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To replant or to irrigate: A silvicultural decision model for afforestation projects

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ABSTRACT

This article develops an economic model that compares the option of replacement planting to maintain target density with the option of enhancing seedling survival from the beginning by applying irrigation. The model we develop uses variables common in forestry practice and yields the threshold value of seedling failure at which both alternatives offer the same economic result based on a comparative analysis of costs and benefits. By comparing this threshold with the level of seedling failure expected for an afforestation in the absence of irrigation, the planner can make an informed decision between both alternatives. The model has been applied to thirteen practical cases covering a wide range of plantations with different density, purpose and average annual net income. Based on the results obtained, a k-means clustering is carried out to identify five groups according to their suitability for irrigation. The sensitivity of the model's input variables in respect to the threshold of seedling failure is also analized. Irrigation is profitable when the expected level of seedling failure is high and/or the value of the threshold decision is low. The latter is usually the case at afforestations that require a low acceptable level of seedling failure and/or in productive plantation forestry.

1. Introduction

One of the main causes for the failure of seedlings or plants in afforestation projects developed in arid climates is drought stress (Burdett, 1990; Pinto et al., 2016). The importance and extent of this problem is not fully known, but data speak for themselves: Afforestation projects in arid or semi-arid climates often contemplate, already in their initial designs, a plant mortality rate above 30% (Chunfeng and Chokkalingam, 2006) or even above 40% (Çalişkan and Boydak, 2017). Such high mortality rates often require prolonged and expensive failure replantings. In Turkey, seedling replacement was applied to 0.30 of 0.87 million hectares afforested from 2002 to 2012 (Çalişkan and Boydak, 2017) and in Spain, it was applied to 0.86 of 5.09 million hectares afforested from 1946 to 2006 (Vadell et al., 2016). These data serve as illustrative examples of the problem we are going to address. As mentioned, traditionally, seedling failures in the early years after plantation establishment are replaced to ensure the original planting density is maintained. However, this strategy does not always yield adequate results, specifically if the economics of such replacement plantings are considered. Therefore, other complementary measures are taken, such as mulching (Peterson et al., 2009), hydrogels (Crous, 2016), tree shelters (Oliet et al., 2016), water harvesting (Prinz, 2001) and/or irrigation (Bainbridge et al., 1995; Bainbridge, 2007). This paper focuses on the most direct measure: irrigation.

1.1. Seedling irrigation or watering

Watering to ensure tree establishment is a common and well known practice in forestry and gardening. However, in regard to afforestation it is less common, though interest is slowly increasing because watering reduces or prevents seedling failures due to drought stress in arid zones and critical areas (Baker, 1955; Murphy, 1989; Bainbridge et al., 1995; Ruiz De la Torre et al., 1996; Grantz et al., 1998; Bean et al., 2004; Sánchez et al., 2004; Squeo et al., 2007; Bainbridge, 2007; Alrababah et al., 2008; Martínez de Azagra and Del Río, 2012).

Although conventional irrigation systems (surface, sprinklers or standard drips) may be used, other more specific procedures like subsurface localized irrigation systems are frequently applied because they are highly efficient in saving water: e.g. irrigation with vertical deep pipes stuck into the soil, horizontal drain tubes, irrigation with wicks, irrigation through porous walls or solar distillers (Martínez de Azagra and Del Río, 2012). As the seedlings per hectare to be irrigated are few,

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the water duty for the establishment of an afforestation is usually lower than 100 $\text{m}^3\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$, compared to 5000 $\text{m}^3\cdot\text{ha}^{-1}\cdot\text{year}^{-1}$, or more, for irrigated crops. Therefore, we speak of *micro-irrigation* or even *nano-irrigation*.

These types of irrigation differ substantially from those practised in agriculture. They do not seek to maximize production but just the establishment of woody vegetation: trees or shrubs that are well adapted to the site and that –once they have taken root– thrive and develop autonomously without needing permanent watering. For that reason, and according to our judgement, in the forestry the term "watering" is more appropriate than "irrigation". It should be also noted that this type of sporadic watering in such low doses does not cause salinization nor modifies the water level in aquifers.

Apart from the fact that water is almost always a scarce resource in drylands, economic aspects are crucial when planning watering for afforestations, as the unit costs of some watering systems may even be higher than the price of the plant to be watered (Del Río et al., 2013). One option is to resort to economic evaluation methods, such as cost-benefit analysis (Hanley and Spash, 1993; Hawkins et al., 2006; Birch et al., 2010), a cost effectiveness analysis (Macmillan et al., 1998; Pywell et al., 2007; Ahtikoski et al., 2010; Wainger et al., 2010), or avoided-cost models (Donovan and Brown, 2008; Snider et al., 2006; Beecher, 1996), in order to choose between the different alternatives and technological options suitable for an afforestation project (Löf et al., 2012; Robbins and Daniels, 2012). The development of decision support models that consider the economic data to be taken into account when planning a plantation poses a big challenge to forestry research (Segura et al., 2014; Nobre et al., 2016). These decision making systems are especially interesting when the available economic resources are scarce (Miller and Hobbs, 2007) and when new afforestation support techniques are applied, e.g. seedling watering systems (Table 1).

1.2. Decision support models in silviculture

There is a long tradition in forestry related to the use of decision models in silviculture, beginning with the classic work of Faustmann in 1849, who determined the most profitable rotation. Faustmann's was the first long term decision model, and it has been followed by many more that we can refer to in numerous works (Kangas and Kangas, 2005; Gilliams et al., 2005; Johnson et al., 2007; Reynolds et al., 2008; Díaz-Balteiro and Romero, 2008; Hanewinkel, 2009; Gardiner and Quine, 2000; Pasalodos-Tato et al., 2013; Borges et al., 2014; Segura et al., 2014; Bare and Weintraub, 2015; Nobre et al., 2016; Grêt-Regamey et al., 2017). These models have evolved in order to adapt to the new drivers and goals of forestry management (Vacik and Lexer, 2014; Masiero et al., 2015; Nobre et al., 2016). They are helpful when it comes to making silvicultural decisions in the course of the entire production cycle, from pre-commercial thinning to pruning and/or other tending treatments. They seek to optimize production and/or productivity on the treated stands (Martell et al., 1998; Hyytiäinen et al., 2006). These models meet the demands of silviculture along the whole cycle but face a strong uncertainty regarding the future behaviour of economic variables and tree growth, which may be considerably altered by natural hazards (Weintraub and Romero, 2006; Pasalodos-Tato et al., 2013; Rönnqvist et al., 2015; Rinaldi et al., 2015).

These considerations have led other researchers to develop short-term decision support models (Macmillan et al., 1998; Snider et al., 2006; Ahtikoski et al., 2010; Wainger et al., 2010; Donovan and Brown, 2008; Beecher, 1996, among others). They diminish the uncertainty of their predictions while remaining closer in time to the moment of stand establishment (Lexer et al., 2005). They focus on survival and juvenile tree growth arguing that achieving these short-term goals means meeting long-term goals as well. Supporters of the first models consider this view too simplistic (Beecher, 1996; Wainger et al., 2010; Uotila et al., 2010). They warn that this approach can lead to wrong or sub-optimal decisions (Pukkala, 1998; Thorsen and Helles, 1998) and handicap economic returns (Eid, 2000; Duvemo and Lämås, 2006; Mechler, 2016).

In order to mitigate this restriction a third group of researchers (Mason et al., 1997; Richardson et al., 2006; Mason and Dzierzon, 2006; Djanibekov and Khamzina, 2016; Pasalodos-Tato et al., 2016, among others) has opted for prolonging the short-term effect of tending

Table 1
Brief description of some micro-irrigation systems for seedling plantation.

Irrigation system	Description	Price (d)	Sources
Deep pipes	Short and small vertical plastic tubes (length about 0.50 to 1.0 m; diameter ≈ 0.05 m) or hollow plant stems (*Arundo, Bamboo*, etc.) driven into the soil down to root depth.	0.93 €·unit^{-1}	①, ③, ⑨
Konkom distillers	Two reused PET bottles with different diameters, conveniently cut and assembled to form the distiller.	0.86 €·unit^{-1}	⑤, ⑨
Porous capsules	Small and closed receptacles of clay (volume $V \leq 0.5$ L) with one or two entrances, to be connected to an irrigation line.	1.07 €·unit^{-1}	④, ⑨
Buried clay pots	Medium to large sized (volume $V \in (1,10)$ L) clay containers; individual watering.	2.24 €·unit^{-1}	②, ⑨
Perforated pipes	Horizontal drain tubes (simple PVC pipelines without envelope) buried down to root depth (approx. 0.5 m to 1.0 m).	2.47 €·m^{-1}	①, ⑨
Plastic bottles with wicks	Any reused container connected to a wick. The seedlings are fed by capillary wicking from a PET bottle.	0.79 €·unit^{-1}	④, ⑨
RIES®	Reused PET bottle with two plastic fibre filters inserted at different heights.	2.90 €·unit^{-1}	⑥, ⑨
Ecobag®	Closed container with a shape like a collar pillow, 20 L capacity; delivering water through a felt.	4.11 €·unit^{-1}	⑦, ⑨
Waterboxx®	Cylindrical PP bucket with 15 L capacity and a ribbed upper funnel that collects rainfall (and sometimes, under special circumstances, horizontal precipitations); water delivery through a wick.	4.89 €·unit^{-1}	⑧, ⑨

Remarks:
Price (d) includes the cost of acquisition, preparation and installation of the watering system at the site to be reforested.
Hourly wage: 5.50 € (taxes not included).
The price for the Waterboxx® considers a three time use.
® Protected by patent rights.
Sources:
① Plastic pipe catalogues.
② Prices of unglazed terracotta.
③ Sánchez et al. (2004).
④ Bainbridge (2002) and Vargas Rodríguez (2012).
⑤ Konkom (Kondenskompressor).
⑥ RIES® (*Reservorios Individuales de Exudación Subterránea*).
⑦ Eco Bag® http://www.ecobagindustries.com.au/.
⑧ Waterboxx® http://www.groasis.com/.
⑨ Martínez de Azagra and Del Río (2012).