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

(**General comments.** Thank you for your rapidity and carefully review! We are amazed with the accuracy and quality of the design work. In addition, we think this is not a easy article to design due to the quantity and complexity of tables. We have seen the result of the proof and we have some suggestions on the position of the tables in the manuscript, but you are the experts in layout. Again, thank you very much! Do not hesitate to contact us, if you think we can help you in this process. Best regards, The authors.)

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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.

Keywords: ~~s~~Seedling survival; ~~d~~Dryland; ~~t~~Tending; ~~e~~Economic threshold; ~~m~~Micro-irrigation

~~1.~~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.~~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., 2004a, 2004b~~ (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, the water duty for the establishment of an afforestation is usually lower than $100\,m^3 \cdot ha^{-1} \cdot year^{-1}$, compared to 5~~,~~000 $m^3 \cdot ha^{-1} \cdot year^{-1}$, 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. (The suggested placement of table 1 is here, before section 1.2.)

~~1.2.~~ 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 suboptimal 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 treatments by using growth models. This way they can classify the alternatives with the help of long-term economic indicators. This approach integrates the short and long-term visions into decision making related to production, but does not do the same for the establishment of afforestations. The reason is that the most profitable techniques do not guarantee the initial success of seedling establishment. Failings may make necessary extensive and prolonged replanting (Ahtikoski et al., 2010) that will delay the success of an afforestation. The delay might cause a failure to comply with legal, financial, or technical requirements or schedules, or even lead to the failure of the afforestation project itself (Zhou, 1999; Löf et al., 2012).

The decision model we develop in this paper makes feasible both a short-term and a long-term approach. It focuses on a specific problem that affects the initial success of plant establishment: preventing seedling failure in afforestations due to drought stress by using watering as tending treatment.

The paper's main goal is to develop and validate a decision model based on economics that helps to choose the best of the following two solutions: replacement planting or seedling watering. As additional goals we have considered: i) applying the model to different types of afforestation projects to find out in which cases watering is more competitive than replacement planting, ii) evaluating the uncertainty and sensitivity of the model~~’~~'s input variables.

~~2.~~2 Materials and ~~M~~methods

~~2.1.~~2.1 Description of the MThreshold Model

The model compares two alternatives (watering or replacement planting) and yields the threshold value (M) that equals them from an economic point of view (Eq. (1)).

The cost-benefit analysis of both alternatives under study requires:

a) A specification of the cost-benefit equations for each option, considering only those elements that differ: watering costs (first element), plant replacement costs (second element), and the difference between the expected benefits (third element), (Eqs. (2) to (4), respectively).

b) Discounting the economic value of each option at the end of each term to its present value using an annual interest rate ($i =$ constant).

c) Establishing a replacement planting strategy for the second alternative (Eq. (5)). The usual procedure is replacing dead plants with new seedlings, which are placed next to the failure. This practice is repeated annually, until a plant density is achieved that meets the acceptable level of seedling failures (ALF).

For a given plantation density ρ and a failure level M referring only to the first year that seedlings grow under open field conditions, the failed seedlings that have to be replaced each year j follow a geometric progression with common ratio M ($\rho \cdot M^{j-1}$). When the year~~’~~'s failed seedlings are less or equal to the required tolerance ($M^{j-1} \leq ALF$), replacement is stopped. Eq~~uation~~. (5) shows this replanting strategy as referred to the last year in which failed seedlings would have to be replaced (year $j = N$).

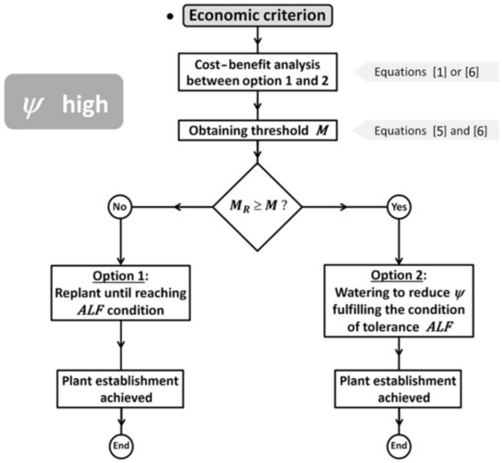
Once the value of M has been obtained (in per unit, $0.0 \leq$ ~~?~~? (Delete symbol ?)~~?~~ $M \leq 1.0$), an informed decision can be made: if the expected level of seedling failure for a given afforestation (M_R) surpasses the threshold M, watering will be a better option than failure replanting. In the opposite case, we recommend resorting to the traditional technique of replacing failed seedlings.

$$\text{Decision rule}: \begin{cases} \text{if } M_R \geq M & \rightarrow \text{ Watering} \\ \text{if } M_R < M & \rightarrow \text{ Replacement planting} \end{cases}$$ A1

Annotations:

A1. Is it possible to adjust equation to the width of one the column?

Fig~~ure~~. 1 shows this decision rule combined with the model in a flow diagram. (The placement figure 1 is correct, before equations, section, but in the proof we don´t see the same result.)



~~Figure 1~~Fig. 1 Flowchart of the economic decision model based on variable *M*. **(Caption is in original word file "Figure1": Fig. 1** Flowchart of the economic decision model based on variable *M*. For tending treatments other than irrigation the procedure is quite similar to that proposed in this paper. The only difference lies in the cost-benefit equations, which have to be specified for each case. The meaning of the acronyms in Table 2.)

alt-text: Fig. 1

The five equations of the model are:

$$\text{Cost − benefit comparison of both alternatives : } {}^{\textbf{A1}} C_{wat} \leq C_{rep} + \Delta B \qquad \textbf{(1)}$$

(We think "Cost-benefit comparison of both alternatives:" must be out of equation editor, like a normal text style)

$$\text{Watering costs : } {}^{\textbf{A2}} C_{wat} = h \cdot d \cdot \rho + \rho \cdot {}^{\textbf{A3}} \sum_{j=1}^{j=n_{ri}} \frac{w_j \cdot NR_j}{(1+i)^{j-1}} \qquad \textbf{(2}$$

(We think "Watering costs:" must be out of equation editor, like a normal text style))

$$\text{Plant replacement costs : } {}^{\textbf{A4}} C_{rep} = \rho \cdot {}^{\textbf{A5}} \sum_{j=2}^{j=N} \frac{c_j \cdot M^{j-1}}{(1+i)^{j-1}} + \sum_{j=2}^{j=N} \frac{a_j + b_j \cdot \rho \cdot M^{j-1}}{(1+i)^{j-1}} \qquad \textbf{(3}$$

(We think "Plant replacement costs: "must be out of equation editor, like a normal text style))

Annotations:

A1. "Cost-benefit comparison of both alternatives:" must be out of equation editor, like a normal text style

A2. "Watering costs:" must be out of equation editor, like a normal text style

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A4. "Plant replacement costs:" must be out of equation editor, like a normal text style

A5. Italic

Difference between the expected benefits for each option:

$$\Delta B = BI_{PV} + LP_{PV} = R \cdot \left[\sum_{j=e-\epsilon}^{j=e-1} \frac{1}{(1+i)^{j-1}} + \sum_{j=e}^{j=e+N-2} \frac{M^{j-e+1}}{(1+i)^{j-1}} \right] \qquad \textbf{(4)}$$

$$\text{Replacement planting strategy : } l^{\textbf{A1}} \geq \frac{\ln ALF}{\ln M} \qquad \textbf{(5}$$

(We think "Replacement planting strategy:" must be out of equation editor, like a normal text style))

Annotations:

A1. "Replacement planting strategy:" must be out of equation like a normal text style

Table 2 includes all symbols and their meaning. The terms of the cost and benefit equations are explained in detail in Appendix A. (The suggested placement of table 2 is here, after "....Appendix A")

Eq~~uations~~s. (2), (3) and (4) are replaced in (Eq. (1)), resulting in the following inequality:

$$h\cdot d\cdot \rho + \rho\cdot \sum_{j=1}^{j=n_{ri}} \frac{w_j\cdot NR_j}{(1+i)^{j-1}} \leq \rho\cdot \sum_{j=2}^{j=N} \frac{c_j\cdot M^{j-1}}{(1+i)^{j-1}} + \sum_{j=2}^{j=N} \frac{a_j + b_j\cdot \rho\cdot M^{j-1}}{(1+i)^{j-1}} + R\cdot \sum_{j=e-\epsilon}^{j=e-1} \frac{1}{(1+i)^{j-1}} + R\cdot \sum_{j=e}^{j=e+N-2} \frac{M^{j-e+1}}{(1+i)^{j-1}} \tag{6}$$

Annotations:

A1. Italic

A2. Italic

Together with (5), this inequality (6) forms a system of diophantine inequations with two unknown variables (M and N). The pair of values (M, N), that satisfies both expressions defines the solution of the problem. The main output variable of the model is the threshold value M. The second variable (N) may also influence the decision. The value of N becomes interesting when we have information about how many times it is necessary to replace the failed seedlings on the studied area in order to have a plantation with the desired target density.

~~2.2.~~2.2 Calculation assumptions

The model starts from the assumptions shown in Table 3. The first four have general validity (i.e., they are inherent to cost-benefit analysis and to seedling planting projects), while the other six are more specific (i.e., they adjust to the most common afforestation conditions, but can be ignored or modified in order to adapt them to a particular situation). (The proposed placement of table 3 is here, before section 2.3)

~~2.3.~~2.3 Case studies

We apply the model to thirteen illustrative dryland afforestation projects that cover an ample range of different types of plantation, selected by the authors based on Ingles et al. (2002), FAO (2005), Batra and Pirard (2015) and our own experience. Each case study is defined by a specific purpose, a forest site quality, a slope gradient, species selection, soil preparation and an expected future income (Table 4). Other more numerical attributes to describe each case are: initial afforestation cost (C), planting density (ρ), acceptable level of seedling failure (ALF), average annual net income (R) from a certain year onwards (e), and watering costs (C_{wat}). (The proposed placement of table 4 is here, after "watering costs (C_{wat}).")

For each case study, values suitable in Spanish forestry for the entry parameters have been used (columns 3 to 10 of Table 5). The meaning of these parameters is described in detail in Appendix A and in Table 2. For all cases, the same watering system has been considered: manual watering through a vertical deep pipe stuck into the soil next to each seedling; a commercial polyethylene pipe (PE) with 32 mm diameter and a length of 500 mm; watering during the first year as follows: $d = 0.93$ €·plant^{-1}; $w = 0.005$ €·L^{-1}; $NR = 6.4$ L·plant^{-1}·year^{-1}; and $n_{ri} = 1$ year (~~Sánchez et al., 2004a, 2004b;~~Sánchez et al. 2004; Del Río et al., 2013, 2016). In order to shorten our presentation and for all cases, we consider that, due to watering, the average annual net income (R) will start two years earlier ($\varepsilon = 2$ years). The interest rate has been established at 4%, which is a common rate applied to the public funding of dryland restoration projects in EU (European Comission and European Investment Bank, 2016), and at 10% for developing countries and REDD projects (Graham et al., 2016). The acceptable level of seedling failure has been set in accordance with the technical specifications defined for each plantation project. When resolving the system of Eq~~uations~~s. (5) and (6), we obtain the values of M and N for each case study (last two columns of Table 5). (The proposed placement of table 5 is here, after "study (last two columns of Table 5).")

Next, we have grouped the studied cases according to their suitability for watering. The unsupervised learning algorithm used is k-means clustering with running means based on the values of M and ALF. The number of groups has been established by elbow rule (Tibshirani et al., 2001). Calculations have been done with SPSS software (IBM Corp. Released 2011. IBM SPSS Statistics for Windows, Version 20.0. Armonk, NY: IBM Corp.).

~~2.4.~~2.4 Sensitivity analysis procedure

For a better use of the model it is advisable to identify the input variables that most influence on the main output variable (M), and to analyze the effect on M of possible uncertainties of these input variables, by means of a global sensitivity analysis (Sobol", 2001 (Sobol', 2001); Saltelli, 2002; Saltelli et al., 2010). Calculations are made using the software SimLab (Joint Research Centre of the European Commission. Released 2008. SimLab, Version 2.2.).

In this paper, we rely on the thirteen case studies we have analyzed to establish the variable's range, i.e., the variation interval for each variable. These intervals, or individual values, are shown in Table 6. Table 1 offers data to determine the range of variable d (the unit cost of different watering systems). The number of years during which it is advisable to apply additional watering to the seedling until it is established (n_{ri}) are usually few; therefore, the corresponding interval is $n_{ri} \leq 5$. In fact, in most cases it is sufficient to water the plants only during the first year ($n_{ri} = 1$), except in those environments where the natural regeneration of species usually fails for several consecutive years (semiarid climates or critical areas). The price of the watering water (w) varies considerably from one site to another, but the range considered covers almost all possible situations ($0 \leq w \leq 0.1$ €·L^{-1}). An ample interval has also been used for the individual annual water supply ($5 \leq NR \leq 100$ L·plant^{-1}·year^{-1}).

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

alt-text: Table 1

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: (end line before remarks section)
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. (2004a, 2004b)
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)

~~Table 2.~~**Table 2** Notation.

alt-text: Table 2

Symbol	Meaning
a, a_j	Constant term of the linear equation to determine Cm in year j {€.ha^{-1}}
ALF	Acceptable level of seedling failure {in per unit}
b, b_j	Slope of the line used to determine Cm in year j {€.plant^{-1}}

BI_j, BI_{PV}	Early gains in year j, Early gains due to the use of irrigation updated to current value {€.ha^{-1}}
c, c_j	Unit price of the seedlings {€.$unit^{-1}$}
C	Initial afforestation costs (when equal for both considered alternatives) {€ ha^{-1}}
C_m	Costs of the replanting works (soil and site preparation, etc.){€.ha^{-1}}: $Cm_j = a_j + b_j \cdot \rho \cdot M^{j-1}$
C_{rep}	Total replanting costs for failed seedlings {€.ha^{-1}}
C_{wat}	Total irrigation costs {€.ha^{-1}}
d	Average price per unit of an irrigation system (including installation costs) {€.$plant^{-1}$}
e	Year in which the plantation begins to be productive without irrigation {year}
h	Difficulty (hardness degree) related to installing an irrigation system. Normally: $h \in (0.75, 1.5)$ {unitless}
i	Discount rate {in per unit}
j	Subscript denoting the order number of a year ($j = 1$ is the year of afforestation) {unitless}
LP_j, LP_{PV}	Lost profit in year j (due to a delay in the obtention of benefits ~~),~~), Lost profit updated to current value {€.ha^{-1}}
M	Threshold of seedling failure (for which the costs of the two considered alternatives match: with/without irrigating) {in per unit}: $0.0 \leq M \leq 1.0$
M_R	Expected level of seedling failure (without irrigation) {in per unit} (mean value)
n_{ri}	Number of years during which the seedlings are irrigated {unitless}: $n_{ri} \geq 1$
N	Last year of beating up (i.e. replanting dead seedlings) {unitless}: $N \geq 1$
NR, NR_j	Annual amount of water supplied to each seedling by irrigation {L.$plant^{-1}$.$year^{-1}$}, (in year j)
PV	Subscript denoting cost discounted to present value {unitless}
R	Average annual net income {€/ha}of a forest at age e (including direct and indirect benefits) {€.ha^{-1}}
w, w_j	Irrigating costs per unit (depending on water application expenses and on the price of the water) {€.L^{-1}}, (in year j)
ΔB	Difference between the benefit resulting from irrigating and the benefit when replacing failed seedlings {€.ha^{-1}}
ε	Number of years by which production is accelerated due to irrigation {unitless} $\varepsilon \ll e$
μ	Level of seedling failure due to causes other than water stress: deficient site preparation works; abiotic damages; herbivory; etc. {in per unit} (mean value)
ρ	Initial plantation density {number of seedlings per hectare; or number of seeding points per hectare}
ψ	Level of seedling failure due to water stress {in per unit} (mean value): $M_R = \psi + \mu$ [7]
€	Euro, official currency of the eurozone

Table 3 Assumptions of the MThreshold Model.

alt-text: Table 3

Number	General assumptions
1	Failure replanting and irrigation are perfect substitute goods; the investor is risk neutral. Marginal rate of substitution equal to one.
2	From an economic point of view, the initial plantation density fixed by the project engineer (ρ) is appropriate as it takes into account both the direct and the indirect benefits of the future forest.

3	With regard to the final density of the afforestation, a certain failure tolerance (*ALF*) is accepted. This does not affect the established economic objective.
4	The value of the expected total seedling failure (M_R) for an afforestation site is known or can be estimated.
	Specific assumptions (It is a subtitle section in table like "General assumptions" Is there any way to highlight it? maybe line up the left, in the column titled "Number")
5	The initial afforestation costs (*C*) are the same with and without irrigation.
6	The failure replanting strategy consists in replacing all failures during the first *(N-1)* years with new and equivalent seedlings, until the final density fulfills the required tolerance (*ALF*).
7	The target woodland produces a constant annual net income (*R*) from a certain year (*e*) onwards. This date can be brought forward or backward depending on the chosen option of afforestation.
8	Seedling failure due to causes other than water stress (herbivory, competition or others) is lower than the established tolerance (*ALF*).
9	When using irrigation, seedling failure due to water stress will not occur.
10	Significant numbers of failures will only occur during the seedlings' first year in the afforested area, being water stress its most common cause.

Table 4 Considered case studies. (We think it is difficult, but is it possible to get the layout of the table 4 fit on one page?)

alt-text: Table 4

Number	Case	Purpose	Forest site	Slope gradient	Species	Soil preparation	Income aspects	Source
1	Commercial timber plantation	Production of commercial timber	Premium quality	~~Less than~~ ≤10%	Commercial timber species (*Juglans* spp.)	Ploughing or ripping	Estimated mean production: 13 $m^3.ha^{-1}$ and selling price is 500 €$.m^{-3}$	Muncharaz (2012); Molina et al. (2014)
2	Habitat restoration plantation	To increase the available forest habitat and improve its connectivity with the landscape	Low quality	~~Less than~~ ≤30%	Conifer or oak	Contour ripping	Only the received income fraction has been considered and the indirect benefits have not been taken into account	Consejería de Medio Ambiente (2005)
3	Multifunctional plantation	Multifunctional	Low quality	10 to 30%	Mixed conifer/broadleaved	Ripping or ploughing	The annual net income (*R*) is comparable to the mean direct (productive) plus indirect (environmental and recreational) benefits established for Spanish forests	Ministerio de Medio Ambiente y Medio Rural y Marino (2011)
4	Afforestation of agricultural land	Marginal parcel for agriculture	Low quality	Flat	Mixed conifer/broadleaved	Ripping a flat	Mean direct (productive) plus indirect (environmental and recreational) benefits	Ministerio de Medio Ambiente y Medio Rural y Marino (2011)
5	Fruticulture	Production of almonds	Premium quality	~~Less than~~ ≤10%	Almond tree	Full ploughing	Estimated production: 1000 $kg.ha^{-1}.year^{-1}$ of almonds with shell	Socias and Couceiro (2014)
6	Truffle cultivation	Production of *Tuber nigrum*	Premium quality	~~Less than~~ ≤10%	Broadleaved trees (*Quercus* spp.) mycorrhized with *Tuber nigrum*	Ripping or ploughing	Production: 20 $kg.ha^{-1}.year^{-1}$. The considered producer price is 300 €$.kg^{-1}$	Morcillo et al. (2015)
7	Non-wood forestry goods (fungi)	Marketable fungi	Medium quality	~~Less than~~ ≤10%	Inoculated seedlings with edible fungi (*Boletus* spp. and/or others)	Ploughing or ripping	The estimated production of marketable fungi is 30 $kg.ha^{-1}.year^{-1}$ and the estimated selling price 12 €$.kg^{-1}$	Martínez-Peña et al. (2011); Ministerio de Medio Ambiente y Medio Rural y Marino (2011); Díaz Balteiro et al. (2013)
8	Extensive xeriscaping	Woodland for recreational use on terrain with a high visual exposure	Low quality	Steep slopes >30%	Mixed conifer and broadleaved plantation	Bench terraces built with a walking excavator	Recreational value	Ministerio de Medio Ambiente y Medio Rural y Marino (2011)
9	Plantation in a critical area	Critical areas where afforestation using classical techniques fails	Low quality	Steep slopes >30%	Conifer plantations (native pines)	Bench terraces built with a walking	Mean indirect benefits	Ruiz De la Torre et al. (1996); Ministerio de Medio Ambiente y Medio Rural y

		due to water stress				excavator		Marino (2011)
10	Windbreak	Protection in all directions of herbaceous crops that are sensitive to wind	Medium quality	~~Less than~~ ≤10%	Mixed windbreak screen of conifers and broadleaved seedlings	Ripping a flat parcel	Avoided loss of crops	Peri and Pastur (1998); Peri and Bloomberg (2002)
11	Protection of hydraulic infrastructures	Forest and hydrologic restoration works on the headwaters of a watershed to protect a reservoir	Low quality	Difficult to access, high gradient terrain >50%	Conifer	Digging holes with a walking excavator on impoverished	Avoided loss	Catalina and Vicente (2001); Ministerio de Medio Ambiente y Medio Rural y Marino (2011)
12	Protection of road infrastructures	Sustainment and stabilization of a highway bank slope	Low quality	Steep slopes >30%	Conifer	Preliminary brushing out and soil treatment by manual hole digging	Avoided cost of a one-hour traffic interruption caused by an unstable highway bank slope. Calculations based on a highway with a mean traffic intensity of 1000 vehicles.h~~-~~$^{-1}$ and a trip cost of 4.7 €.h~~-~~$^{-1}$	García-Viñas et al. (1993); Salado and Astals (2010); Ministerio de Fomento (2014)
13	Protection of rail infrastructures	Sustainment and stabilization of a railway bank slope	Low quality	Steep slopes >30%	Conifer	Manual hole digging	Avoided cost of the refunding of a rail ticket as a compensation for a delay caused by the blockage of the rails due to an unstable railway bank slope. Calculations based on a train with a capacity of 400 passengers, a 60% occupancy rate and an average ticket price of 60 €	García-Viñas et al. (1993); Salado and Astals (2010); Fernández and Vázquez (2012)

Note: These case studies are established to obtain a wide vision about plantations for the model MThreshold. They should not be interpreted as precise or local afforestation methods.

Table 5 Input data and results of the model for the considered plantation designs.

alt-text: Table 5

Case	Number	*a*	*b*	*c*	*ρ*	*ALF*	*R*	*e*	*i*	*C*	*M*	*N*
Commercial timber plantation	1	60	0.53	0.49	1600	0.3	2500	41	0.04	1692	0.300*	1
Habitat restoration plantation	2	60	0.53	0.3	800	0.3	60	61	0.04	724	0.625	3
Multifunctional plantation	3	80	1.3	0.3	1100	0.3	287	21	0.04	1840	0.386	2
Afforestation of agricultural land	4	60	0.53	0.41	800	0.3	287	21	0.04	812	0.508	2
Fruticulture	5	60	0.53	1	2315	0.03	5000	11	0.04	3602	0.030*	1
Truffle cultivation	6	60	0.53	6	400	0.03	5000	21	0.1	2672	0.030*	1
Non-wood forestry goods (fungi)	7	80	1.3	0.62	1600	0.03	650	21	0.04	3152	0.196	3
Extensive xeriscaping	8	80	1.3	0.62	1100	0.03	1500	41	0.04	2192	0.137	2
Plantation in a critical area	9	90	1.75	0.3	800	0.3	135	21	0.04	1730	0.337	2
Windbreak screen	10	20	0.63	1	2500	0.03	1100	21	0.04	4095	0.240	3
Protection of hydraulic infrastructures	11	90	1.75	0.3	1600	0.03	2823	21	0.04	3370	0.030*	1
Protection of road infrastructures	12	90	1.75	0.3	400	0.03	4700	5	0.1	910	0.030*	1
Protection of rail infrastructures	13	90	1.75	0.62	400	0.03	12,000	5	0.1	1038	0.030*	1

Data sources: *a, b, c, ρ, ALF, R, e:* Values based on the references shown on Tables~~table~~ 1 and 4.

Monetary unit: euro (€) (Only one end line before data sources section. The style of the lines of equations in the table is very different from the main text and is also very spaced and with lines. Is it possible to eliminate these separation lines and improve this aspect of the table?)

h = 1.0

$C = a + (b + c) \cdot \rho$ (7 **(It is [8]. [Eq 7] is in table 1, penultimate row.)**~~[8]~~)

(*) The inferior limit of *M* is *ALF*, a situation in which failure replacement is not necessary; $N = 1$.

Table 6 Range of the model~~'~~'s input variables and their effect on the value of *M*. (table 6. We are not sure if the result is attractive and clear. but can it be adjusted to a column layout?)

alt-text: Table 6

Variable	Unit	Intervals (limits between brackets) or individual values	S_i	S_{Ti}	*Effect*
a	€.ha$^{\cancel{-}-1}$	(60,90)	0.00	0.00	(0)
ALF	in per unit	(0.00,0.30)	0.01	0.02	(+)
b	€.plant$^{\cancel{-}-1}$	(0.50,1.75)	0.01	0.01	(~~-~~–)
c	€.plant$^{\cancel{-}-1}$	(0.2, 10.0)	0.16	0.18	(~~-~~– ~~-~~–)
d	€.plant$^{\cancel{-}-1}$	(0.75,5.0)	0.05	0.08	(+)
e	year	5,20,40,60	0.04	0.18	(+ +)
h	unitless	(0.75,1.50)	0.01	0.02	(~~-~~–)
i	in per unit	(0.00,0.15)	0.05	0.15	(+ +)
n_{ri}	unitless	1,2,3,4,5	0.03	0.05	(+)
NR	L.plant$^{\cancel{-}-1}$.year$^{\cancel{-}-1}$	(5.0,100.0)	0.05	0.09	(+)
R	€.ha$^{\cancel{-}-1}$	(30.0,12,000.0)	0.18	0.35	(~~-~~– ~~-~~–)
w	€.L$^{\cancel{-}-1}$	(0.0,0.1)	0.08	0.12	(+ +)
ε	year	0,1,2,3 4	0.01	0.08	(~~-~~–)
ρ	plants.ha$^{\cancel{-}-1}$	(200,2500)	0.04	0.12	(~~-~~– ~~-~~–)

Values and intervals based on case studies, Tables~~table~~ 1 and 4 and expert knowledge.

Effect: (+): *M* increases when the variable~~'~~'s value does it, and (~~-~~–): *M* decreases when the variable~~'~~'s value increases. The variables that most influence *M* are identified with a double addition or subtraction sign. The sign (0) indicates that the variable has almost no effect on *M*.

The value given to the effect each input variable has on the output variable *M* is based on the variances S_{Ti} and S_i (Sobol, 2001 (Sobol', 2001)).

~~3.~~3 Results

The first and main result of this paper is the decision support model MThreshold itself. By means of a system of two inequations [Eqs. (5) and (6)] with two unknowns, (variables *M* and *N*) the model answers the question of when it is profitable, from an economic point of view, to irrigate seedlings in order to avoid failures, instead of not irrigate them and carrying out replacement planting during a number of years to maintain the target density.

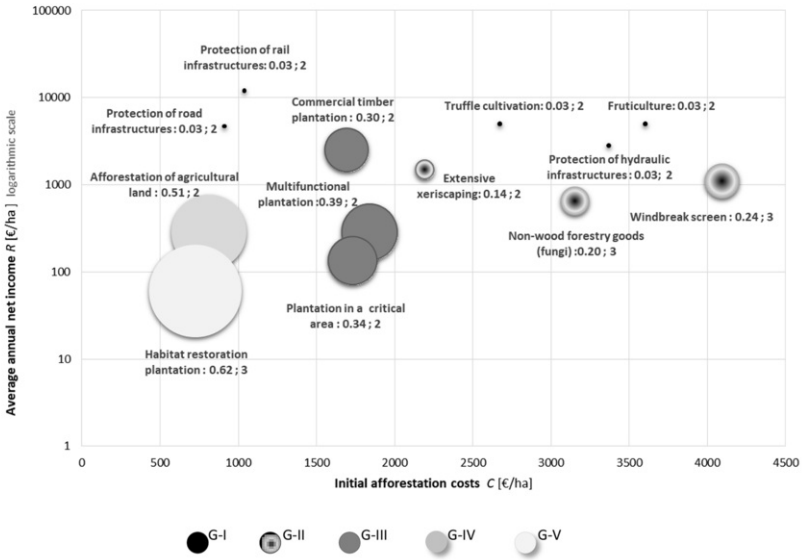
~~3.1.~~3.1 Model application results

The model has been applied to thirteen case studies; results are shown in the last two columns on the right side of Table 5.

The threshold value marking the limit between the two options, watering and replacement planting (main output variable *M*), varies significantly from case to case. The lowest decision threshold *M* is that obtained for protection of hydraulic, road and rail infrastructures, fruticulture and truffle cultivation: 0.03 (in per unit). From that value onwards, watering is the economically more advantageous option. This value rises up to 0.625 (in per unit) in habitat restoration plantations. In timber plantations, intermediate values of M are obtained, 0.30 (in per unit). On the other hand, the last year (N) in which failures have to be replanted in order to reach the plant density that satisfies the acceptable level of seedling failure (*ALF*), varies between one and three. Therefore, for the cases studied we get: $M \in (0.03, 0.625)$ and $N \in (1, 3)$. Obviously, both intervals can be wider if more extreme case studies are included.

In those cases in which the value obtained for M is close to zero, watering will be worth considering, as the expected level of failed seedlings within the area to be afforested will generally be higher than threshold M. On the contrary, high values for M favour the option of failure replanting, except at forest sites where conditions for replanting are very adverse and the value of M_R is even higher. Therefore, on specific and exceptional plantations similar to those of case studies 5, 6, 11, 12 and 13 watering is generally attractive. However, in the case of more common afforestations, more similar to case studies 2 and 4, replacement planting is the better option.

The unsupervised learning algorithm detects five groups. Fig~~ure~~. 2 shows these five groups represented on a coordinate system.



~~Figure 2~~Fig. 2 Position of the thirteen case studies in a coordinate system (C, R) grouped by grayscale. (Fig. 2 caption is in original word file: **Figure 2.** Position of the thirteen case studies in a coordinate system (C, R) grouped by grayscale. The circle's area represents the threshold M, whose value appears on the label of each circle. The circle's grayscale indicates the group to which each plantation type. The label shows the name of the scenario, the value of M and, separated by a semicolon, the value of N.
Note: The abscissa shows the plantation cost (C), while the ordinate reflects the average annual net income (R) on a logarithmic scale. Cost C is the initial investment made by the developer of the plantation. On the other hand, the income generated by the future woodland R is a good indicator of the future economic and social importance of the afforestation (Masiero et al. 2015), as it considers the direct as well as the indirect benefits.)

alt-text: Fig. 2

Cases that yield a high income are in group I; they also have a very low acceptable level of seedling failure and a wide range of initial afforestation costs. This is common for plantations meant to protect roads, railways or hydraulic infrastructures; plantations of fruit trees; or oak (*Quercus* spp.) plantations mycorrhized to produce black truffles (*Tuber nigrum*). The interest of this group in the application of watering is very high (G-I).

Group II comprises costly plantations with a very low acceptable level of seedling failure, but which yield a lower income than in group I. For this group, e.g., xero-gardening projects, windbreaks and areas used to produce high-value non timber-forest products, such as high-quality edible mushrooms, watering might be of considerable interest (G-II).

Group III includes those cases that present medium levels of cost and income, and have a high level of acceptable seedling failure: timber producing plantations, multifunctional plantations, and plantations established in critical areas. The interest of this group in the application of watering would be moderate (G-III).

In group IV we find afforestations common in silviculture have a low expected future income and a high acceptable level of seedling failure. These are the conditions prevailing on plantations belonging to the European program for afforestation of marginal agricultural land. The interest of this group in watering is low (G-IV). Seedling replacement usually has advantage over watering.

Group V includes those afforestations have a low expected future income, and a high acceptable level of seedling failure. These are the conditions prevailing in most afforestations planned to restore the habitat in areas of low forest site quality. In this group, the interest in supplemental watering is quite low (G-V). Almost always, replacement planting is the economically most advantageous option, except when climate conditions are extreme (e.g., semi-desert or desert).

~~3.2.~~3.2 Sensitivity analysis results

The effect of each output variable on M is shown on Table 6 (external column on the right side). (The proposed placement of table 6 is here, after "external column on the right side")

M increases along with variables identified with (+), and diminishes along with variables identified with (~~-~~–). The variables that most influence M are identified with a double addition or subtraction sign. They are: plantation density (ρ, ~~-~~––), cost per unit of seedling (c, ~~-~~––), the plantation~~’~~'s profit or average annual net income (R, ~~-~~––), watering costs (w, ++), time before coming into production (e, ++) and annual interest rate (i, ++).

Of all the above mentioned variables, average annual net income R is the one with the strongest impact due to its wide range of input values and also because of its strong interaction with other input variables (e, ε and i). The following are, in order of importance, c, e, i, ρ (Table 6). The two variables of economic nature (R, i) are those that contain the most uncertainty. If the future behaviour of the species that has been introduced is unknown, there will also be an uncertainty when setting the values of the temporal variables e and ε.

~~4.~~4 Discussion

~~4.1.~~4.1 Contributions of this model

For the forestry sector, there is a consolidated economic procedure available that makes it possible to determine the optimal moment for felling a stand: the Faustmann-Preßler-Ohlin model (Johansson and Löfgren, 1985; Díaz-Balteiro, 1997). However, there is no equivalent proposal for the phase of seedling establishment, for which specific evaluations based on experiments or knowledge-based systems have been developed (Mason, 1995; Hobbs and Harris, 2001; Matthews et al., 2009; Kettenring and Adams, 2011; Löf et al., 2012; Robbins and Daniels, 2012).

The economy based decision support models for choosing among several silvicultural alternatives with a long-term focus compare the net present value obtained from a cost benefit analysis (e.g., Zhou, 1999). Short-term models resort to indexes based on cost-effectiveness analysis (e.g., Ahtikoski et al., 2010) or on avoided-cost models (e.g., Donovan and Brown, 2008).

However, in all cases, they make an economic comparison without interrelating the alternatives through some decision variable. For this reason, none of these models can resolve the question posed in this paper. The threshold of seedling failure (M) is a variable crucial for decision making, as it connects both the alternatives we are considering: watering or replacement planting. This variable must be taken into account in order to make the correct decision. However, it is not taken into account by any of the current decision support models, nor can it be compensated by the inclusion of uncertainties.

Other approaches based on economic criteria and that are close to silviculture are the calculation of the economic threshold in integrated pest management (Stern et al., 1959; Pedigo et al., 1986; Bor, 1995), or some recommendations for technical change proposed in agronomy (CIMMYT, 1988). Our model and method differ from these proposals because it relies on cost-benefit analysis and introduces a decision rule that takes into account uncertainties (M_R).

An important initial requirement before developing or applying any decision support model, is to clarify if we are in fact facing a decision making problem (Grünig and Kühn, 2009). According to these two authors, this is a preliminary question that many decision support models tend to forget, thereby reducing their practical value. In our opinion, MThreshold does not have this shortcoming, as it tackles the question directly in its decision rule when comparing the threshold of seedling failure (M) with the expected level of seedling failure (M_R).

The first output variable of MThreshold deals about seedling failures (M). M is a common indicator used in forestry management to evaluate the successful establishment of the first planting and to choose among possible alternatives during the phase of stand establishment (Ivetić, 2015). By resorting to the variable M, the model takes into account short-term criticism on the long-term focus, avoiding the use of indicators related only to a plantation~~’~~'s purpose and which are far away in time from the initial survival of the seedlings (Löf et al., 2012; Le et al., 2014; Jacobs et al., 2015). Simultaneously, the model keeps the focus on the long-term, as it considers the economic repercussion of failing and the effect of tending treatments on the profit (ΔB), as suggested by Mason (1995).

The model~~’~~'s second output variable is the time (N) needed to obtain, by replacement planting, a plant density that fits in well with the established acceptable level of seedling failure. Variable N is interesting for stand establishment (Ahtikoski et al., 2010; Löf et al., 2012) when there is a legally established time limit for reaching and maintaining the target density, as the European Agricultural Fund for Rural Development (EC, 2015) does. To find the value of N we have developed an equation (Eq. (5)) that determines the number of years of replacement planting needed to reach a plant density which is compatible with the acceptable level of seedling failure (ALF).

MTthreshold uses just two output variables (M and N). Both are closely related to forestry management and can therefore be easily interpreted by a forester. Furthermore, the input variables needed to calculate M and N are of common use in daily forestry practice.

All its input variables can be obtained from the information a plantation project should include. The description of the project, budget, technical specifications and economic evaluation are the documents that contain the data

MThreshold requires: the unit costs of the different materials and works, the density of the plantation, the expected future net income, the time it will take to reach that annual income, and the annual interest rate.

The decision rule set out by the model compares the admissible threshold of seedling failure (M) with the expected level of seedling failure (M_R). This decision rule integrates the risk of seedlings dying off into the decision, as proposed by Hildebrandt and Knoke (2011), Yousefpour et al. (2012) and Pasalodos-Tato et al. (2013). This way, it is avoided that the model might offer results leading to suboptimal or wrong decisions (Duvemo and Lämås, 2006; Mechler, 2016), and that managers respond to an expected level of seedling failure over-reacting (knee-jerk response) or under-reacting (atrophy of vigilance) (Gardiner and Quine, 2000).

Although our economic model is a cost-benefit analysis, when the future annual net income of a plantation (R) is uncertain or difficult to quantify, the term ΔB can be left out in Eq~~uation~~. (1). This transforms our model into an avoided cost model (Del Río et al., 2013). However, this simplified approach is only suitable for plantations where the expected income is very low, as M is very sensitive to changes of R. This has been proved by a sensitivity analysis. Input variable R, followed by the variables c, e, i, ρ (in that order), has the greatest impact on M.

In order to improve the perception of the usefulness of the decision support models by potentially stakeholders (Gordon et al., 2014; Muys et al., 2010; Rinaldi et al., 2015) it may be convenient to explicitly state the hypotheses and calculation assumptions on which each model is based (Pastorella et al., 2016). That is what Díaz-Balteiro (1997), Newman (1988) and Kula (1988) have done with the decision support model based on optimal rotation. The rigorous explanation of a model~~’~~'s basis (Table 3, assumptions) is useful not only for specifying its limitations and present application range, but also for facilitating the model~~’~~'s adaptation to future demands. In this paper we focus on seedling watering, but the decision support model we are proposing can be used for other tending treatments (seed shelters, greenhouse pipes, mulching, weeding tools, use of herbicides, pruning, and other) as well.

~~4.2.~~4.2 Advice for efficient watering

The decision rule of the model establishes that watering has economic sense when the level of expected seedling failure (M_R) is higher or equal to the obtained threshold value (M). This would explain why, so far, watering techniques have not become more widespread in common afforestation projects (case study numbers 1, 2, 3, 4 and 9). In these cases M is usually high, which confirms the practice, widely extended among forest managers, of applying irrigation only in harsh sites. Only in such critical sites (Ruiz De la Torre et al., 1996) predicted failures will be higher than M and, therefore, irrigation should be recommended.

It is worth mentioning two extreme situations in which watering is almost compulsory: when the expected level of seedling failure is close to one and/or the failing tolerance is strictly limited ($ALF \approx 0$). Or, conversely, watering is usually not an interesting option if M_R is low and/or the acceptable level of seedling failure is high (for example, if $ALF > 0.5$).

M_R will be close to one for afforestations in semi-desert or desert areas, even if we use local plant species. This is because, in such environments, natural regeneration will only seldom happen, as abundant rainfall is a rare phenomenon. The tamarugo tree (*Prosopis tamarugo*), the welwitschia plant (*Welwitschia mirabilis*) or the Saharan cipres (*Cupressus dupreziana*) are three examples that appropriately illustrate this extreme situation (Altamirano, 2006; Van Jaarsveld and Pond, 2013; Abdoun and Beddiaf, 2002; respectively, for each of the aforementioned species).

When there is a strict limit for failing tolerance (for example, imposed by the demands of the developer of the plantation, or when planting fast growing light demanding species) failed seedlings have to be replaced almost immediately, even during the same year (in $j = 1$). Under these circumstances, and in arid climates, watering will be almost always the best option. Frequently, arboriculture and viticulture work under such demanding conditions. Truffle cultivation also commonly establishes a minimal or even zero failing tolerance. Case studies number 5, 6, 11, 12 and 13 follow this standard of very low thresholds of seedling failure ($M = 0.03$). This result supports the recommendations provided in technical publications (e.g., García-Viñas et al., 1993) of watering this type of plantations, since M_R values in dryland sites are usually higher than 0.03.

As a useful strategy, Batra and Pirard (2015) suggest classifying tree plantations into different types. The convenience of watering as analyzed in this paper could be a case in point. Groups have been defined according to the criteria of the value of M and the value of the acceptable level of seedling failure ALF. The latter is a highly relevant input variable when designing a plantation, as it strongly affects the final density. Thus, the thirteen case studies we have analyzed form five functional typologies. Group I would show the highest interest in watering, followed by groups II, III and IV, with group V as the least interested.

Plantations with strict limits for failing tolerance ALF favour a low admissible threshold of seedling failure M. In the extreme case of zero failing tolerance, the value of M is also zero, a situation in which watering always results highly recommendable (Group I). A progressive increase of ALF diminishes the interest on watering as the value of M increases as well. Thus, the alternative option - seedling replacement - becomes more attractive, as is the case for groups IV and V. When the failing tolerance is intermediate (groups II and III), we observe that threshold M decreases as the plant replacement costs (C) and/or the average annual net income (R) increase.

The results yielded by the model and the sensitivity analysis help explain why, so far, watering techniques have not become more widespread in regions where the value of M_R is lower than the commonly accepted tolerance of failing replacement, and in plantations that fit into group III with mean values for M close to the value of ALF.

On plantations that produce a high net income only a few years after having been established (low e and high R), watering is the economically convenient option. Replaced failings reach productive age at a later point, therefore causing lost profit (LP_{PV}). This advantage increases if watering allows an earlier extraction of benefits (BI_{PV}) due to an earlier coming into production (ε years in advance). This is usually the case of plantations overview included in groups I and II.

Although to date we do not have international statistics on the value of M_R, the figures available for Spain (Tragsatec, 2008; Pemán and Vadell, 2009) show that in groups IV and V the use of watering is restricted to those critical areas where the foreseeable seedling mortality due to drought stress is very high.

Depending on the timing of the investment, an economic context with low interest rates (i) may favour the option of watering when compared to replacement planting. Watering (with $n_{ri} = 1$) demands an important initial investment, and planners may be less reluctant to take up a loan if interest rates are low. On the other hand, the investments necessary for replacement planting can be divided into successive parts and distributed over a prolonged time, until reaching the year N.

Watering systems may vary greatly (Bainbridge, 2007; Martínez de Azagra and Del Río, 2012) and have a wide potential scope of application. The market for these systems is still quite small, but it seems likely that a more professional management of forest plantations, as well as the growing challenges of climate change, will motivate their use (Ivetić and Devetaković, 2016). It is therefore possible that watering systems may become cheaper which, in turn, may favour their widespread use (or at least their popularity) for forest restorations in arid areas, such as are included in groups III, IV and V. Lower prices (low d) will improve their competitiveness in regions with a low or medium expected level of seedling failure (M_R). Moreover, the resulting accumulation of experience will allow our model to work with more precise input data.

~~5.~~5 Conclusions

MThreshold is a decision model that compares two alternative options for managing a plantation (with and without watering seedlings) and yields the threshold value M which makes both options comparable from an economic point of view. The model uses common input variables and offers output variables that are well known in the forestry sector. It is therefore easy to understand and to use.

To illustrate the utilization of the model we have applied it to thirteen case studies. As a result, we obtain widely differing values for M (from almost zero up to over 0.6). This reveals the practical utility of the model as a decision making tool for project engineers and afforestation managers. Mthreshold is a tool that allows an informed decision making, avoiding over-reacting or under-reacting to an issue as important as seedling survival. The model could also be attractive for producers of micro irrigation systems for forestry, as it enables them to put competitive prices on their products.

The more arid a plantation site, the higher the level of expected seedling failure (M_R). Consequently, watering, especially highly water efficient micro-watering, becomes the more attractive option. Seedling watering is competitive in situations where the threshold value M is low. This is the case with plantations with strict limits for seedling failure (low ALF), a high average annual net income (R), and an early coming into production (low e). Other factors favouring watering are: expensive site preparation, plants with a high unit cost, and a low interest rate. Conversely, for afforestations with low site preparation costs, inexpensive seedlings, high plantation densities and a high level of acceptable seedling failure, the advantage of watering will remain limited to small stands impossible to afforest without supplemental watering.

Finally, we would like to point out that in the near future the model can be expanded in two ways: in allowing different irrigation and replacement planting strategies, and in considering other tending treatments. For this purpose, certain hypotheses and assumptions must be modified or adjusted, which will lead to a set of equations different (although similar) to those developed in this work.

~~Appendix A.~~Appendix A. ~~Supplementary data~~ Description of the cost and benefit terms

~~Supplementary data~~ Appendix with description of the cost and benefit terms to this article can be found online at https://doi.org/10.1016/j.forpol.2018.05.007.

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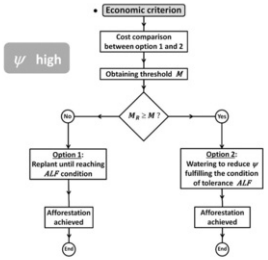
~~Appendix A.~~Appendix A. ~~Supplementary data~~

Multimedia Component 1

Supplementary material

alt-text: Image 1

Graphical abstract



alt-text: Unlabelled Image

Highlights

- The model answers when it is more profitable to irrigate seedlings than to replant failures
- Seedling failure should be treated as a design parameter prior to afforestation
- **Watering is competitive in plantations with strict limits for failures, or high incomes, or an early coming into production** ~~Seedling watering becomes competitive in plantations with strict limits for seedling failure, or with a high average annual net income, or with an early coming into production~~

Queries and Answers

Query:

Please check the layout of Table 1 is okay.

Answer: Yes

Query:

The citation “Sánchez et al. (2004)” has been changed to “Sánchez et al. (2004a, b)” to match the author name/date in the reference list. Please check if the change is fine in this occurrence and modify the subsequent occurrences, if necessary.

Answer: The citation is: Sánchez et al. (2004) We have deleted duplicate reference in the References section. Thank you!

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Query:

Highlights should only consist of 125 characters per bullet point, including spaces. The highlights provided are too long; please edit them to meet the requirement.

Answer: Yes

Query:

Supplementary caption was not provided. Please check the suggested data if appropriate, and correct if necessary.

Answer: Appendix A. Description of the cost and benefit terms