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Productivity model and reference diagram for short rotation biomass crops of poplar grown in Mediterranean environments

N. Oliveira [a,*], H. Sixto [a], I. Cañellas [a], R. Rodríguez-Soalleiro [b], C. Pérez-Cruzado [c]

[a] Dpto. Selvicultura y Gestión de los Sistemas Forestales, INIA-CIFOR, Madrid E-28040, Spain
[b] Unidad de Gestión Forestal Sostenible, Universidad de Santiago de Compostela, Lugo E-27002, Spain
[c] Chair of Forest Inventory and Remote Sensing, Georg-August-Universität Göttingen, D-37077, Germany

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ABSTRACT

A Reference Diagram (RD) was constructed for first rotations of the Euroamerican poplar 'I-214' grown as short rotation coppice (SRC). Data from 144 plots, established in eleven sites in Mediterranean environments, were used to develop the model. The density at establishment of the plantations ranged between 6666 and 33,333 stools ha^{-1}, covering the usual densities ranges used in short rotation forestry (SRF). The RD was based on a density-independent mortality model that relates the density of living stools to the average height of dominant shoot and the initial plantation density, and it includes a system of two simultaneously fitted equations relating a) quadratic mean basal diameter of dominant shoots to the average height of dominant shoot and the final density, and b) total above-ground woody dry biomass to quadratic mean basal diameter and final density. The iso-lines in the RD represented mortality, quadratic mean basal diameter of dominant shoots and total above-ground woody dry biomass at the end of a first rotation of three years. The final yield in terms of biomass ranged from 1 to 85 Mg dm ha^{-1}. The RD enables rapid and straightforward comparison of different situations, both at planting and at harvesting, and is a useful tool, based on a wide range of empirical data, for management and decision making regarding short rotation poplar crops.

1. Introduction

Woody biomass is a renewable resource that is suitable for getting different bioproducts, including bioenergy for different applications (heat, electricity or second generation biofuels) [1,2]. Use of woody biomass for bioenergy purposes represents a promising opportunity to contribute to the mitigation of climate change, to the extent that the presence of this resource may become important in the overall energy mix. The production and management of woody biomass may provide a new opportunity for economic development of rural areas [3] involving many different productive sectors.

Forestry crops represent one source of supply of woody biomass, which is characterized by its spatiality and

* *Corresponding author*. Tel.: +34 913 473579; fax: +34 913 572 293.
E-mail addresses: nerea.oliveira@inia.es, nereadeoliveirarodriguez@gmail.com (N. Oliveira).
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temporality [4]. Such crops can be established on both abandoned agricultural land and on marginal land. Short rotation woody crops under coppicing management (SRC), such as *Salicaceae* (*Populus* spp. or *Salix* spp.), are well represented in northern and central Europe and to a lesser extent in southern Europe [5–7]. Studies involving the production of these crops have revealed a wide range of biomass yield depending on different factors such as plant material, site characteristics, crop design (density and rotation), management regime, presence of pest and diseases, and survival after planting [8–10].

Plantation density is an important factor to be considered in SRC and has both production and economic implications. As tree density increases, the total yield rises initially in proportion to the number of plants per area if individual plants receive sufficient resources for growth. However, the specific density at which optimal production is attained has not yet been determined, although the range within which production remains constant is known [11]. Several experimental and commercial plantations have been established to test densities ranging from 1000 to more than 40,000 plants ha^{-1} [12–14].

Density Management Diagrams (DMDs) are used to graphically illustrate the relationships between density, yield and density dependant mortality at all stages of stand development [15], including concepts such as competition, site occupancy and self-thinning. These biological models are mainly used for decision-making in density management, for example to determine the post-thinning density or even to display and evaluate alternative density regimes in forest management [16]. There are many examples for different areas and species, such as *Pinus palustris* Mill. [16], *Quercus robur* L. [17] and *Pseudotsuga menziesii* (Mirb.) Franco [18]. However, as far we know, models relating the initial cutting density to yield, stool mortality or height and basal diameter growth for different developmental stages in SRC are scarce. Such models have been developed, e.g. for *Eucalyptus globulus* Labill. and *Eucalyptus nitens* (Deane and Maiden) Maiden, on the basis of plantations established at the usual range of initial forest densities used in southwestern Europe and managed in short rotations [19]. In SRC, density reduction is not a common management practice and because of the short rotation, these crops rarely reach self-thinning limits, so that the application of DMD will be severely limited. We have therefore applied the basic concepts used in the construction of DMDs to propose a Reference Diagram (RD) for SRC management. These models may play an important role in helping understand short rotation yield patterns in poplar plantations as adaptation of the models may assist in the assessment of energy yield potential, and optimum stand management in terms of density and rotations, as reported for eucalypts [19].

The SRC yield of poplar has been considered in many studies by the application of allometric equations that can estimate shoot biomass from basal diameter and shoot height, which must therefore be measured in sample plots [20–24]. As basal diameter growth is directly related to stool density, and height growth is more dependent on site properties and management [24], the development of whole crop yield models can provide estimation tools based on easily measured crop variables, particularly height and living stool density. However, as coppicing causes large changes in shoot density and growth rate, different sets of equations must be developed for the first and subsequent rotations. This is the most important factor limiting the application of process-based models to SRC [22]. Whole crop empirical statistical based models, which are powerful tools for estimating biomass, calculating economic gains and helping managers reach decisions about the timing of harvesting, are not yet available. A wide range of empirical data is required to enable development of such models [25].

The aim of the present study was to develop a whole crop model based on biomass, mean basal diameter and stool evolution as a function of mortality in a short rotation poplar crop, thus enabling subsequent development of a practical and dynamic adaptation of Density Management Diagram concept, that we call Reference Diagram. A further objective was to study the effect of initial density on biomass production at a rotation age of 3 years.

2. Materials and methods

2.1. Data

The study was carried out using data from a trial network of short rotation *Populus* plots established in 11 sites in Spain under Mediterranean conditions (Table 1). The clone selected for development of the DMD was 'I-214' (*Populus* × *canadensis* Moench), this clone is a hybrid between *Populus deltoides* Marsh and *Populus nigra* L. This is a well known clone widely planted in Mediterranean environments because of its high site plasticity and yield. This justifies use of 'I-214' as the reference clone in the trial plots for comparison of yield and other growth-related features. Data from 144 plots were available for fitting the base equations, these data were taken from three types of experimental plots in which the aim was to evaluate the clone effect, stocking rate and site by measuring variables related to production. Clone 'I-214' was used in all the experiments. As the trial design took competition effects into account, the plot size is large enough to ensure that the measured samples are not subjected to an edge effect. The trial plots include plantations ranging in surface area from 0.25 ha to 8 ha. Plots were established in early spring between 2005 and 2009, with 3–11 replications per site and plant densities. These densities ranged from 6666 cuttings ha^{-1} to 33,333 cuttings ha^{-1}.

Plantations were established using hardwood cuttings of 20–30 cm in length, planted in single rows 3 m apart, either by hand or by use of adapted planting machines. Similar management was applied, including fertilization during soil tillage according to the specific soil characteristics, pre-emergence treatment with oxyfluorfen (4 l ha^{-1}) to control weeds, and drip or flooding irrigation (to field capacity) during the summer months [26]. A rotation length of three years was established in all plots. In some (32) plots, trees were cut back to a height of 0.1 m one year after planting, to stimulate sprouting [27,28]. In these plots, root age was 4 and shoot age was 3 years (R4S3) at harvest time (Table 2). In the remaining plots (112), root age and shoot age were both 3 years (R3S3). In addition, 16 plots in the database had been already harvested once and