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Review

Nutritional Prescriptions for *Eucalyptus* Plantations: Lessons Learned from Spain

Márcio Viera [1,*], Federico Ruíz Fernández [2] and Roque Rodríguez-Soalleiro [3]

1 Department Multidisciplinary, Federal University of Santa Maria (UFSM), Silveira Martins, 97195000, Brazil
2 ENCE Energía y Celulosa SA, Ctra. A-5000. Huelva 21007, Spain; fruiz@ence.es
3 Department of Vegetal Production, University of Santiago de Compostela (USC), Lugo 27002, Spain; roque.rodriguez@usc.es
* Correspondence: marcio.viera@ufsm.br; Tel.: +55-55-9959-6923

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Abstract: *Eucalyptus globulus* Labill is the main exotic broadleaf species planted and managed for pulp and energy production in Spain, where it covers an area of more than 0.6 million ha. The climatic and soil conditions of the planting areas range from the predominantly acidic or fertile soils developed over limestone in Atlantic areas of the north and northwest of the Iberian Peninsula to the less weathered soils developed from slates, sandy deposits or limestone in the drier southwest. The widely varying conditions explain the large differences in proposed fertilizer prescriptions. This review paper provides an analysis of the proposed practices and prescriptions by considering trial results and the need to develop site specific prescriptions for seedling standards and fertilization at planting establishment. Analysis of nutritional studies and of nutrient balances over a whole rotation is presented in order to provide basic information for defining maintenance fertilization, identified as the main bottleneck for sustainable wood production in these stands. Different fertilization practices are used by non industrial owners and Spanish pulp companies, with the last one applying a more intense management relying in more fertilization. A complete consideration of nutrition-related operation and decisions is shown to be essential for maintaining potential productivity, reduce biotic and abiotic damages and reduce mineral fertilization needs.

Keywords: *Eucalyptus globulus*; nursery fertilization; planting fertilization; maintenance fertilization; post-harvesting fertilization; nutritional status

1. Introduction

The genus *Eucalyptus* is thought to have been introduced to Spain by the monk Fray Rosendo Salvado, who sent seeds soon after his first return to Australia in 1852 [1]. For the rest of the 19th century, the species was planted as a result of landowners' interests, which ranged from gardening to medicinal and honey production. The first commercial plantation for producing poles dates back to the early 20th century and planting for pulp production dates back to 1940 [2]. In Spain, some 0.64 million hectares of land are nowadays planted with *Eucalyptus* [3], mostly *E. globulus*, but also with an increasing presence of *Eucalyptus nitens* Maiden in the north and *Eucalyptus camaldulensis* Dehnh. in the south. *Eucalyptus globulus* is mainly cultivated in the north, northwest and southwest of the Iberian Peninsula. Planted areas are generally located at low elevations (below 500 m) close to the coast.

The total volume of *E. globulus* harvested in Spain is 6 M m^3 $year^{-1}$. *Eucalyptus* biomass is basically used as a raw material for producing bleached kraft and dissolved pulp, as well as for energy cogeneration [3]. The two main regions where *Eucalyptus* are planted in Spain are contrasting sites in term of water and soil resources availability, which makes the differences in the management particularly relevant, especially concerning nutritional aspects. The plantation yield is much lower in acidic, shallow or degraded soils of low natural fertility, which are the types of soil usually available for large plantations of pulp companies in Northern Spain [4]. The Northern area of plantations is characterized by a temperate and relatively humid climate, with weathered soils developed from a range of geological materials, ranging from granitic rocks to slates and schist and predominantly limestone towards the east [5]. The relatively high soil organic matter content is the basis of soil fertility in the north, where rainfall ranges between 1000 and 2000 mm year^{-1} [4], with no critical period of hydric deficit. The south and southwestern area has a Mediterranean climate with long summer droughts and an annual rainfall of 400 to 700 mm. The soils have lower organic matter contents and are less weathered. In this Southern area, the bedrocks are slates and greywacke (shallower soils in mountain ranges), sand deposits (deeper soils near the coast) or even limestone or carbonate clays (basic soils).

Eucalypt plantation yields depend on site parameters [6] and also on management factors such as plant quality, genetic improvement [7], spacing, fertilization [8] and even pruning and thinning, if solid wood production is envisaged [9]. However, plantation health is a major factor explaining current eucalypt productivity in Spain. Damage by pests and diseases of Australian origin have increased dramatically since *Gonipterus scutellatus* Gyllenhal (now denominated *Gonipterus platensis* Mar.) was first recorded in Spain [10]. Introduction of the parasitoid *Anaphes nitens* Girault is the main method of controlling *Gonipterus*, although defoliation can reach high levels if the intensity of spread of *Anaphes* is low, particularly in the north. Diseases include several types of leaf blotch caused by Mycosphaerella (particularly *Mycosphaerella nubilosa* (Cooke) Hansf.) and affecting young leaves. This disease was recorded in 2001 and 2002 in Northern Spain and represents a serious threat to young plantations [11]. Although some advancements in breeding systems have yielded plants that are less sensitive to leaf blotch in Northern Spain, development of commercial clones that are largely resistant to *Phoracantha semipunctata* (Fabr.) and the availability of larger plots of land where sound silvicultural practices can be applied have increased productivity in the Southern region.

Plantation density for pulp production ranges in the north between 1430 and 1140 trees ha^{-1}, depending on site index (3.5 m × 2 m or 3.2 m × 2.5 m spacing), whereas in the south the recommended initial densities are always lower than 1000 trees ha^{-1} [2]. The plantation productivity recorded for Northern Spain in the scenario of almost no presence of pest and diseases ranged from 8–34 m^3 ha^{-1} year^{-1} (over bark stem volume > 7.5 cm in diameter) for the first rotation and 13–36 m^3 ha^{-1} year^{-1} for the second. Rotation length is usually 12 to 16 years [12]. Most economic analyses have considered that the yield from the second rotation (first felling after coppice) is 25% higher than the first, and the third is similar to the first [13]. A recent evaluation of clonal and non clonal plots in Northern Spain reported values ranging from 5 to 30 ha^{-1} year^{-1}, with the highest values found in deep soils at low elevations [14]. The range observed in the south for clonal plantations is 10 to 25 m^3 ha^{-1} year^{-1} for under bark stem volume and rotations of 10–15 years.

Management of soil fertility and plant nutrition has been demonstrated to be important for increasing plantation productivity [15–17], or at least for maintaining levels for future rotations [8,18]. In areas of low natural fertility, the limitation to production may be associated with inadequate plant nutrition, and fertilization is considered essential [6]. The characteristics and quantity of fertilizers to be applied depend on the nutritional needs of the species, the fertility of the soil, the way that the fertilizer reacts with the soil, fertilizer efficiency, economic factors [17,19] and hydric availability [20]. However, for adequate plant nutrition, the demands should be balanced with provision of nutrients in time and space [21]. Models considering soil nutrient balance and yield classes [22,23] and critical soil nutrient levels [8,24] are important tools for defining fertilization needs. Fertilizer doses can be reduced if biomass removal and management of slash take into consideration the important nutrient contents of some biomass components.

This review aims to elucidate the fertilization practices adopted both in nursery and commercial plantations of *Eucalyptus globulus* in Spain from a critical perspective. In a changing scenario where pests and diseases are limiting plantation productivity, the current study proposes fertilization and nutrition management practices aimed at obtaining sustainable yields of this species. Published studies and fertilization practices applied in the nursery and at different stages of plantation development (establishment, maintenance and post harvesting) are reviewed, and alternative practices are discussed.

2. Nursery Fertilization

Plant mineral nutrition is considered an important quality attribute to define eucalypts planting stock specifications, as it influences the ability of acclimation to the planting environment and then survive and grow [25]. Two types of *Eucalyptus globulus* planting stocks are usually grown in nurseries in Spain: containerized seedlings and rooted macro- and mini- cuttings. The former predominate in Northern Spain, where plants are grown in a variety of container types of volume preferably $\geqslant$100 cm^3, usually within a period of four to five months and with target height and root collar diameter of 25 cm and >3 mm, respectively. The seedling specifications regarding plant size and the fertilization pattern vary depending on the ecological conditions of the planting site and period of cultivation. In the more Mediterranean sites of southwestern Spain, a period of physiological drought of 1–5 months makes planting in autumn preferable [26], whereas in Northern Spain, where the climate is largely temperate with much lower hydric stress in summer, planting in spring or even summer is more usual.

The results of accumulation of biomass on *Eucalyptus* species shows that higher N concentration at planting promotes the after-planting growth [27], provided that N fertilization is applied after shoot growth cessation. This is in line with the observed strong relationship between N and planting success [26]. Even so, the relevance of N deprivance at the end of the cultivation has been shown particularly in Northern Spain. In experiments with seedlings destined for planting in cold areas with fertigation as the only method of adding nutrients, N withholding was applied at the end of the nursery period in spring, reducing the weekly dose for active growth of 100 ppm to only 5 ppm; however, plant survival was good [28], probably due to the induction of anthocianin, which has been show to confer cold hardiness after removal of shadecloths [25]. In a study of the fertilizer regime in relation to the month of seeding, Majada [29] considered doses of 0.5, 1 and 2 kg of slow release fertilizer (16-8-11-2MgO plus trace elements per m^3 of substrate), reporting the risk of applying too much N as to increase too much the shoot: root ratio for spring planting.

The exponential fertilizer regime, involving matching relative rates of addition of nutrients to relative growth rate of seedlings, is commonly applied to eucalypts in Spain, in combination with the nutrient loading paradigm [26]. Practical prescriptions also depend on the composition of the irrigation water, substrate composition (which is relatively high in Ca and Mg in the case of pine bark), and on the container size, with a higher dose required for smaller containers. The base fertilization for both seedlings and cuttings usually considers application of a mixture of a controlled released fertilizer of composition 16-9-12 (N-P_2O_5-K_2O) and dose 1 kg m^{-3} of substrate, which also contains Mg and trace elements, over a period of 3-4 months. Additionally, fertigation is applied once a week with doses for the active growth period of 100-25-25 ppm (N-P-K), although this varies according to the development status of the seedling. For a medium container size (100 cm^3), this would be equivalent to the total addition of 51 mg N, 6 mg P, 18 mg K per plant, which is similar to the N objective established by Close *et al.* [27]. The loading is achieved once the seedling has been appropriately hardened and shoot growth has been stopped by applying mono ammonium phosphate (MAP) and exposing the plants to direct sunlight immediately before outplanting. The mean levels of foliar nutrients in planting stock in Northern Spain are 15 g N kg^{-1}, 0.8 g P kg^{-1} and 5.3 g K kg^{-1} [30]. The base fertilization of the substrate (peat and mixtures of peat and vermiculite or composted milled pine bark) has the advantage of remaining available for the first stage of planting establishment.

The pattern of nursery fertilization in Southern Spain, where the climate is Mediterranean and summer drought is the main cause of seedling mortality, fits well within the ecophysiological conceptual model of plant survival developed by Villar-Salvador [31]. Increases in seedling size and nutrient concentration enhance photosynthesis, nutrient remobilization capacity, and non-structural carbohydrate storage, thus promoting high shoot and root growth during the wet season. The target dimension for both seedlings and rooted cuttings is usually a height of 40 cm, with root collar diameter > 4 mm. Some nurseries have had to adapt the prescriptions of nursery fertilization to the high levels of metals found in the very low pH irrigation water, particularly Mn, Cu and Zn. In the case of Mn in particular, antagonism with Fe leads to the need to increase the dose of Fe to avoid plant chlorosis. In Southern Spain, survival and early growth of rooted cuttings have been shown to increase when weekly N fertigation doses are maintained at a level of 126 ppm before planting [32]. These authors reported foliar N concentration of 1.53% for the high nitrogen treatment, well within the range (15–20 g kg^{-1}) established as optimum for outplanting in Australia [25]. Production of clonal planting stock aged seven months (plus rooting for two months) typically involves the addition of 160 mg N, 54 mg P_2O_5 and 90 mg K_2O per plant. The average concentrations of macronutrients found in clonal stock at planting in this region are 12 g N kg^{-1}, 0.8 g P kg^{-1} and 10.4 g K kg^{-1} [5]; the N concentration is low in comparison with the desirable range of 13–16 g N kg^{-1} proposed by the same authors [32,33].

The relationship between the nutrient status of other macronutrients as P and K and establishment of *Eucalyptus* has been less studied, as happens for Mediterranean species [26]. Fernández *et al.* [32] showed that P, in combination with N, favored root formation in planting stock. In a parallel experiment, the same authors indicated the predominant effect of N on clonal stock nutrition, with a positive effect of K on the root regeneration capacity immediately after planting [33]. In the commercial nursery practice, balancing the doses of N and K is considered when base substrate fertilization and fertigation are applied in combination with foliar fertilizers, because of the low nutrient requirements at the rooting stage and the need to force the plant for early use in planting or hardening for autumn planting. A good level of P fertilization can also be crucial in Northern Spain sites, which are prone to *Mycosphaerella* damage and to toppling by winterstorms of plants established previously as rooted cuttings. Carnegie and Ades [34] found evidence that low levels of P were correlated with increased susceptibility of six-year-old plants to *Mycosphaerella cryptica* (Cooke) Hansf. in Australia, which the authors attributed to a better ability to replace damaged foliage.

3. Planting Fertilization

Fertilization at planting is considered to play an important role in survival and early growth of the plantation. This can extend throughout the whole forest rotation by creating favorable soil chemical properties for root establishment. In soils with low natural fertility, and also in more fertile soils, forest productivity can be increased by early fertilization [19]. The planting establishment stage is characterized by a high nutrient demand from plants with poorly developed root systems, a decrease in vigor and frequent presence of deficiency symptoms. There is a strong dependence on soils as a nutrient source and also a high risk of nutrient loss through leachate or uptake by weeds. Indeed, many of the recommended practices combine fertilization and weeding [19].

Adequate availability of nutrients at the initial stage of eucalyptus establishment favors homogeneous plant growth and consequently faster canopy closure. Although initial fertilization is considered necessary in Spain, a single dose is often only applied, and the effects may disappear within two years [35], well before canopy closure in temperate countries. In Brazil, forest plantations are repeatedly fertilized after establishment (although 100% of the phosphorus, which is rather immobile, can be applied in the first operation) until canopy closure (which occurs within one to two years, depending on the growth rate) [36]. The N and K are usually applied in one or more doses, to prevent nutrient loss by leaching. Greater absorption of N and K usually occurs at the canopy closure stage, when the eucalyptus leaf area index is higher [37]. In this review, we will consider the additional applications after one year as maintenance fertilization, which will be covered in the next section.

The pattern of fertilization at planting in Spain has changed over the years. The application of compressed forest fertilizer tablets of composition adapted to the acid soils of northwestern Spain (5-15-15-18-2.3:N, P_2O_5, K_2O, CaO, MgO) was common after experiments carried out in the 1970s [38]. The dose varied from three to six tablets (each of 50 g), placed at a distance of 10 cm and a depth of 5 cm around each plant, some time after planting. There were some variations in compositions (11-18-11 or 8-8-16) and the studies on the pattern of nutrient release and leachate risk showed that they lost 80% of their initial N, P and K contents after 1.5 years equivalent of rainfall [39]. Delgado [40] found 25% and 76% (3 and 6 tablets, respectively, 32 g each) greater on wood production in nine-year-old eucalyptus in relation to the control plots. Although several assessments of experimental plots have shown positive effects on growth [40,41], the relatively high cost of application and the difficulty in achieving a high enough dose per plant were the main drawbacks of its use.

The use of slow release coated fertilizers was tested in eucalyptus plantations, and the advantage was found to be the ease of application, as the granules come into direct contact with the roots. Nonetheless, for the cost to be similar to that of soluble granulated N-P-K fertilizers, the dose must be very low (40 g per plant). Furthermore, the orientation of the roots was greatly affected by the addition of fertilizer, causing malformations and eventually a greater risk of the plants toppling. To prevent this happening, the fertilizer should be applied close to the plant and homogenized with the soil, thus increasing the effort and cost involved. A comparative advantage is the reduction of nutrient loss by leaching.

The most extensive trials of initial fertilization in Spain are those installed by the pulp company ENCE both in Northern [42] and Southern Spain [43]. Readily soluble agricultural fertilizers were applied in both cases (urea, superphosphate and potassium sulphate), with a factorial design of N-P_2O_5-K_2O and 4 doses (0, 20, 40 and 60 g/plant). The results show that even in the less rainy southwestern area of *E. globulus* plantations, the effect disappeared after one year, and the optimum dose varied depending on the soil type. In additional studies carried out in commercial plantations, observed volume growth increases always higher than 38% relative to the unfertilized control two years after planting. The recommended doses at planting are summarized in Table 1, which also includes results reported by Merino *et al.* [35] and Vega-Nieva *et al.* [44] and the risk of fertilizer leaching in the rainier regions.

Table 1. Recommended dose of fertilizer for *Eucalyptus globulus* in Spain and soil properties for each site (reported in the literature with adaptations).

Site	Recommended Dose at Planting	Soil Depth (cm)	Rainfall (mm)	pH	SOM (%)	N (%)	C/N	K (ppm)	P (ppm)	Ca (ppm)	Mg (ppm)
Coastal sands of SW Spain	250 g/plant 15-15-15	120	450	7.2	0.5	0.02	14	40	1	774	80
Slates of the Andévalo range SW	200 g/plant 9-18-27	40	500	7.3	2.1	0.15	8	75	< 5	687	106
Weathered granites NW Spain	200 g/plant 0-24-8	80	1500	4.5	17	0.70	14	58	9	90	28
Schists and slates NW Spain	100 g/plant 8-24-16	60	1500	4.2	10	0.30	20	65	4	70	18

Unsurprisingly, responses to mainly N and P were found in the soil with low organic matter content in SW Spain (Mediterranean climate, with rainfall between 450 and 950 mm $year^{-1}$) [43]. Ruíz *et al.* [43] reported that fertilization induced increases of 10% in height, relative to the unfertilized treatment and the higher dose did not increase the plant mortality. Only a high dose of P in the absence of K or a high dose of N increased the plant mortality in SW Spain [43]. The soils in Northern Spain are richer in N and the main differences were found in response to application of P and, to a lesser extent, K. N only appears necessary for soils that are relatively poor in SOM and covered by heath vegetation rather than legumes. *Ulex europaeus* L. has been shown to be able to fix N at a rate of between 8.1 and 57.4 kg N ha^{-1} $year^{-1}$ in young open stands of maritime pine [45], and atmospheric deposition exceeds 15 kg N ha^{-1} $year^{-1}$ in 70% of the sites studied by Rodríguez and Macías [46]. Basurco *et al.* [42] observed increases of 50% relative to the unfertilized treatment with only 50 g P_2O_5 $plant^{-1}$ after 3 years growth. For the same region, González-Río *et al.* [47] suggest the addition of 100 g $plant^{-1}$ of NPK (8-24-16) during the planting phase. The lower dose may have the advantage of reducing fertilizer leaching but would lead to the need for another application within a short time, as a very low amount would be applied per ha (8 kg N, 24 kg P_2O_5 and 16 kg K_2O for an average planting density of 1000 stems ha^{-1}). In the northern region, the frequent winter storms cause severe toppling in poorly rooted young trees, which accumulate much leaf biomass, pointing also to the need of reducing nitrogen doses.

Fertilization at planting should clearly match the properties of soils; however, not all the sites where *E. globulus* is usually planted have been considered in fertilization experiments, e.g., soils over limestone in Northern Spain, which are characterized by a strong decarbonatation and intermediate or low pH levels, even with desaturated cation exchange complexes. Growth of *E. globulus* under these conditions is mainly limited by P, even by waterlogging on gentle slopes. In Southern Spain, the alkaline soils developed over calcareous clays and limestone are suitable for planting *E. camaldulensis*, as *E. globulus* is known to show signs of Fe chlorosis in such sites.

For practical reasons, the fertilizers are usually pre-established combinations of ternary soluble products applied as granules. These are preferably placed in the furrows at planting or around the plant immediately after planting, at a distance of 10 cm, and are covered with soil rather than combinations of single nutrient fertilizers. Some trials carried out in SW Spain showed a decrease in growth when fertilization was delayed for only a few days after planting. In Northern Spain, fertilizer should be applied at the moment of maximum plant demand in spring, as the product may be easily leached if applied during the rainy autumn or winter. The acidic nature of the Northern soils indicates a good response to lime or biomass ash addition, which provides Ca and Mg and reduces the Al saturation of the exchange complex [48]. Although an abundance of Al can have a toxic effect and lead to immobilization of P in forms of insoluble salts, studies concerning the combination of N-P-K fertilizer with a pH corrector are scarce.

The fertilization regimes should also consider the micronutrients added, being B the main limiting one for the productivity of eucalyptus plantations. Boron deficiency can occur in highly weathered, deep and permeable soils (mainly originated from sedimentary rocks) of coarse texture and low organic matter content in regions with long periods of water stress [6]. Negative effects of B deficiency (growth reduction and dieback) are more intense at the early stages of plant growth, before canopy closure. Therefore, B should be added with fertilizers at planting or maintenance fertilization. Water deficiency mainly occurs in southeast Spain. In this case, application of 4 g of B per plant is recommended. However, in northwest Spain, B fertilization is unusual because of the low or no water deficiency and high organic matter in most cultivated soils. When eucalyptus plantations are established in soils with low or intermediate amounts of organic matter, application of 1 to 2 g of B per plant is recommended.

4. Assessing the Nutritional Status and Completing a Nutrient Balance

Immediately after plantation establishment, assessment of plant growth and survival should consider any visual symptoms of nutrient deficiency, and foliar nutrient concentrations should be evaluated regularly [15]. Such assessment considers sampling the upper third of the crown and, as deficiency symptoms are usually found at the first stages, nutrient status is evaluated during the early years of plantation development. Measurement of early growth, in combination with foliar and soil analysis, would provide relevant information about additional nutrients required through maintenance fertilization. It is important to note that any nutritional deficiencies identified cannot usually be resolved before tree growth has already been affected [36].

The visual symptoms of nutrient deficiency in *E. globulus* were first compiled in Spain by Marzo Muñoz-Cobo and Marcos de Lanuza [49] for N, P, K, Ca and Mg and were considered by Bará [41] as a first step in identifying the presence of deficiencies based on analytical methods. The average nutrient concentrations in leaves of some *Eucalyptus globulus* plantations in Spain are shown in Table 2. Merino *et al.* [35] found that foliar concentrations of N and micronutrients were satisfactory in all of the 44 *E. globulus* plantations aged 2–6 years assessed in northwest Spain. However, levels of P and Ca were low in most of the plantations, and levels of Mg and K were low in some plantations. The low nutrient concentration in the plantations coincided with low availability in the soil and insufficient input via fertilization [35].

Table 2. Average nutrient concentrations in *Eucalyptus globulus* leaves in Northwest Spain. The standard deviations are show within brackets for [35], [50] and [51]. Standard errors are shown within brackets for [52].

Authors	Bará [30]	Español *et al.* [52]	Brañas *et al.* [50]	Merino *et al.* [35]	Merino *et al.* [4]	Afif *et al.* [51]
Age-years	–	4	6–18	2–6	13–24	13–52
g kg^{-1}						
N	15.0	15.0 (0.2)	13.07 (1.18)	15.2 (2.8)	14.8	9.95 (0.28)
P	0.8	0.8 (0.02)	0.23 (0.03)	0.58 (0.15)	0.55	0.68 (0.01)
K	5.3	4.9 (0.2)	5.55 (1.26)	6.04 (1.91)	3.8	1.82 (0.03)
Ca	4.6	11.0 (0.4)	6.13 (2.43)	3.21 (1.77)	6.34	7.73 (0.16)
Mg	2.0	1.8 (0.07)	0.58 (0.55)	1.66 (0.51)	1.84	0.98 (0.02)
S	–	–	–	1.43 (0.35)	0.82	–
mg kg^{-1}						
B	15.0	–	–	–	13.3	–
Cu	5.0	6.2 (0.4)	–	6.0 (3)	5.1	–
Fe	–	33.2 (0.9)	–	87 (31)	100	–
Mn	670	577 (27)	1140 (1050)	620 (500)	650	–
Zn	11.0	7.1 (0.3)	–	25 (88)	60.2	–

Although the foliar values and normal ranges given in Tables 2 and 3 serve as a basis for identifying further fertilization needs in planted stands, the dose of each nutrient that should be applied can be better defined when a complete nutrient balance for the whole rotation is available. Such quantification requires detailed information about the nutrient cycles that take place throughout the different plantation stages. The main input of nutrients in forest ecosystems occurs via mineral weathering, atmospheric deposition, asymbiotic and symbiotic fixation of nitrogen, and fertilization [56]. However, nutrient outputs occur via leaching, erosion, volatilization, organic material removal, harvesting of different biomass components and even through litter removal [56]. Nutrient inputs through rainfall and weathering of minerals have been reported by Dambrine *et al.* [57], in an analysis of small catchments with eucalypts plantations in Galicia (Northwest Spain) (Table 4).

Table 3. Range of nutrient concentrations in eucalyptus leaves.

Nutrient (g kg^{-1})	González *et al.* [53] [1]	Judd *et al.* [54] [2]	Unpublished Results [3]	Dell [55] [4]	Gonçalves [36] [5]
	E. globulus	*Eucalyptus*	*E. globulus*	*E. maculata*	Eucalyptus
N	2.0	10–23	26–35	17–26	21–30
P	1.4	0.5–1.5	1.5–3.8	1.0–2.6	1.0–1.3
K	6.0	4–14	10–15	10–17	5.5–8.5
Ca	–	5–10	6.5	2.9–4.0	3.5–6.0
Mg	–	2–4	2.1–4.1	0.9–2.4	2.0–3.0
S	–	1–2	2.0–2.4	1.8–4.2	0.5–1.5
mg kg^{-1}					
B	–	20–50	20–30	–	30–60
Cu	–	4–10	3.0–4.2	6–12	7–10
Fe	–	50–250	–	39–50	70–200
Mn	–	100–1000	90–134	22–32	100–800
Zn	–	15–40	20–26	12–54	10–18

[1] Adequate concentration for plantations; [2] Typical range for eucalyptus plantations; [3] Adequate range for seedlings in Spain (ENCE company reference); [4] Adequate range for seedlings; [5] Adequate range for eucalyptus plantation in Brazil.

Table 4. Nutrient inputs through rainfall and weathering of minerals and output through drainage in Spain (kg ha^{-1} year^{-1}) by Dambrine *et al.* [57].

Nutrient	Rainfall Input	Weathering Input	Drainage
K	4.1	3.0–6.5	2.0
Ca	5.3	5.0–8.0	3.4
Mg	9.0	2.5–3.0	7.1

Nutrient demands by plants after canopy closure can be satisfied by internal or external plant nutrient cycling. Internal nutrient cycling involves transfer (retranslocation) of mineral elements from old to new tissues, and is an important physiological process for maintaining the pool of nutrients in the plant to satisfy its demand [58]. In a study evaluating nutrient concentrations in full-sized mature leaves in 27-month-old plantations of *Eucalyptus globulus* during a 10 month period (initial age of the leaf 12 months and final age 22 months during which the leaf remained green), Fife *et al.* [59] observed retranslocation rates of 31, 53.8 and 18.3% of the initial amounts of N, P and K, respectively. For the same species in another site, Saur *et al.* [60] reported values of 51, 54 and 31% for N, P and K, respectively, in mature green leaves. For the same species, the retranslocation rates have been found to vary according to site and stand characteristic, age of the leaves during their life cycle and factors such as leaf shading [59].

Nutrient cycling external to the plant, via litter production and decomposition, is also responsible for a significant amount of the nutrients available to tree roots after canopy closure. For *Eucalyptus globulus* plantations aged 13 to 24 years in northwest Spain, the nutrient pool in the litter was 474.4, 12.9, 29.9, 74.2 and 30.0 kg ha^{-1} of N, P, K, Ca, Mg, respectively [4]. A significant pool of nutrients becomes available to the trees after litter decomposition and release of nutrients to the soil to be absorbed by the fine roots in the surface layers. Cubillas *et al.* [61] studied the pattern of nutrient liberation from leaves and twigs decomposition for two sites of NW Spain using litterbags. They found semi-decomposition times of 266–402 days for leaves and 547–859 for twigs. There was a net and rapid mineralization of K, and net mineralization of N, P, Ca and Mg from leaves in the first year, whereas the decomposition of twigs led mainly to immobilization of nutrients. They also found a positive effect of fertilization in the quality of the litter, expressed as reduced C/N rates.

Nutrient export via biomass removal is a major process that affects the whole nutrient balance. The procedure for calculating such removals entails knowledge of the amounts of biomass for each compartment removed (stumps, wood, bark, branches of different sizes and leaves) and the nutrient concentrations. The main drawback of this approach is that nutrient concentrations in biomass compartments are known to vary greatly depending on plantation age, site and even tree density, although the concentrations stabilize at the mature stage [62]. For pulp production, biomass removal is concentrated at the end of the rotation in eucalypts, and the stabilized concentrations have been used to estimate the removals considering a rotation age of 18 years [4]. These authors already reported that the comparison between nutrient removals and natural inputs (rainfall and weathering) and outputs (stream water) indicated that intensive harvesting may lead to negative budgets, especially when whole tree harvesting is carried out. Figure 1 shows the distribution of nutrients in each biomass compartment, in the litter and available levels in soil, for a rotation age of 18 years and average productivity of 209.6 dry tons/ha of undebarked wood (total aboveground biomass 233.4 tons ha^{-1}, standard error 22.9 tons ha^{-1}).

Forest harvesting systems have a major effect on nutrient extractions, depending on the objectives of the pulp companies. The companies producing bleached kraft pulp from eucalyptus usually harvest undebarked wood, as the bark is used for biomass power generation. The process of bark removal has an important effect on the nutrient balance, particularly in the case of Ca but also on other nutrients. From the perspective of forest owners, and considering that the share of bark biomass in undebarked logs tends to stabilize at 15%–16% for breast height diameter over 20 cm, the usual overprice of debarked wood is worth very little and bark would therefore be better left in place.

Another major issue affecting the nutrient balance and the need to replenish nutrients by fertilization is the removal of logging residues such as branches and leaves. Some pulp companies now have biomass cogeneration power plants that require additional supplies of biomass in the form of chips or bundles. Figure 1 shows the impact of such removal in terms of nutrients. The analysis should also be made from different perspectives. A forest owner selling biomass to a pulp company must consider the income derived from removal of the logging residues in comparison with alternative management of slash by e.g. chipping. In the case of pulp companies managing their own plots of land, such intensive practices lead to the need for fertilization.

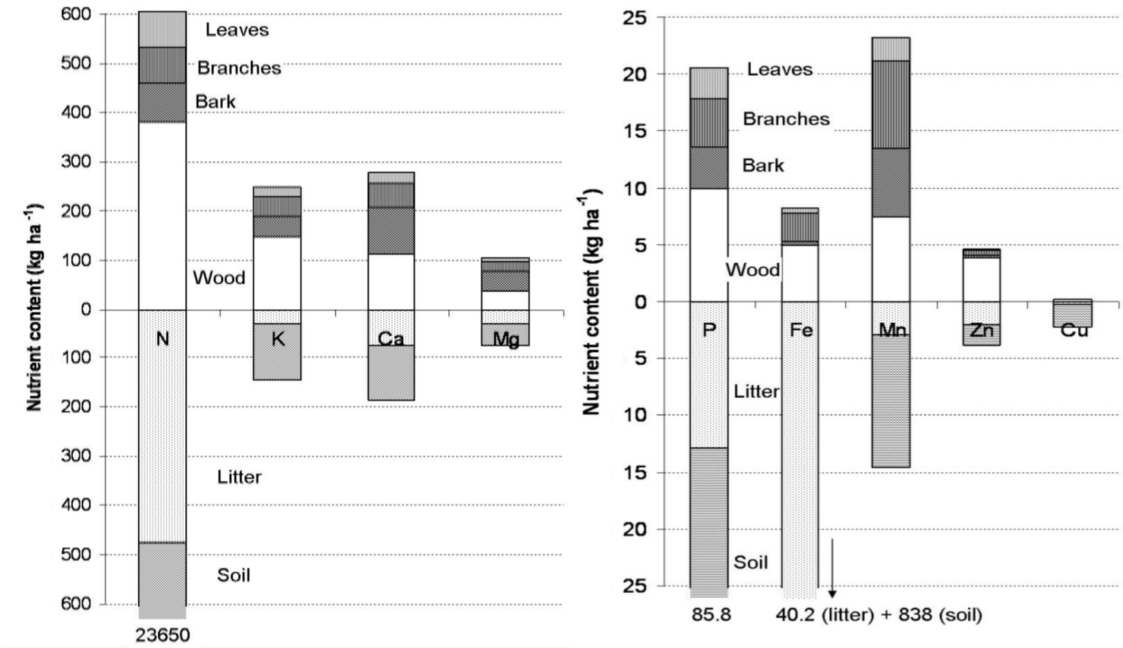

Figure 1. Biomass (Mg ha^{-1}) and nutrients (kg ha^{-1}) in the *Eucalyptus globulus* fractions and nutrients in the soil (kg ha^{-1}), in northwest Spain. Data are estimates for a rotation of 18 years [4]. Total N in soil and available for other nutrients.

5. Maintenance Fertilization

Maintenance fertilization is carried out when fertilization at establishment (nutrient levels in the soil and plant) does not meet the growing needs of plants throughout the rotation. In Spain, this refers to application of fertilizer at least one year after planting but usually before canopy closure. This stage of eucalypt plantation is characterized by a rapid increase in above and underground biomass, with the highest increment in leaf area index (LAI) and the whole soil volume still not explored by fine roots [63,64]. The basic objective of maintenance fertilization is to charge the system with nutrients just before the biogeochemical cycling is completely underway, providing important amounts of fertilizers that can balance the processes occurring throughout the whole rotation, as discussed in the previous section.

Maintenance fertilization needs vary greatly depending on the site, and detailed information is necessary to apply precision silviculture and optimize doses. Maintenance fertilization is seldom applied by small scale non industrial owners, but is regularly included in the codes of good forestry practices of areas managed by Spanish pulp companies. Maintenance fertilization doses should consider the (usually low) amounts of nutrients applied at the planting fertilization (Table 1). For soils low in organic matter and available P, which mainly occurs in SW Spain, application of 40–60 kg ha^{-1} N, 30–40 kg ha^{-1} P_2O_5 and 40–60 kg ha^{-1} K_2O is recommended, considering planting plus maintenance fertilization. In NW Spain, where soils are richer in OM and water deficiency is lower, the application (planting + maintenance fertilization) of 15–30 kg ha^{-1} N, 30–40 kg ha^{-1} P_2O_5 and 60–80 kg ha^{-1} K_2O is recommended.

Other sources of nutrient inputs by fertilization are necessary because the cost of fertilizer tends to increase [15]. Furthermore, the life cycle assessment (LCA) analysis applied to forest operations has shown that silviculture made an important contribution to eutrophication, mainly due to phosphorus-based fertilizer application [65]. Alternatives to mineral fertilizers as the use of biomass combustion ash has been studied in Spain, although hindered by administrative problems derived from the very general regulations for industrial residues that are still in place. Ash derived from fluidized boilers contains high concentrations of readily available nutrients, especially K and Ca, which directly influence soil chemical properties [66]. To avoid nutrient leaching, especially in sandy soils, ash should be applied once the tree root systems are well structured. Several trials have recently been established in Northern Spain using biomass ash in eucalypt plantations managed by pulp companies [67]. In SW Spain, 10–15 Mg ha^{-1} is applied before new planting during the soil preparation or 2–3 years after sprouting establishment. This dose would supply most of the Ca, K and Mg needs (490 kg Ca ha^{-1}, 420 kg K ha^{-1} and 75 kg Mg ha^{-1} are applied), but almost no P or N. Further studies are needed to test mixtures of ash and other nutrient sources (crushed mussel shell, fish waste, seaweed, sewage sludge) and to establish optimal doses and ideal timing of application to achieve maximum tree growth.

Late fertilization, also called fertilization at middle rotation, is applied in some cases and may enhance biomass production at the end of rotation [68]. These authors tested different combinations of NPK in southeast Spain and found that tree growth in sandy soils (fertilizer application in a five-year-old *E. globulus* plantation) was significantly enhanced by addition of N. In soils over slates (fertilizer application in a seven-year-old *E. globulus* plantation), the trees responded to fertilization with N and K [68]. However, these proposals are controversial, as different results were obtained in fertilization trial in five-year-old *E. globulus* plantation in central Portugal, where Madeira *et al.* [69] reported no positive response to fertilizer application for a cutting cycle of 14 years. The authors suggest that fertilizer application may be useful for enhancing soil quality and ensuring the long-term sustainability of eucalyptus plantations.

6. Post-Harvest Fertilization

Production can be maintained from other rotations due to the good regeneration capacity of *E. globulus* through stump sprouting. Plantations with four or more cycles of coppice can be found in Northern Spain and with three to four cycles of coppice in southeast Spain. Total seedling planting in the area was justified by stand mortality (which caused a significant reduction in productivity) and also by the use of seedling or selected clones in term of productivity [2].

Fertilization of the post-harvesting phase aims to promote regrowth and adequate development of new sprouts, and nutrient inputs mainly replace those removed during the harvesting system adopted in each rotation. Harvesting debarked wood leads to macronutrient exports of between 66 to 76% and micronutrient exports of between 58 and 89% of the amount in the aboveground biomass. When all the aboveground biomass is removed, the rate of nutrient exportation is very high, reaching 33.6 of N, 1.15 of P, 13.8 of K, 15.5 of Ca and 5.8 kg ha^{-1} year^{-1} of Mg. The residues contain only around 10% of the total biomass in the tree, without bark, but they also concentrate significant amounts of nutrients. This occurs because of the high levels of nutrients in the leaves and branches relative to the wood [4,50,70,71]. Removal of all aboveground biomass can easily reduce productivity in future rotations [70–72].

The use of fertilizers is therefore essential to meet tree nutritional demand and prevent reduced stand productivity. For initial growth, sprouts are strongly dependent on the amount of available nutrients in soil. Teixeira *et al.* [73] found that 60 days after harvesting in an *Eucalyptus urophylla* S. T. Blake plantation, all nutrients allocated to the sprouts, excluding potassium, were supplied by the soil. Thus, after tree harvesting with bark and, in some cases removal of other residues (leaves and branches), post harvesting fertilization is essential to maintain the site productivity for new rotation. Considering the studies of González *et al.* [53] for Southern Spain and the abovementioned ones for the North, we can conclude that adding 20–40 kg ha^{-1} N via fertilization (the lowest dose for soil with high organic matter and the highest for soil with low organic matter) could be envisaged. For P and K, doses of between 15–30 kg ha^{-1} P_2O_5 and 40–60 kg ha^{-1} K_2O are required. Considering bark removal (usual practice) and removal of other residues (canopy), at least 200 kg ha^{-1} Ca should be applied.

As for the first rotation, application of B (1–4 g/plant) and other micronutrients removed during harvesting, mainly Zn and Cu (present in small amounts in the soil) could also be recommended.

7. Conclusions

Nutrient management of eucalypt plantations is a basic tool for maintaining the economic profitability of short rotation pulp forestry in Spain. Several silvicultural decisions, such as the biomass components to be harvested, the promotion of a rapid canopy closure, the assessment of nutrient status or the use of forest residues as fertilizers, can decrease the needs of applying more mineral fertilizers, thus reducing the risk of environmental problems as eutrophication. Different fertilization practices are used by non industrial owners and Spanish pulp companies, with more intensive harvesting and fertilizing in the last case. Plant fertilization in nurseries is necessary to reduce post-planting stress and ensure acclimatization and rapid leaf development. Considering the soil properties in which the eucalypts are planted in Spain, and in order to maintain the productive capacity, fertilization should be carried out at least twice. The first application should be carried out during the planting period (adaptation of the seedlings in the field) and the second about one year after planting, when the plants are at an intensive stage of canopy expansion (LAI increase). These applications of fertilizer (planting and maintenance) are essential for establishing healthy forests that are more resistant to biotic and abiotic factors. The ability of *E. globulus* to produce vigorous stump sprouting and thus successive cycles of coppice is strongly dependent on the availability of nutrients in the soil after the first harvest, and so a complete balance is needed to quantify the amount of nutrients to add via post-harvest fertilization. The literature reviewed emphasize the recommended silviculture practice of maintaining the bark and other logging residues on the ground after harvesting eucalyptus plantations, because large amounts of nutrients are removed from the ecosystem, mainly P, K and Ca. The future research in eucalypt planting nutrition should consider the possibility of using by-products such as crushed mussel shell, fish waste, seaweed, sewage sludge or biomass ash as fertilizers, with biomass ash being particularly appropriate as a way of returning the nutrients previously removed by harvesting to the site. New fertilization standards and management practices of plantations, as mixed plantations with N-fixing species, should be defined in a site specific way.

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