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Nutrient Release through Litterfall in Short Rotation Poplar Crops in Mediterranean Marginal Land

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Abstract: A detailed knowledge of how poplar leaf litter decomposes under Mediterranean marginal conditions can help to minimize fertilization inputs and determine the profitability and sustainability of energy crops established in these particularly sensitive areas for bioenergy. Leaf litter decomposition was monitored for 32 months using the litterbag technique in a poplar crop under short rotation conditions in a marginal Mediterranean area. In addition, nutrient dynamics, together with the production and composition of the woody and foliar biomass produced, were studied for a period of four years. Leaf litter decomposition was relatively slow, particularly during the winter months, and accelerated in early spring, coinciding with the rainy season. At the end of the decomposition study 50% of the initial litterfall was decomposed, releasing roughly 60% of the N, 40% of the K, and 70% of the P initially present in fresh leaves. Annual yields of 6.0 dry Mg ha^{-1} were obtained. The aerial biomass produced the first year of the second rotation cycle extracted 83, 8.7, and 29 kg ha^{-1} of N, P, and K, respectively, whereas the amount of nutrients that were estimated to be naturally supplied to the system through leaf litter decomposition were 180 kg ha^{-1} of N, 19 kg ha^{-1} of P, and 30 kg ha^{-1} of K. Therefore, four years after establishing the energy crop, leaf litter was able to release higher amounts of primary macronutrients into the environment than the nutrient uptake by the produced aboveground biomass (woody and foliar biomass).

Keywords: biomass; leaf litter; nutrient cycling; poplar; short rotation coppice

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1. Introduction

The ambitious targets set by the recent EU Renewable Energy Directive (RED II) 2018/2001/EC [1], which stipulates that 32% of member states' total energy consumption should come from renewable sources by 2030, has drawn the attention of the scientific community towards the use of marginal land that is not suitable for food production to produce bioenergy feedstock. The planting of energy crops in arable marginal lands with low agricultural profitability can supply biomass which can contribute to meeting the EU energy targets, while avoiding, at the same time, the energy–food dilemma. Moreover, it also can be seen as a way to contribute to the restoration of degraded soils, controlling erosion, and slowing down the depopulation of rural areas [2]. In Europe, it has been estimated that a total area of 63.7 Mha of marginal land is suitable for the production of bioenergy resources [3]. In Spain, the area of arable marginal lands with bioenergy potential, and where traditional food crops are not economically sustainable, is about 2 Mha [4]. Most of them are low productivity areas where winter cereal grain production is below 1.5 Mg ha^{-1} due to poor soils that have organic matter contents below 2% [4].

It has been demonstrated that poplar (*Populus* spp.) is a fast-growing tree species that is well adapted to the unfavourable conditions of poor low productivity soils in the Mediterranean region [5,6], the limiting growing temperatures being <5–10 °C and >30–40 °C [7].

In Spain, for example, an average annual biomass production of 9 Mg ha^{-1} can be obtained under these unfavourable conditions [6,8]. However, at this time, less than 4% of the Spain's total land is devoted to poplar plantations (approx. 144 thousand hectares) targeted for the produce of fuelwood biomass [9]. Poplar species have deciduous leaves, so part of the minerals extracted by these trees when growing are returned to the soil annually through leaf litterfall. On the floor, leaf litter acts as an input–output system for nutrients, serving as a temporary nutrient sink, and functioning as a "slow release" nutrient source for plants and microorganisms [10,11], Because of this key role of litter decomposition, factors influencing litter quality and production have important implications for long-term productivity of poplar plantations. Quantitatively, the release of nutrients during the decomposition of the leaf litter is one of the most relevant processes that contribute to the cycling of nutrients [12]. Leaf litter decomposition can be divided into two phases [13]: (1) an early decomposition stage, which is influenced by factors, such as climate, concentrations of the major nutrients, and the solubility of nutrients and (2) a later slower phase in which decomposed leaves turn into soil organic matter. Generally, studies have not been focused on the later decomposition stages of plant litter, and they clearly deserve further attention [14].

In agroforestry systems, these plant residues have been shown to be sources of nutrients and organic matter when they decompose [15], contributing to the maintenance of soil fertility, and naturally decreasing fertilization requirements [16]. It has been reported that on poor soils the processes that guide the sustainability and the productivity of fast-growing plantations are fertilization and litter decomposition, promoting increased mineralization and nutrient release [17]. However, biomass producers tend to calculate the nutritional needs of their crop by estimating fertilization inputs and only accounting for the expected wood production and associated nutrient uptake requirements, without considering those that would be naturally supplied through leaf litter decomposition. In low productive areas, an over-application of fertilization inputs can limit the profitability of this activity and therefore the viability of producing biomass from energy crops [18]. In this sense, it is true that nutrient dynamics in decomposing leaf litter can only indicate a potential available nutrient pool to the system as other processes such as bioaccumulation, immobilization, or volatilization are likely taking place simultaneously, excluding a portion of soil nutrients from being available to the crops [10,19]. Nevertheless, a more accurate and detailed knowledge of how this natural process occurs is particularly relevant for these marginal areas and would provide valuable information to help to minimize fertilization inputs in a balanced sustainable way thereby maintaining biomass production at acceptable levels without exhausting soil nutrients. To our knowledge, the dynamics and nutrient release of the decomposition of poplar litterfall have not yet been studied in energy crops established on marginal lands.

The aim of this work is to describe the decomposition and nutrient release from poplar leaf litter in short rotation coppice systems grown on marginal lands in a Mediterranean climate in order to minimize inorganic fertilizer inputs and maintain crop productivity and soil nutrient levels. This research aims to reduce inorganic fertilizer inputs while maintaining crop productivity levels and soil nutrient levels. The results obtained could be of great interest for the commercial implementation of poplar crop in short rotation in the Mediterranean area, particularly for low productive agricultural regions.

2. Materials and Methods

2.1. Location and Weather Conditions

This research was carried out in Soria, an inland Spanish province in the north of the Iberian Peninsula. It is situated at 41°36′ N and 2°30′ W, at an altitude of about 1100 m above sea level. The climate in the area is a continental Mediterranean type Cfb, according to the Köppen–Geiger climate classification, a warm temperate climate (mesothermal) with warm summers [20]. The mean annual temperature during the study period (2006–2010) was 10.4 °C, and the average annual rainfall was 507 mm (Table 1), close to the historical averages of 11.0 °C and 512 mm recorded during the period from 1981 to 2010 [21]. In this region, the frost-free period usually lasts four months (between June and September), with an annual average of 83 days of frost and an annual average of 21 days of snow (average value 1981 to 2010). As can be seen in Table 1, it is important to note that rainfall in this region can vary largely from year to year. Rainfall was below 400 mm in 2007 and 2009, whereas roughly 600 mm were recorded in 2008 and 2010.

Table 1. Weather conditions measured at the experimental site during the study period.

Year		P (mm)	MT (°C)	RH (%)
2006	0	554	11.6	69.0
2007	1	342	10.0	68.0
2008	2	649	9.9	70.7
2009	3	390	10.8	64.8
2010	4	599	9.6	68,0
Mean		507	10.4	68.1

P: Accumulated precipitation; MT: Mean temperature; RH: relative ambient humidity.

The measured meteorological conditions during the in situ leaf litter decay study (from December 2006 to August 2009) are summarized in Figure 1. The historical maximum number of rainy days per month in the area (23) was registered in May 2008, with a total accumulated rainfall of 300 mm between May and August.

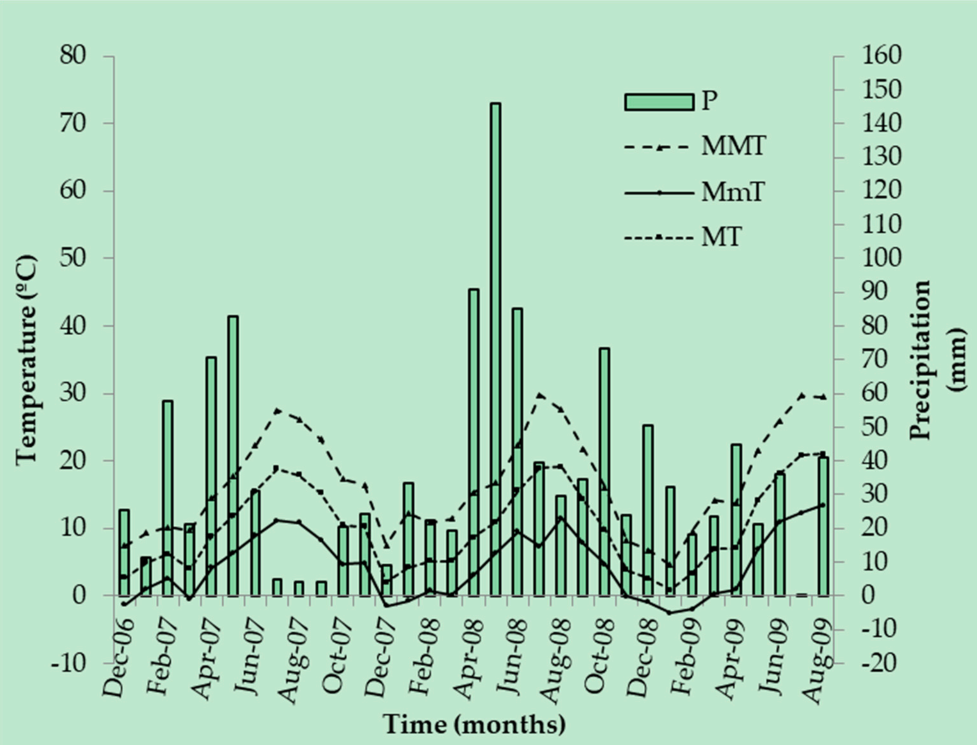

Figure 1. Meteorological conditions during the decay assay. Notes: P: Precipitation, MMT: Mean maximum temperature, MmT: Mean minimum temperature, MT: Mean temperature.

The experimental plot was located in an area characterized by shrubs, grass, pines, and oaks. The most dominant shrub species was *Cistus laurifolius* L. There may also have been, although not covering large areas, broom, lavender, rosemary, and thyme. This site had been used to produce winter cereals until the 1980s. After that, it was overgrown with shrubs (*Cistus laurifolius* L.) until 2005, when soil conditioning operations started prior to poplar planting.

2.2. Soil Analysis

Soil was sampled at the beginning (December 2006) and at the end (August 2009) of the decomposition study (Table 2). Six soil cores (8 cm in diameter) were sampled to a depth of 60 cm, with each core split into 3 subsamples: 0 to 20 cm, 20 to 40 cm, and 40 to 60 cm.

Table 2. Soil characteristics at the beginning (initial) and at the end of the litter decay study (final).

Sampling		**Initial**	**Final**	**Initial**	**Final**	**Initial**	**Final**
Depth (cm)		**0 to 20**		**20 to 40**		**40 to 60**	
pH		6.8 ± 0.2 ^{a}	6.3 ± 0.2 ^{b}	6.5 ± 0.2 ^{a}	6.1 ± 0.2 ^{b}	6.4 ± 0.5 ^{a}	6.1 ± 0.5 ^{b}
N_t	(mg kg^{-1})	320 ± 110 ^{a}	675 ± 210 ^{b}	200 ± 100 ^{a}	610 ± 90 ^{b}	180 ± 90 ^{a}	650 ± 110 ^{b}
P_{av}	(mg kg^{-1})	14 ± 2 ^{a}	43 ± 2 ^{b}	12 ± 4 ^{a}	33 ± 6 ^{b}	36 ± 5 ^{a}	24 ± 3 ^{b}
K_{av}	(mg kg^{-1})	61 ± 12 ^{a}	92 ± 18 ^{b}	66 ± 15 ^{a}	65 ± 15 ^{a}	65 ± 19 ^{a}	61 ± 17 ^{a}
Organic C	(%)	0.5 ± 0.2 ^{a}	0.6 ± 0.1 ^{a}	0.2 ± 0.1 ^{a}	0.6 ± 0.2 ^{b}	0.06 ± 0.01 ^{a}	0.49± 0.05 ^{b}
Organic matter	(%)	0.8 ± 0.3 ^{a}	1.0 ± 0.2 ^{a}	0.4 ± 0.2 ^{a}	1.0 ± 0.3 ^{b}	0.11± 0.09 ^{a}	0.84 ± 0.08 ^{b}
C/N ratio		15 ± 3 ^{a}	9 ± 3 ^{b}	12 ± 4 ^{a}	10 ± 3 ^{a}	4 ± 1 ^{a}	8 ± 2 ^{b}

Mean values ± standard deviations. Different letters (^{a},^{b}) denote significant differences between the initial and final samplings at each depth at 95% confidence level. Subscripts "t" and "av" refer to the total and available element in the soil, respectively.

The pH values were in the optimal pH range for poplar crops, estimated to be between 6.5 and 7.0 [22]. The pH values, total N (N_t), organic content, organic matter, and C/N ratio in the soil tended to decrease with depth. This soil had a sandy texture with 84% sand, 6% silt, and 10% clay. The proportion of stones was high (37%). It was a well-drained soil, with a bulk density of 1.6 Mg m^{-3}, low organic matter (<1%), and also low contents of available nutrients (see Table 2), particularly with respect to available phosphorous (P_{av}) and potassium (K_{av}). Collectively, it would be classified as a poor low productive soil for arable marginal land.

2.3. Agronomical Practices

Planting was completed manually in April 2006 (year 0, marking the beginning of the study), utilizing unrooted 25 cm long cuttings of poplar clon I-214 (*P. x euramericana* (Dode) Guinier→*P. deltoides March x P.nigra L.*). The plantation was established at high density (25,000 tree ha^{-1}) and short rotation conditions. It was designed in double rows with 1 m × 0.40 m spacing.

The crop was drip irrigated during the summer months (from mid-June to mid-September) up to 265 mm year^{-1}. As the crop was established in a low quality soil (see Table 2), a dose of N–P–K (48–40–75 kg ha^{-1}) was applied before planting (April 2006) to favour poplar establishment.

Total aboveground biomass was harvested in December 2006 (year 0) to boost sucker production and in December 2009 (year 3), constituting the first 3 year rotation cycle. The crop was monitored for 4 years until the end of 2010 (year 4).

2.4. Biomass Sampling

At the end of each growing period, 75 trees were randomly harvested to estimate aboveground woody biomass production (stem and branches). The total dry production was expressed in Mg ha^{-1} year^{-1}, taking into account the planting density and the number of failed plants.

Foliar production was estimated by using litter traps located between rows of poplar trees. A series of 36 litter traps were randomly distributed monthly in three replications. Each trap was made of a 0.25 m^2 plastic box and a synthetic bag of a 1 mm size mesh. The bag was attached to the box and elevated about 5 cm above the soil. The overall trap (perforated box and permeable bag) as well as the position of the bag were designed to allow rapid drainage of rainwater. Litterfall collected in the traps was weighed and foliar production was estimated converting the litter trap collecting surface used to a per hectare basis.

Root biomass was estimated using a root to woody biomass ratio of 0.22, according to Lodhiyal et al. [23,24]. It was also assumed that the underground biomass sequestered 25% of the C fixed by the aerial biomass [23].

2.5. Decay Assay

Leaf litter decomposition was monitored for 32 months (from December 2006 until August 2009).

The decomposition and patterns of nutrient release from poplar leaves was examined using the litterbag technique, which is described elsewhere [17]. This method allows for an evaluation of the decomposition of leaves by estimating their mass loss over time. Leaves begin to fall in mid-July, and this period is usually extended until the end of November. At the end of the first growing period (December 2006), when the decay assay was initiated, leaves were collected and distributed in 54 nylon litterbags (18 cm × 18 cm) of 4 mm size mesh, which were secured to the floor with steel pins. A total of 7.2 g of dried leaves were placed in each litterbag and then left undisturbed in the poplar plantation until collection. The mesh size of the litterbags was considered small enough to prevent major losses of the smallest leaves, yet large enough to permit aerobic microbial activity and free entry of small soil organisms in order to avoid interfering with the mesofauna activity. Every four months, six litterbags were randomly collected. Although the decay assay was scheduled to last for 3 years, only 32 months were monitored because most litterbags fell apart before the last scheduled sampling date.

In addition, 24 control samples were collected at the beginning of the experiment, and they were dried, milled (>2 mm), and kept at 5 °C during the whole decomposition study.

2.6. Analysis

Soil samples were dried to a constant weight in an oven maintained at 40 °C. These samples were sieved (2 mm size mesh), and stones (fraction over 2 mm) were separated. Soil organic C, total soil N (N_t), pH, and available soil phosphorus (P_{av}) and potassium (K_{av}) were analyzed on the fraction below 2 mm as specified elsewhere [25].

Woody biomass production and their total C, N, P, and K contents were determined every growing season for 4 years. Leaf litter dry mass was determined every 4 months for 32 months. Total C, N, P, and K concentration in leaf litter samples were determined at the beginning of the decay essay, and again after 8, 20, and 32 months. Two control samples per repetition were always simultaneously analysed with the leaf litter collected in the field in order to verify that the chemical composition of the leaves would remain constant when dried, stored, and kept at 5 °C during the entire assay. Variations in the chemical composition of control samples were found to be less than 5%.

Dry matter in foliar and woody biomass was determined by taking into account the weight before and after being oven-dried at 60 °C until constant weight. These samples were prepared before analysis as suggested by ISO 14780. Total C and N contents were determined by catalytic combustion followed by infrared CO_2 measurement (in the case of C) and thermal conductivity detection (for N) using a Leco elemental analyser and according to the International Standard ISO 16948:2015.

Total P and K contents were determined by inductively coupled plasma–optical emission spectrometry (ICP–OES) after acid digestion assisted by microwave radiation using a Thermo Jarrell Ash simultaneous spectrometer and following the International Standard ISO 16967:2015.

The calorific value was determined by calorimetry (Ika) following ISO 18125:2017.

2.7. Calculations and Data Analysis

Remaining dry matter, and remaining nutrient contents in litter bags at a specific time *t* were estimated according to Van Wesemael (1993) [26], while the nutrient release (R) was calculated by applying Guo and Sims' equation (1999) [27].

A single negative exponential model was used to estimate the annual decay constant k [18]:

$$M_t = M_0 \exp^{-kt} + S_0 \quad (1)$$

where Mt is the residual mass (%) at time *t* (years), M_0 is the initial mass of the material subjected to loss (%), S_0 is the asymptote (%), and k is the decomposition rate (year^{-1}). The sum of M_0 and S_0 is 100%, and an estimate of one of these can be used to derive the other, as explained elsewhere [28].

Data were analysed by the statistical software Statgraphics Plus 5.0 in order to determine how soil characteristics, leaf litter mass, and nutrient concentration in decomposing leaf litter changed over time through analyses of variance (ANOVA). Mean differences across sampling dates were assessed using multiple range tests according to the Fisher´s Least Significant Difference (LSD) procedure. Significant effects were considered when *p*-values were $\leq$0.05. In the tables, different letters denote significant differences between the reported values at 95% confidence level.

3. Results and Discussion

3.1. Biomass Production and Composition

Annual woody biomass production ranged between 2.6 and 11 dry Mg ha^{-1} year^{-1}, averaging 6.0 dry Mg ha^{-1} year^{-1} (Table 3). As can be seen in Table 3, yields varied widely across years over the study timeframe, probably in connection with the variable annual precipitation (Section 2.1). The highest yield (10.9 Mg ha^{-1} year^{-1}) was obtained in 2008. This was, in part, attributed to the growing season precipitation (May to August) recorded (Figure 1). Similar yields were obtained on long-term studies of poplar crops in short rotation systems on marginal Mediterranean conditions, reporting annual production between 2 and 10 Mg ha^{-1} year^{-1} across clones, fertilization treatments, and different harvest alternatives [6,8]. Similarly, annual poplar productions ranged between 3 and 13 Mg ha^{-1} year^{-1} for six 3 year rotation cycles on marginal soils in other European areas [29].

Table 3. Woody and foliar biomass annual production and composition.

	Year	Annual DM Production	C	N	P	K
		(Mg ha^{-1} year^{-1})	(g/kg, db)			
Woody biomass	0 (cut)	2.6 ± 1.3	489	5.1	0.77	3.6
	1	7.5 ± 2.5	493	4.8	0.76	3.1
	2	10.9 ± 5.8	492	4.1	0.63	2.8
	3 (cut)	4.3 ± 2.5	490	3.1	0.90	3.3
	4	4.6 ± 1.0	490	4.9	0.76	3.6
	Mean	6.0 ± 3.2	491	4.4	0.77	3.3
Foliar biomass	0 (cut)	1.6 ± 0.8	445	22.6	1.94	4.7
	1	4.7 ± 1.6	443	22.4	1.99	4.6
	2	10.3 ± 4.6	447	23.2	1.85	4.7
	3 (cut)	11.4 ± 6.7	446	22.8	1.95	4.7
	4	2.6 ± 0.6	447	22.5	1.96	4.8
	Mean	6.1 ± 2.7	446	22.7	1.94	4.7

Net calorific values of woody biomass (stems and branches) were estimated at 18.3–18.4 MJ kg^{-1} (db) over the duration of the study (data not shown). The average annual energy content was calculated at 110 ± 60 GJ ha^{-1} year^{-1} but did vary across years driven by variations in annual yield.

Sixty seven percent of the annual leaves fell in autumn, between September and November, a pattern common in temperate deciduous forests [30]. Foliar to woody biomass ratio was calculated annually taking into account the amount of leaves produced in a given year and the woody biomass of the crop (Table 3), ratios ranging between 0.50 and 0.62. Annual foliar biomass production averaged 6.1 dry Mg ha^{-1} year^{-1} (Table 3). Foliar production did vary significantly over time, linked to tree growth annual crown development, registering the lowest the first year of the study (1.6 dry Mg ha^{-1} year^{-1}) and reaching maximum values when trees were 2 and 3 years old (10 and 11 dry Mg ha^{-1} year^{-1}, respectively), which was consistent with the results obtained by Meiresonne et al. [31] and Lodhiyal and Lodhiyal [23].

Woody biomass averaged 4.4, 0.77, and 3.3 g kg^{-1} nutrient concentrations of N, P, and K, respectively, across years, close to the values found by the authors in a recent study under similar conditions [8]. NPK concentrations in the produced foliar biomass were higher than in branches and stems, and averaged 23, 1.9, and 4.7 g kg^{-1} across years.

3.2. Leaf Litter Decomposition

Litter mass in the bags largely remained stable (<2% mass loss) during the first four months of the study (Figure 2), coinciding with the winter season, probably due to the low temperatures and low relative ambient humidities that likely limited microbial activity [32]. Litter decomposition became active in the spring, coinciding with the rainy period in the area (Figure 1), resulting in a litter mass loss of 26% by 243 days. Litter mass again remained constant until the following spring (486 days), when decomposition resulted in additional litter mass loss to 41% of initial mass. At this stage, slow decomposition was observed, when almost a steady stabilized period was observed. In the end, maximum mass losses of 58% occurred after 2 years of exposure in the field (730 days). Mass losses were not statistically significant until the end of the study (973 days) compared to the initial values. Similar litter mass loss patterns were also observed in different land use types in the restoration trials in the Taihang Mountain ecosystems of China [33]; there they observed a rapid mass loss during the post-rainy season, but also documented nearly stable phases during their cold dry winters. It is known that the near surface microclimate has a direct effect on litter decomposition through the regulation of microorganism activity, and has an indirect effect on litter chemistry due to the influence that climate exerts on soil formation and nutrient cycling [10,34].

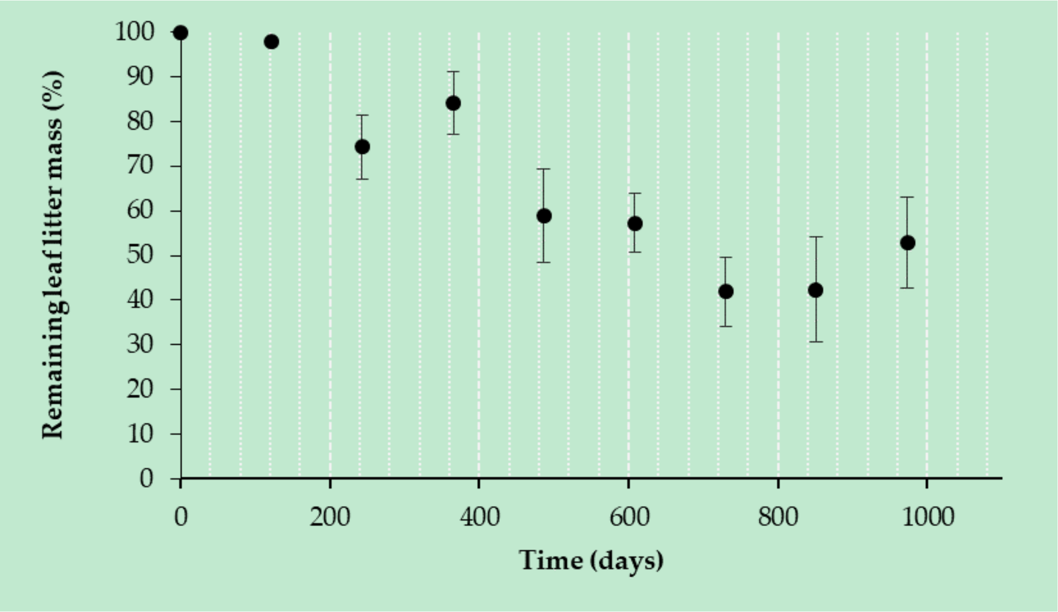

Figure 2. Remaining dry mass of decomposing leaf litter over time.

The evolution of litter mass over time (residual mass, %) was described using the exponential model described in Section 2.7, $M_t = M_0 \exp^{-kt} + S_0$ (Equation (1)) resulting in the following equation (r = 0.828):

$$M_t = 84.16 \exp^{-0.445\,t} + 16.27 \quad (2)$$

According to $M_t = 84.16 \exp^{-0.445\,t} + 16.27$ (Equation (2)), the decomposition rate was estimated at 0.44 year^{-1}, suggesting that the decomposition of poplar leaf litter in this semi-arid, marginal land was relatively slow. Faster decomposition has been observed for several poplar clones in riverine areas of central Spain, where estimated decomposition rates ranged from 0.65–0.78 year^{-1} for *Populus nigra* L. [35] to 2.01 year^{-1} for *Populus x hybrida* [10].

3.3. Nutrient Dynamics Associated with Leaf Litter Decomposition

Nutrients were released into the environment as the decomposition of leaf litter advanced. Nutrient concentrations in decomposing leaf litter over time are included in Table 4 whereas the percentage still present in decomposing leaf litter with respect to the initial litter nutrient was depicted in Figure 3.

Table 4. Nutrient concentration in decomposing leaf litter over time.

Time	Leaf Litter Mass in Bags	C	N	P	K
(days)	(dry g)	(mg g^{-1}, db)			
0	7.2 ± 0.0 ^{a}	447 ± 14 ^{a}	23 ± 2 ^{a}	1.9 ± 0.2 ^{a}	4.7 ± 0.5 ^{a}
243	5.3 ± 1.0 ^{b}	325 ± 37 ^{b}	21 ± 2 ^{ab}	1.2 ± 0.2 ^{b}	3.9 ± 0.8 ^{b}
608	4.1 ± 0.9 ^{c}	271 ± 61 ^{c}	17 ± 3 ^{c}	1.3 ± 0.2 ^{b}	5.6 ± 0.7 ^{c}
973	3.8 ± 1.5 ^{c}	304 ± 27 ^{bc}	18 ± 3 ^{bc}	1.1 ± 0.1 ^{b}	4.6 ± 0.5 ^{ab}
Diff (%)	−47	−32	−18	−42	−2

Mean values ± standard deviations. Values in columns with different letters (^{a},^{b},^{c}) indicate statistically significant differences over time at 95% confidence level (significance level < 0.05, *n* = 6). Diff (%): Nutrient concentration loss or dry matter release in the final sampling with respect to the initial sampling of the decay assay.

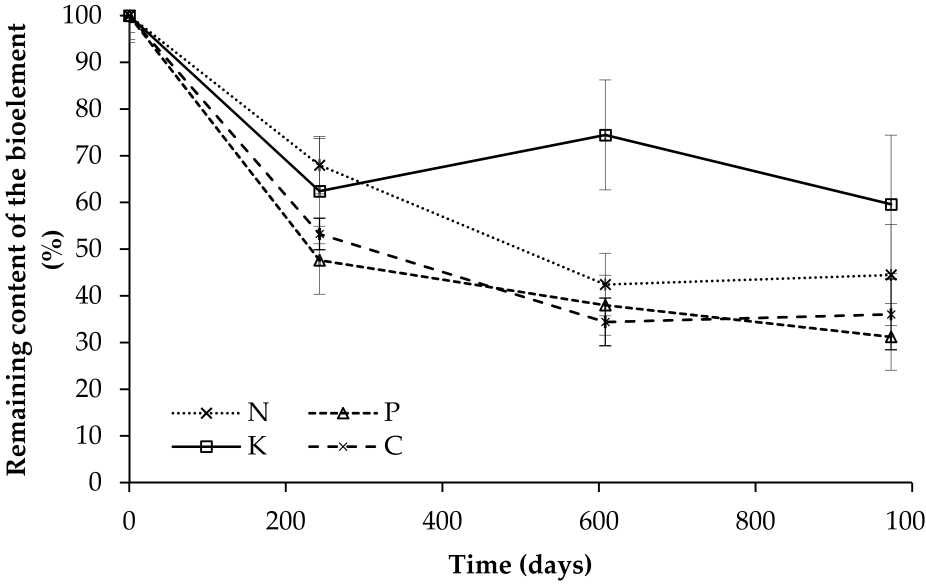

Figure 3. Remaining C, N, P, and K in decomposing leaf litter over time.

Fresh leaves showed initial nutrient concentrations of 23, 1.9, and 4.7 mg g^{-1} of N, P, and K, respectively (Table 4). After 8 months of exposure in the field, significant releases of all bioelements were measured (Figure 3), coinciding with the statistically significant mass losses that also occurred during this period (26%, Figure 2). At this time, 32% of N, 38% of K and 52% of P were released from decomposing leaves (Figure 3).

After a rapid K nutrient loss, K remained constant during the rest of the study period, stabilizing at an overall mean loss of 40% by the end of the study. This has been commonly reported in other leaf litter decomposition studies [15,36,37]. In contrast, P was released throughout the whole study period, reaching mean losses of 62% after 20 months and an overall mean loss of 69% after 32 months. Litter decomposition has been reported as a major input pool of P [31].

The initial release of N halted after 20 months, peaking at an overall loss of approx. 60%.

3.4. Carbon Dynamics

The initial C concentration in fresh leaves was 447 mg g^{-1} (Table 4). C was progressively released through the decomposition of leaves over the 20 month period, accumulating a loss of 66% after 20 months (Figure 3).

As illustrated in Table 5, the annual C release through decomposing leaves was estimated at 2.2 Mg ha^{-1}. Those losses are comparable to C annual releases (2.0–2.8 Mg ha^{-1}) through foliar C losses (52–69%) over the same period in northern Poland, where different poplar clones were planted on more productive soils [36].

Where marginal lands are used to grow bioenergy crops, C accumulation over a specified period, as well as C distribution among the different tree components, should also be considered as it contributes to the EU policy objective of reducing CO_2 emissions through C sequestration by roots. During the study period (2006–2009), this energy crop produced a total of 25.3, 28.0, and 5.6 Mg ha^{-1} of woody (stems and branches), foliar (leaves), and underground (roots) biomass, respectively (Table 5). The total C accumulated in the poplar woody biomass was estimated to be 12.4 Mg ha^{-1}. Roots sequestered a total of 3.1 Mg ha^{-1} of C during the same period. After three years, C in the planted poplar trees were distributed as follows: 68.0% in woody biomass, 15.0% in the topmost layer of the soil, and 17.0% in underground biomass. These values, particularly for the soil and roots, do differ from those reported in the literature [38,39], but may be the result of stand age (11–20 year old trees) or lower densities (roughly 1000 trees/ha) reported in these other studies.

Table 5. C dynamics after a 3 year rotation cycle.

Parameters	Units	
Woody biomass production (2006–2009)	Mg ha^{-1}	25.3
Foliar biomass production (2006–2009)	Mg ha^{-1}	28.0
Underground biomass production (2006–2009)	Mg ha^{-1}	5.6
Accumulated C in woody biomass (2006–2009)	Mg ha^{-1}	12.4
C sequestered by underground biomass (2006–2009)	Mg ha^{-1}	3.1
C content in the upper layer of the soil (2006–2009)	Mg ha^{-1}	2.8
Annual C foliar production	Mg ha^{-1}	3.2
Annual C output by litter decomposition	Mg ha^{-1}	2.2

3.5. Soil

To determine whether nutrient release through foliage was enough to restore soil nutrients without the need of additional fertilization application, soil characteristics were compared between the beginning (December 2006) and the end of the litter decay study (August 2009) (Table 2).

N_t, P_{av}, and K_{av} increased significantly in the top soil layer during leaf litter decomposition. After 32 months, two- and three-fold increases were obtained for N_t and P_{av}, respectively. N_t increases were significant across all soil layers. In contrast, soil organic C and organic matter did not experience any significant changes over the same period in the upper soil layers, but did increase significantly in the deeper layers. C/N ratio and pH did decrease over time. Results suggest that even though no fertilization was applied after planting, this marginal soil showed no evidence of being exhausted of nutrients by the end of the decomposition study.

3.6. Nutrient Balance between Litter Decomposition and Crop Uptake

The balance between the annual nutrient uptake by the aerial biomass (stems, branches, and leaves) and the annual nutrient release to the soil through leaf litter decomposition is shown in Figure 4. The nutrient uptake by the aerial biomass was calculated annually by considering the aboveground biomass produced that given year and the composition of the woody and foliar biomass. Nutrient release from litterfall in a given year was estimated by taken into account the leaves that fell that season plus the rest of the leaves that had accumulated on the ground and were still undergoing decomposition. Calculations assumed that the newly produced fresh leaves would follow the same decomposition pattern over the 32 month decay study described in Figure 3.

As illustrated in Figure 4, the supply of nutrients into the system through litter decomposition increased every year. Based on our calculations, by the fourth year after establishing the crop (i.e., after the first rotation cycle), leaf litter released greater amounts of primary macronutrients to the environment than the nutrient uptake requirements by the growing poplar crop (woody and foliar biomass). Over this timeframe, decomposing leaves were able to provide 180, 19, and 30 kg ha^{-1} of NPK, respectively, in contrast to crop uptake estimates of 83, 8.7, and 29 kg ha^{-1}, respectively (Figure 4). Biomass production was relatively low (7.2 Mg ha^{-1} year^{-1}) the first year of the second rotation cycle (Table 3) in comparison with the first rotation cycle (12–21 Mg ha^{-1} year^{-1}), where nutrient release from litterfall was clearly higher due to the accumulation of decomposing leaves and the elevated foliar production in the two previous years combined (21 Mg ha^{-1}). Therefore, during the first year of the second rotation cycle, the poplar crop should have been able to naturally access available nutrients through leaf litter decomposition.

Further research is needed to confirm the extent to which the nutrients released by the decomposition of leaf litter can be actually available to the crop, as the origin of the nutrients extracted by the crop or the ultimate destination of the nutrients from decomposing leaf litter was not evaluated in this study. The use of an isotope tracer would be very useful in this regard [33,40]. Nutrients from decomposing leaves could be partially unavailable through simultaneous processes such as microbial immobilization, deep percolation into groundwater, volatilization, or countered through the addition into the system, e.g., by atmospheric deposition. The amount of NPK supplied into the system via inorganic fertilization addition would also be subjected to losses from these processes. These soil process interactions could be of relevance in marginal environments and should be further investigated.

In addition, the study of nutrient dynamics over multiple rotations in a short rotation poplar crop (e.g., three rotation cycles) in Mediterranean marginal areas [6,8] would also be advantageous to more accurately estimate the nutritional needs (supply/demand) of these energy plantations and develop sustainable management systems.

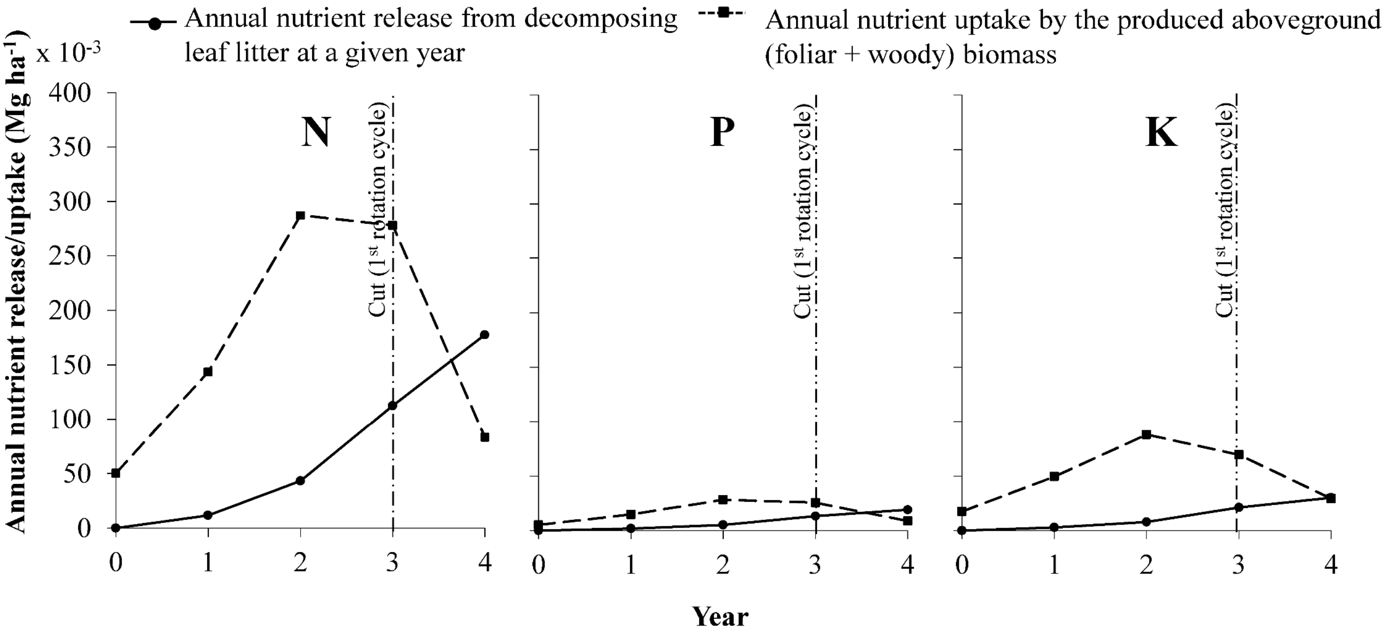

Figure 4. Balance between the release of nutrients into the environment through leaf litter decomposition and the nutrient uptake by the aerial biomass.

4. Conclusions

In our experiment, it was found that leaf litter decomposition was very slow during the first winter months and was accelerated in early spring, around April, coinciding with the rainy season and the period when temperatures begin to increase in the area. Overall, the decomposition rate of poplar leaves under the conditions of this study can be considered slow in comparison with other Mediterranean environments, probably in connection with the particular meteorological conditions of the study site, located at high altitude above sea level and with a continental influence that results in relatively cold winters with low minimum temperatures.

At the beginning of the first spring, 30% of the N, 40% of the K, and 50% of the P that were initially present in fresh leaves had already been released into the environment. No more K was released from that moment on. At the end of the study (32 months), only 50% of the initial litterfall was decomposed, releasing roughly 60% of the N and 70% of the P initially present in fresh leaves.

No NPK deficiencies were noticed in the soil at the end of the decay study.

Even in a marginal low productive soil such as the one in this study, it was estimated that, in the fourth year after establishing the energy crop, nutrient release through leaf litter decomposition was able to provide higher amounts of primary macronutrients to the environment than the nutrient uptake by the produced aboveground biomass (woody and foliar biomass). Moreover, after the first 3 year rotation cycle, the roots of this energy crop contributed to reduce CO_2 emissions by sequestering a total of 3.1 Mg ha^{-1} of C, which can enhance carbon soil restoration and avoid soil erosion.

This study offers a more accurate and detailed knowledge of how leaves decompose in a poplar crop established at high tree density under Mediterranean marginal conditions and a low input agricultural management system, and to what extent nutrients are released into the environment through leaf litter decomposition. The consideration of nutrient inputs from decomposing poplar leaves would result in fertilization savings that might be of relevance to low productive areas and help to estimate the viability of biomass production from this type crop under Mediterranean marginal conditions.

Further research would be needed to determine the origin of the nutrients extracted by the crop or the ultimate destination of the nutrients released from decomposing leaves during the whole useful lifespan of a short rotation poplar crop in these particularly sensitive areas.

The generation of energy or other non-food uses from short rotation woody crops from agricultural marginal lands is not in conflict with food production and would increase opportunities in rural areas.

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