Bambusa spp.	[68, 69]
Betula spp.	[58, 59]
Casuarina spp.	[55, 70]
Eucalyptus spp.	[1, 37, 50, 71–75]
Fraxinus spp.	[76]
Gmelina arborea	[77–79]
Leucaena spp.	[1, 55, 77]
Liquidambar styraciflua	[1, 80, 81]
Paulownia spp.	[82, 83]
Pinus taeda	[1, 84]
Platanus occidentalis	[57, 80, 81, 84–87]
Platanus spp.	[48]
Populus spp	[1, 38, 47, 50, 56, 58, 59, 63, 80, 86, 88–93]
Prosopis spp.	[94, 95]
Robinia pseudoacacia	[56, 96, 97]
Salix spp.	[1, 38, 50, 58, 59, 63, 92, 98]
Swetenia mahogany	[99]
Tectona spp.	[99, 100]
Ulmus pumila	[48]
Yushane spp.	[68]

upper threshold, above which it becomes independent of density. It can be used to determine the maximum number of stems per area unit; (b) *The development of social classes in a stand*, with dominant and dominated individuals competing among them. Harvest should be done before competition affects the growth of the individuals and the vitality of stumps; (c) *Self-thinning law* states that without mortality total biomass per area unit increases exponentially until canopy closure, after which stems tend to reduce growth. After canopy closure, some trees become dominated and eventually die unless there is a density reduction. Thus, canopy closure should be avoided.

The three aforementioned principles are the basis for trials to determine both density and rotation length in energy plantations. A wide range of densities has been studied, from 1000 stems·ha^{-1} to 310 000 stems·ha^{-1} [12, 21, 48, 58, 59, 92, 98, 101, 107–109]. Similarly, a large range of rotations has been studied, from 1 to 20 years [12, 21, 38, 48, 58, 59, 92, 98, 101, 107–109].

Fig. 3 Density versus rotation length



According to Dickmann [1], there seems to be a dichotomy regarding density and rotation length that is also linked with the woody products and yields to be obtained. It should be taken into consideration the production per area *versus* per individual tree. Higher densities result in higher biomass per area unit but lower biomass per individual stem [103, 110]. Thus, energy plantations can be divided into (Fig. 3): (i) higher densities and shorter rotations, and (ii) lower densities and longer rotations. The former has densities ranging from 5 000 to 200 000 stems/ha, and rotations from 1 to 5 years. Their main goal is biomass for energy where the maximum conversion of solar energy is attained and the flexibility of the biomass as raw material is not important. This strategy is also used when phytoremediation or application of vegetation as a filter of soil contaminants is needed. The latter have densities ranging from 1000 to 2500 stems·ha^{-1}, rotations from 8 to 12 years, and enables more flexibility in terms of woody products, small dimension timber, pulp and paper, and biomass for energy. Yet, a wide variety of combinations of densities and rotations can be found in the literature. Examples of stands of higher densities and shorter rotations are suggested by some authors [21, 26, 39, 86, 98, 101, 107, 108, 111, 112], while stands of lower densities and longer rotations are suggested by other authors [37, 39, 58, 59, 74, 75, 109–111, 113–115].

Though there is a wide range of literature references focused on determining the optimal density, and rotation, the results are not always coincident. This is, at least partially, explained by the constraints related to the tree species, clone, site, and climate. It is well known in silviculture that the maximum volume (or biomass) is reached when the mean annual increment equals the current annual increment [10, 116–118]. Several authors have studied the rotation that maximised biomass production as a function of density (*e.g.*, [92, 101, 106, 119]). For densities up to 10 000 stems·ha^{-1} higher yields are attained at longer rotations (*e.g.*, 4 years *versus* 2 years) [101] while densities higher than 10 000 stems·ha^{-1} the higher yields are attained at shorter rotations [119]. The wider the spacing the higher the growing space for each individual, and the higher the dimensions of the individual stems. The reduction of biomass production seems to be related to biomass allocation due to full growing space occupancy and competition among individuals [62]. The reduction of the yield with the increase of rotation length for high densities seems to be related to self-thinning. Its effects result from the increase of competition between individuals and an overall reduction of growth and, consequently, of yield. Thus, the mitigation of the self-thinning effect on yield can be attained with shorter rotations [119]. It seems that for a density equal or higher to 10 000 stems·ha^{-1} rotations of 2-years length are better suited for maximising yield while for lower density longer rotations can be used [106].

Two other aspects should be considered: one is technical, and the other is the maximization of biomass per stem or per area unit. The rotation length can be influenced by *technical aspects*. On one hand, mechanical harvest equipment has a maximum threshold cutting diameter, which can reduce rotation length [26]. On the other hand, mechanical harvest is also described as problematic for high densities, in which case the option is to reduce density and increase rotation length [1]. The other aspect relates to the *maximisation of production per stem* or *per area unit*, *i.e.*, fewer stems with larger dimensions or otherwise. In the former, products have a higher proportion of wood, and smaller of bark, leaves, and branches. This implies smaller densities, longer rotations, and products that can be used for energy, pulp and paper, or other small dimension timber products. Thus, the model of silviculture is more flexible in terms of products. As growth is concentrated in fewer trees, whenever competition is a limiting factor thinning or sprout selection could be considered as well as pruning for small dimension timber products, to increase quality [1, 117]. But this approach has the disadvantage of having lower densities and longer rotations [1, 19], resins, and other undesirable chemical components for the use of biomass for energy [19]. The energy plantations with higher densities and trees of small dimensions have the advantage of maximising the conversion of solar energy in biomass, which results in a yield of biomass oriented to bioenergy, but with less flexibility in terms of woody products [1, 107]. Other advantages are reducing the spontaneous vegetation [120] and not needing thinning, sprout selection, or pruning [1].

The *harvest cycle*, *i.e.,* the number of harvests until the end of the production cycle, when there is the need to regenerate the stands, is constrained by stump vigour, stump mortality, and rotation. *Stump vigour* influences the stump's ability to resprout as well as stool survival. The higher the stump vigour the higher the resprout ability and the stool survival. Thus, the higher the stump vigour the higher the potential yield. *Stump mortality* influences density and productivity. The lower mortality rates enhance higher productions [121]. Productivity is also affected by the successive *rotations* with a trend towards the increase from the first to second or third rotation, and a tendency towards yield decrease more or less accentuated, from the fourth rotation onwards. Yet, it also depends on the stump vigour, stump mortality, species, and site. In general, the harvest cycle's length is determined by productivity. When productivity between successive harvests decrease it is considered that the end of the production cycle has been reached [122]. Several authors refer to cutting cycles between 10 and 30 years with 3 to 10 rotations [12, 17, 26, 56, 63, 123].

Site Selection and Management Practices

In the establishment of any forest stand, and in particular of energy plantations, *site selection* (Fig. 4), which is related to the soil and climate [1, 3, 17], has a strong influence on the survival, growth, and yield. Overall, there is a trend toward higher yields on better quality sites [1, 26, 104]. But it is also dependent on the ecological traits of the species or clones. Thus, considering that a high yield is to be attained, soils should have adequate physical and chemical properties. The soil characteristics that enhance biomass production are soil moisture availability during the yearly growing season, nutrient availability, and aeration. The soils that should be avoided are those with drainage problems (either poorly or excessively drained), with pH too acid or too alkaline, degraded through erosion, saline, shallow, or infertile. Climate should also be considered in particular, the mean annual temperature, annual precipitation and precipitation during the growing season, frosts, and snow. Climate conditions should be within the ecological range of the species or clones, preferably close to their optimum for their growth. Steep slopes should be avoided if mechanisation is foreseen [1, 12, 19, 26].

One issue related to biomass for energy is the identification of the areas available for energy plantations. These areas can be determined following a methodology in four steps [17]: (1) selection of the species to be used and assessment of their ecological and cultural characteristics; (2) determination of the suitability of the sites, which refers to the selection of a set of data, frequently in a geographical

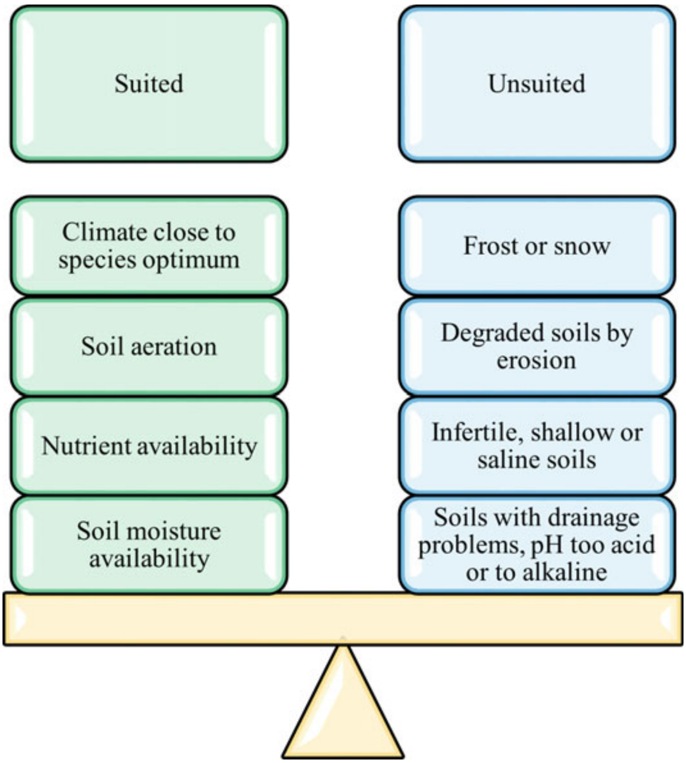


Fig. 4 Site characteristics suited and unsuited for energy plantations

information systems (GIS) environment, including soils, land morphology, climate, protected areas, administrative boundaries, a suite of assumptions and a subsequent set of operations that enable the identification of the areas where the selected species can be grown; (3) availability of land, which refers to the identification of the potential areas available, considering the existing restrictions, whether economic or social; (4) assignment of the land, which refers to the definition of a decision process that enables the determination of the areas where the energy plantations can be installed. The areas identified are dependent on the initial assumptions made. If only the optimal conditions that potentially originate the higher yields are considered, then the area estimation could be rather conservative [17].

Management practices include the control of spontaneous vegetation, planting techniques, initial development, control of pathogens, and irrigation (Fig. 5). The *control of spontaneous vegetation* enables the reduction of competition between the tree species or clones and other vegetation. It is especially relevant in the competition for light, water, and nutrients [19, 124]. It should be done during site preparation, as the control of herbaceous and shrub species is simpler and makes plantation operations easier. Several methods of control of spontaneous vegetation can be considered. Their selection should take into account a suite of factors that include the type of spontaneous vegetation, site, climate, and tree species or clones to be planted. It can be mechanical or chemical or even a combination of both [1, 26, 86, 124–126]. The control of spontaneous vegetation after each harvest might [127] or not [128] be necessary and is frequently chemical [129]. It is recommended when competition with spontaneous vegetation and/or production losses are expected, though care should be taken not to affect either the stumps or the sprouts [6, 26].

Regarding the selection of *planting techniques*, two main choices can be pointed out, namely plantation of cuttings or plantation of seedlings. Cuttings, *i.e.*, unrooted hardwood cuttings for species that have a good ability to develop the root system and the aerial part, are frequently used with *Salix* spp. [1, 26, 130–132]. Seedlings, most of the times, with plants produced in containers whether from seed origin or

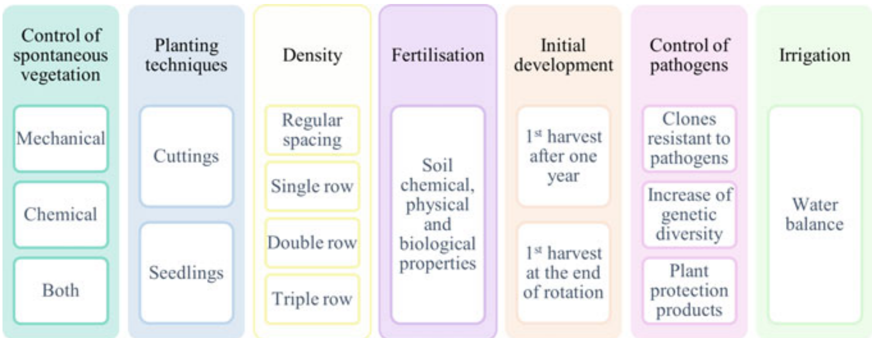


Fig. 5 Management practices

vegetative propagation [1], are used with for example *Populus* spp. or *Eucalyptus* spp. [1, 130–132],

Energy plantations establishment should consider the spatial arrangement of the individuals, which is related to spacing and density. Regular spacing design is frequently used to promote better use of the growing space while at the same time enhancing its mechanical harvest. The spacing can be in single, double, or triple rows (Fig. 6) depending on the density. Typically, the distance between rows ranges from 2.0 m to 3.0 m in the higher density and shorter rotation plantations and between 4.0 m to 6.0 m in the lower density and longer rotation ones [12, 16, 75, 133]. In the single row design, the distance within the rows ranges from 0.5 m to 3.0 m [12, 16, 75, 133]. In the double row design, the spacing between the double rows is between 0.75 m and 1.50 m, and the distance within the rows ranges from 0.45 m to 0.80 m [12, 133, 134]. For the triple row design, the spacing between the triple rows is about 0.6 m, and the distance within the rows of 0.6 m [135]. According to some authors [12, 136], long lines increase the efficiency of harvest. Also, the head and boundaries of the energy plantations should be wide enough for the machinery manoeuvres and to reduce to a minimum its turns [12]. Density and spatial arrangement affect competition between individuals. There is a trend towards lower competition in the square spacing when compared with the rectangular one [103].

Regarding the *initial development* of the plantation, two approaches can be followed [26, 107, 108]: (i) the plantation is harvested at about 1 year old to promote coppicing, which increases the density. The sprouts take advantage of the existing stump root system that promotes the growth rate and the increase of biomass production; and (ii) the first harvest is done at the end of the rotation and the coppice derives from this first harvest. Before choosing one or the other, both costs and biomass production should be considered to increase the economic viability [6].

The need for *fertilisation* is determined by the site, especially by the site's productive potential as it plays a key role in the intensive forest systems of biomass production [6]. Because it is an expensive operation its necessity should be evaluated [1]. Some energy plantations' studies reported that fertilisation did not increase yield when compared with not fertilised ones (e.g., [12, 130–132, 137–141]). This effect could be due to the high quality of the soils, as many are set aside agricultural lands

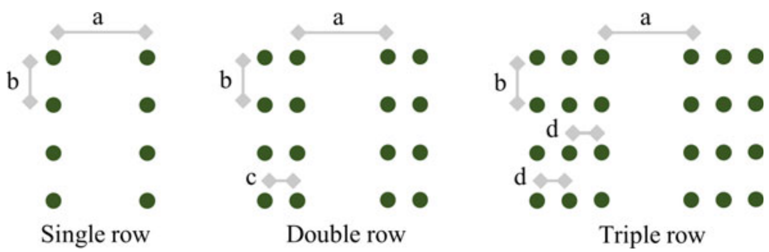


Fig. 6 Schematic representation of single, double and triple row energy plantation design (where a is the distance between rows, b distance within the row, c the distance between double rows, and d the distance between triple rows)

[6, 132]. Conversely, in other studies, fertilisation originated the increase in yield, due to the increase of the nutrients' availability (*e.g.*, [12, 131, 139, 141–143]). In others still, a negative effect of fertilisation was described, which was related to polluting mineral elements (*e.g.*, salts) and/or antibiotics (*e.g.*, [144–146]). A thorough revision of the effects of fertilisation on energy plantations can be found in Marron [147].

The assessment of soil and foliar nutrient levels should be considered to determine the need and quantity of fertiliser. If the nutrient's concentrations are below their critical level then fertilisation should be done [1]. It can either be done by inorganic fertilisers [26, 86, 148], or organic fertilisers, residual waters, or intensive cattle grazing muds [98, 149–153]. In any case, a thorough evaluation of the soil's physical, chemical, and biological (*e.g.*, organic matter and amount of seeds of spontaneous vegetation) characteristics should be carried out before considering the application of fertilisers [26] as well as their application costs [6]. The distinction between the first and the other successive harvests should also be made. In successive harvests, the export of large amounts of nutrients from the site is expectable. Yet, leaf fall and its decomposition incorporate nutrients in the soil, though the reallocation of nutrients from leaves to woody organs varies between species. Thus, the decomposition of leaves incorporates larger or smaller amounts of nitrogen, phosphorous, potassium, calcium, and magnesium promoting the maintenance of soil fertility and, potentially, compensating for the removal of woody biomass [154]. When the exports are not compensated forest energy plantations might need to be fertilised [1, 22, 155].

The *control of pathogens* should be considered whenever outbreaks of pests or diseases occur. One of the ways to minimise the effect of pathogens is by using clones resistant to pests and diseases [156, 157] or increasing the genetic diversity [1, 158]. Alternatively, plant protection products (phytopharmaceuticals) can be used, in which case legislation should be followed [6] and the economic and environmental viability should be justified [1, 86, 159]. These products should only be applied as an answer to a specific problem when large damages are to be expected and not as a prophylactic treatment [6].

Irrigation in forestry is not frequent [10, 116–118, 160]. In many forest energy plantations, annual precipitation and its annual distribution along with soil water holding capacity are sufficient to cover the trees' water needs. Irrigation should be considered when water stress is expected to occur, to avoid the reduction of biomass production or mortality [161–163]. The quantity of water to be used should be calculated as a function of the plantation evapotranspiration and cultural coefficient (*i.e.*, water balance) to promote the best possible use of water [6, 164].

Harvesting

The optimisation of harvesting is of the utmost importance [165], due to its share of costs and inputs. The harvesting costs correspond to about 45% of the total energy plantation costs [134]. Also, the energy input corresponds to up to 33% of the total input of energy [166], being the second largest (the first is fertilisation) fossil energy inputs in the system [167].

Several machinery existing on the market has been used to harvest energy plantations. Moreover, to improve harvest efficiency other machinery has been developed (for detailed revision see [168]). In literature four main harvesting techniques are referred [136]: single pass cut-and-chip, double pass cut-and-store, single pass cut-and-bale, and single pass cut-and-billet. The single pass cut-and-chip being the most flexible, can be used with different stand structures (species, ages, diameter, density, and stocking). The harvesting is done with a single pass making the operations simpler and reducing labour and machinery costs [169] because other cultural practices can be done with these machinery [170]. Furthermore, single tree harvesting productivity was improved by multiple tree harvesting with a system based on software [171]. In the double pass cut-and-store harvest system, the stems are cut and left to dry in a specific location after which are chipped, corresponding to two passes. When compared with the other systems its advantages are related to not needing biomass to be stored in a covered place; to the reduction of the losses due to microbial activity and emission of undesired gases during the storage of the chips; the reduction of the costs of transport because of the lower moisture content of the chips; forest chipper provides a high material effective capacity as well as a favourable particle size distribution [172]. The two latter harvesting systems are much less representative than the former two. The cut-and-bale and cut-and-billet derive in different biomass formats than the single pass cut-and-chip and double pass cut-and-store, resulting in biomass bales, billets, and chips, respectively [136]. The most used and improved mechanical harvesting technique is single pass cut-and chip, followed by double pass cut-and store (for details see [136]).

Species dormant season (winter in the northern hemisphere) is the best one for harvesting. The advantages are related to the recycling of leaf nutrients [154]. Additionally, cutting should leave stumps between 10 cm and 20 cm to preserve the buds and to maintain resprouting stump ability [173].

3 Biomass Yields in Energy Plantations

Estimation of Biomass in Energy Plantations

Biomass can be estimated by destructive or non-destructive methods (*cf. chapter* "Modelling Biomass"). The former can be done either through sampling, frequently used for modelling; or at the end of the rotation when trees in a certain area are harvested. The disadvantage of the latter is that it does not allow to make predictions. The non-destructive methods use allometric biomass functions and enable to predict yields. However, due to the specificities of these forest systems the numerous existing allometric equations, many developed for high forest systems, originate bias in the estimation of biomass. Thus, several authors developed allometric equations specific to energy plantations for tree species and/or clones. In literature was found a set of allometric equations for *Populus* spp. [39, 47, 59, 88, 91, 93, 108, 109, 113, 133, 174], for *Salix* spp. ([26, 59, 62, 112, 175–178], and for *Eucalyptus* spp. [37, 74, 75, 114, 179, 180].

Estimations of biomass of energy plantations have been done at the local or regional levels. Frequently growth and production models (which include allometric biomass functions) are used to generate several scenarios of management [130, 181–185]. At local level, the models are frequently based on the biomass allometric functions per species. Conversely, at broader scales, the models used in the estimation of biomass include usually several soil and climatic data variables, along with plant growth principles and management options, and also the interaction between the four factors. Bandaru et al. [186] classified climatic data sets in two categories: (i) collected from meteorological stations; and (ii) gridded weather data sets. The first is predominantly used at a local scale while the latter are used at a regional scale [187]. The gridded weather data can be obtained by (i) interpolation techniques of weather data and topographic characteristics or (ii) modelling and assimilation techniques [188]. A modified version of 3-PG for energy plantations with coppice management, 3-PG-Coppice model [183] was used by Bandaru et al. [186]. It requires four types of variables, namely weather, soil characteristics, plant growth parameters, and management regime. The main goal of the study was to analyse the effect of different weather data sets in the estimation of biomass from short rotation woody crops of hybrid *Populus* spp., using flux towers and four different high resolution gridded weather data at five different locations. The same authors refer that high resolution gridded weather data has some bias when compared with that of the flux towers [186]. This can be, at least partially, explained as modelling and assimilation techniques are not able to characterise in detail the climate that is affected by the topography and land use [186, 187, 189, 190]. Moreover, there seem to be smaller biases for the higher spatial resolutions [186, 188, 191, 192]. Bandaru et al. [186] also stress the importance of the bias determination on the weather as influences as well the biomass estimations. Other authors [28, 193] estimated the biomass for a short rotation coppice in a geographical information systems environment allowing the inclusion of climate and soil variables and the analysis of biomass spatial variability. The use of average yields to estimate biomass over a region results in bias on biomass potential, which might affect the planning of its use due to the variability of local conditions, species, and growth rates. Moreover, in the case of need, short term biomass potential yield can be increased by reducing coppices rotation lengths [28].

Biomass Yield of Energy Plantations

Biomass yield is related to initial density, regime, rotation length, and cultural practices. The analysis will be focused on three *genera Populus* spp., *Salix* spp., and *Eucalyptus* spp. It was based on 33 literature references, corresponding to a total of 415 trials (Table 2). Overall, there seems to be a trend towards higher densities for

Salix spp., when compared to *Populus* spp. and *Eucalyptus* spp., whereas yield tends to be higher for *Eucalyptus* spp. than for the other two *genera*. Rotation length shows similar trends for all three *genera*. Yet, the variability is rather large (Fig. 7). This variability results from the interactions between species and/or clone traits, site, and management practices. The yield of the *Eucalyptus* spp., *Populus* spp., and *Salix* spp. varies between 1–63.8 $t \cdot ha^{-1} \cdot y^{-1}$,0.3–66 $t \cdot ha^{-1} \cdot y^{-1}$ and 0.3–27.5 $t \cdot ha^{-1} \cdot y^{-1}$; density varies between 2000–7142 $stems \cdot ha^{-1}$, 278–33,333 $stemsha^{-1}$ and 6666–107,600 $stems \cdot ha^{-1}$; and rotation length among 2–6 y, 1–12 y and 2–19 y, respectively.

For all *genera*, there is a yield increase from the first to the second rotation, due to the increase of density, *i.e.*, each stump had more than one stool, for *Eucalyptus* [74], *Populus* [101, 109, 113, 133, 165, 174] and *Salix* [26]. However, other studies report a decrease in yield from the first to the second rotation for *Populus* [21, 108]. From the second to the third rotation some studies report an increase in yield for *Eucalyptus* [74] and *Populus* [101, 109, 113] while others account for its reduction for *Populus* [133, 165] and for *Salix* [26]. In the fourth rotation, it is observed a reduction of yield for all species [26, 74, 113].

There was no clear trend between density and production. This is probably related to the site quality and climate as well as the management practices. Yet, considering studies where several densities have been analysed it can be seen an increase in production with the increase of density. For example, for *Salix*, Schweier and Becker [178] reported for an initial density of 12,000 $stems \cdot ha^{-1}$ a yield of 6.8 $t \cdot ha^{-1} \cdot y^{-1}$ and 9.7 $t \cdot ha^{-1} \cdot y^{-1}$, while for a density of 13,200 $stems \cdot ha^{-1}$ a yield of 11.7 $t \cdot ha^{-1} \cdot y^{-1}$. This corresponds to an increase of 10% in the number of stems and an increase in yield of 72% and 20%, respectively. For *Populus*, in Italy, Di Matteo et al. [111] reported that an increase in initial density from 7140 $stems \cdot ha^{-1}$ to 10,360 $stems \cdot ha^{-1}$ (an increase of *circa* 45%) resulted in an increase of yield, from 12.2 $t \cdot ha^{-1} \cdot y^{-1}$ to 13.9 $t \cdot ha^{-1} \cdot y^{-1}$ (*circa* plus 14%). For *Populus*, in Germany, an increase of 10% in density (from 10,000 $stems \cdot ha^{-1}$ to 11,000 $stems \cdot ha^{-1}$) [199] attained an increase in yield between 27% and 86% (from 4.4 $t \cdot ha^{-1} \cdot y^{-1}$ and 5.9 $t \cdot ha^{-1} \cdot y^{-1}$to 5.6 $t \cdot ha^{-1} \cdot y^{-1}$, and 8.2 $t \cdot ha^{-1} \cdot y^{-1}$, respectively). Yet, the same authors for the same initial density increase observed also a reduction of yield of—6.2% (from 5.9 $t \cdot ha^{-1} \cdot y^{-1}$to 5.6 $t \cdot ha^{-1} \cdot y^{-1}$). In another study, for *Populus*, Oliveira at al. [39] tested eight different initial densities (6666 $stems \cdot ha^{-1}$, 10,000 $stems \cdot ha^{-1}$, 13,333 $stems \cdot ha^{-1}$, 15,000 $stems \cdot ha^{-1}$, 17,316 $stems \cdot ha^{-1}$, 20,000 $stems \cdot ha^{-1}$, 25,000 $stems \cdot ha^{-1}$, and 33,333 $stems \cdot ha^{-1}$) resulting in the increase of yield from the lowest initial density (6666 $stems \cdot ha^{-1}$) to the fourth lowest (15,000 $stems \cdot ha^{-1}$) when compared with the highest one (33,333 $stems \cdot ha^{-1}$) of 179.6%, 54.3%, 76.0%, and 24.7%, respectively. The fifth and the seventh initial densities (17,316 $stems \cdot ha^{-1}$ and 25,000 $stems \cdot ha^{-1}$) resulted in a reduction of yield of −38.8% and −13.2%, respectively, while for the sixth (20,000 $stems \cdot ha^{-1}$) a small increase of 8.3% was observed. These results underpin the variability in the yields, which are probably related to the site conditions, climate, and competition between individuals.

It is known that some broadleaved species show considerable variability in their ability to coppice which is associated with their ability to produce sprouts from dormant or adventitious buds or ligno-tubers [117, 200, 201]. Sims et al. [74] observed

Table 2 Energy plantations density, rotation, and cultural practices referred on literature (where C is control of spontaneous vegetation, F fertilisation, and I irrigation)

Genus	Country	Density	Rotation length	Rotation number	Cultural practices	Number of trials	Reference
Eucalyptus	Brazil	2380, 7142	2	1	F	4	[114]
Eucalyptus	Spain	2000	6	1	C,F	1	[37]
Eucalyptus	New Zeeland	2200	3	1	C	19	[75]
Eucalyptus	New Zeeland	2200	3	1,2,3,4,5	C	62	[74]
Eucalyptus	Australia	4000	3	1	F	2	[180]
Populus	UK	10,000	2,4	1,2	C	9	[101]
Populus	UK	10,000	3	1,2	C	32	[194]
Populus	Czech Republic	2222	4	1,2,3,4	C,F,I	48	[113]
Populus	Italy	6666	3	2	–	7	[179]
Populus	Italy	7140, 10,360	3	1	C,F,I	2	[111]
Populus	Belgium	10,000	4	1–4	C	1	[195]
Populus	Italy	14,100	2	1,2,3	–	5	[165]
Populus	Canada	18,000	4	1	None	4	[98]
Populus	Belgium	10,000	3	1,2	C,F,I	3	[21]
Populus	Belgium	10,000	4	1	C,F,I	2	[108]
Populus	Belgium	10,000	3	2	None	17	[108]
Populus	Belgium	10,000	3	2	C	2	[107]
Populus	Belgium	10,000	4	2	None	6	[107]
Populus	Italy	5000	3	2	F	1	[196]
Populus	Italy	5000	3	2	F	1	[196]
Populus	Spain	6666, 10,000, 13,333, 15,000, 17,316, 20,000, 25,000, 33,333	3	1	F,I	8	[39]
Populus	Italy	5900	3, 10	1,2	C,F,I	52	[109]
Populus	France	15,625	2	1	C,F,I	2	[197]
Populus	UK	4444, 10,000	5	1	None	3	[63]
Populus	UK	10,000	5	1	–	1	[92]

(continued)

Table 2 (continued)

Genus	Country	Density	Rotation length	Rotation number	Cultural practices	Number of trials	Reference
Populus	China	278, 4000	12	1	F	12	[103]
Populus	Spain	33,333	3	1	C,F,I	1	[198]
Populus	Italy	10,000	1, 2	1,2,3	–	10	[133]
Populus	Czech Republic	2222, 7407	3	5,6	None	16	[123]
Populus	France	7272	3	1	C	4	[174]
Populus	Belgium	20,000	4	1	None	1	[58]
Salix	USA	107,600	3	–	F, F,I	10	[175]
Salix	UK	10,000	3	1,2	C	32	[194]
Salix	Canada	17,000	3	1,2,3,4,5	C,F	5	[26])
Salix	Finland	20,000	6, 11, 19	1	F	6	[112]
Salix	Canada	18,000	4	1	None	10	[98])
Salix	UK	10,000	5	1	None	1	[63]
Salix	UK	10,000	5	1	–	1	[92]
Salix	Germany	14,800	3	1	–	5	[199]
Salix	Germany	13,200	2,3	1	C,I	6	[178]
Salix	Belgium	20,000	4	1	None	1	[58]

a wide variation in the ability to sprout of 19 *Eucalyptus* species and Dillen at al. [195] of 17 *Populus* clones. Furthermore, survival rates had considerable variations in both studies. As yield in energy plantations depends on density [75] the *Eucalyptus* species with higher densities were those that reached the higher yields [74], regardless of the rotation. The higher yields in the coppice regime can also be explained by the faster growth of the sprouts as their initial development takes advantage of the existing stump root system, thus not experiencing the plantation stress that the seedlings have to surpass [117, 200–202]. It is also known that the ability of a stump to resprout after successive harvests tends to decline. One or several factors can contribute to this decline: stump mortality due to competition, root mortality, disease infection of the cut surfaces, nutrient depletion of the soil, and variation of the tree ratios root/shoot [74, 117, 200, 201]. Thus, the better suited species for energy plantations, under the coppice regime, are those that are able to maintain stumps and root systems with high vigour, to resprout vigorously, and have sprouts with high growth rates, enabling in this way to have stands of high densities and yields [74].

Overall, *circa* 19% of the studies had no information (7%) or was not made (12%) the control of spontaneous vegetation, fertilisation, and irrigation. From the remaining 81% of studies, control of spontaneous vegetation was used in about 85% of the studies, fertilisation with or without control of spontaneous vegetation in 51%, and irrigation with or without spontaneous vegetation and fertilisation in

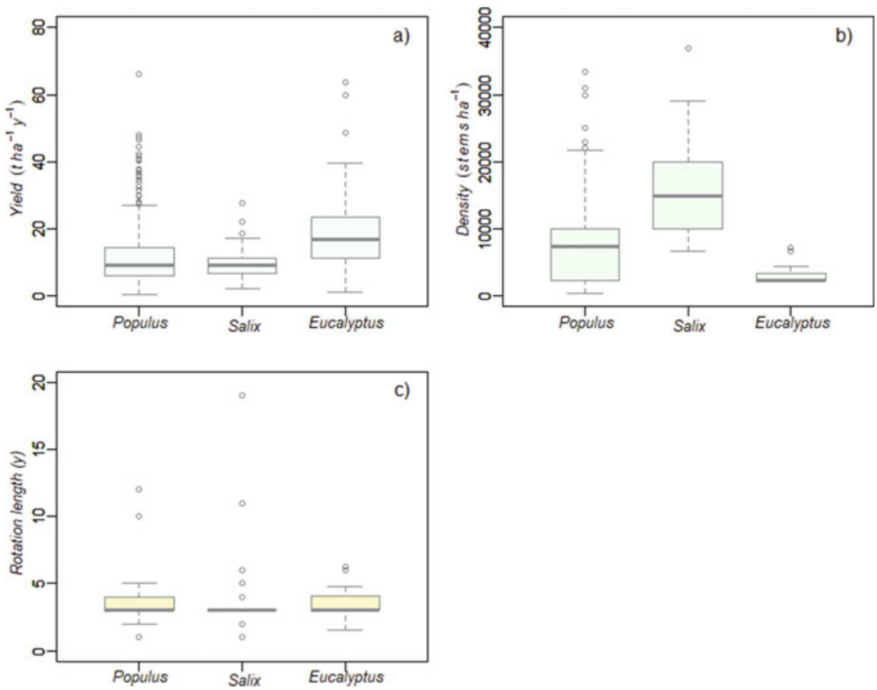


Fig. 7 Boxplots of yield, density, and rotation length

32%. The analysis per species revealed that for *Eucalyptus* spp., none of the trials was irrigated, in 60% control of spontaneous vegetation was done, in 36% control of spontaneous vegetation and fertilisation were used, and in 4% were fertilised. For *Populus* spp., 35% had control of spontaneous vegetation, 54% had control of spontaneous vegetation, fertilisation, and irrigation, 7% were fertilised and 4% were fertilised and irrigated. For *Salix* spp., in 61% control of spontaneous vegetation was made, 12% were fertilised, 12% were fertilised, and irrigated, 7% control of spontaneous vegetation, and fertilisation was made, and 7% control of spontaneous vegetation, and irrigation were used.

The large variability of yields of the energy plantations seems to be related to soil fertility (physical, and chemical characteristics) [58, 59]. The decrease in yields was also associated with the decrease in rainfall (the lower the site quality, and rainfall the lower the yield) [108, 113]. Another source of variability in yields is related to different mortality, growth rates, and patterns of the species, and clones [74, 75, 107, 108, 174].

4 Final Considerations

Energy plantations have an important role in the biomass for energy availability and may release pressure on other forest systems to supply bioenergy (*e.g.*, [2, 7]). Their advantages are related to their high yields [26], short rotations [12], worldwide availability [31], harvest flexibility through anticipated or delayed harvest [28, 33], and easy transportation, and storage [28].

The energy plantations are most frequently pure even-aged stands of high densities, and usually under coppice regime [1, 12, 21]. Many species can be used (*cf*. Table 1) although the most frequent, at least in Europe, are *Populus* spp., *Salix* spp., and *Eucalyptus* spp. [51, 53].

The selection of the site and management should be suited to the species or clones [1]. Soil and climate are of primordial importance to achieve high yields, and should be near the optimum of the ecological range of the species [12]. Management practices range from planting to harvest and include the selection of density, [12], rotation [109], harvest cycle [110], spatial arrangement [133, 135], plantations techniques [1], control of spontaneous vegetation [86], fertilisation [147], irrigation [163], control of pests, and diseases [86], and harvesting [136]. A wide range of species and management options exist, and the suitability of the species or clones to the site and management practices is of primordial importance to the optimisation of the yield.

Biomass estimation is frequently assessed with allometric functions. Due to the energy plantations' specificities, the existing functions resulted in biased estimations, especially the functions developed for high forest, and long production cycles [113]. Thus, allometric functions were developed for energy plantations (*e.g.*, [26, 174, 179]).

Moreover, yield has a trend towards the increase from the first to the second rotation, due to density increase; and a decrease from the third to the fourth rotation. Yet, the variability is high and contrasting results are found in the literature (*cf*. Sect. 3), which were related to site productivity and climate.

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