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Article

Influence of Different Tillage Systems and Weed Treatments in the Establishment Year on the Final Biomass Production of Short Rotation Coppice Poplar

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Abstract: In this study the influence of three different tillage systems in combination with eight varying weed treatments applied within the establishment year and its effect on the final above ground leafless biomass production (after the third growing season) of short rotation coppice poplar is presented. The three tillage systems included variants with ploughing and harrowing, variants with cultivation and ley cropping and variants without tillage. Weed treatments included the application of different herbicides, but also more environmentally sound variants such as mulching and the use of mulch materials to avoid the use of herbicides. To estimate the influence on final biomass production, regression analysis was undertaken using DBH as the predictor variable. Based on 1056 DBH measurements the biomass production of the different variants was compared. The interactions of tillage system and weed treatment on biomass yield were found to be statistically significant. Between tillage systems the ploughing variant displayed a better overall performance than the cultivation with ley crop variant and the variant without any tillage. Differing weed treatments reveal greater success for the whole area application of herbicides than band application, both being better than the use of mulch materials. These results suggest that the right tillage system in combination with effective chemical weed control is the key to the successful establishment of Short rotation coppice (SRC) poplar plantation following the principles of an integrated weed management approach. Furthermore, ecological variants such as ploughing in combination with the use of mulch materials and mechanical vegetation control between the rows could be a solution to reduce dependence on chemical control. However, this comes at the expense of a considerable loss in yield.

Keywords: SRC; short rotation coppice; plantation establishment; biomass; herbicide; weed control; poplar

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1. Introduction

The increasing demand for wood for energetic purposes in the last decades has raised attention in plantations stocked with fast growing trees such as poplar (*Populus* spp.) and willow (*Salix* spp.). Short rotation coppice (SRC) plantations providing high wood yields are now a strong focus of research with an aim to improve planting material as well as plantation design and management. A successful establishment phase is essential for the long-term productive success of poplar plantations [1]. The control of weed species to ensure a maximal yield is an important element of SRC management, since the occurrence of weeds can present a significant suppression of crop growth coupled with an increased rate of mortality. It has previously been estimated that during the establishment year vigorous weeds were found to reduce SRC growth by 50% to 95% [2]. A weed has previously been defined as "*a plant that is growing where it is not wanted by humans*" [3] and as "*plants [...] that grow in sites where they are not wanted and which usually have detectable, negative economic, environmental and/or social effects*" [4]. Problematic weed species are in direct competition with the crop for water, nutrients and light and can potentially harbour species that can cause detrimental effects to the SRC crop. It has been suggested that the competitiveness of a weed species is closely linked to both the crop's growth strategy and morphology thus allowing it to effectively compete with the crop, primarily for available nutrient, water and secondarily light [5]. Successful weed control should include the eradication of root competition since the removal of above ground weed biomass can be considered ineffective as a long-term solution [6]. Most research and guidance emphasises the importance of weed control due to the low competitive ability of SRC poplar and willow during the early stages of growth [7]. SRC poplar is known to be most sensitive in regards to weed competition during the establishment phase, but such sensitivity differs considerably between hybrid varieties [8]. Moreover, weed control can be considered as one of the most critical factors determining the success or failure of plantation establishment [9]. The longer the suppression of weeds is successful, the better the poplar will grow and the less potential damage will occur through late stage weed control [9]. Guidance has been provided suggesting that the site should be clean-tilled and weed free at the time of planting and this should be maintained until canopy closure when the crop is able to naturally suppress weeds [9,10]. Nevertheless, weeds are able to re-establish quickly [9] and therefore, guidance recommends the use of pre- and post-emergence herbicides to intensify and prolong the effect of the initial tillage operations [1,7,9–12]. Beyond this, the application of a "contact" herbicide, post first year cutback and after subsequent harvests is recommended [12]. Nonetheless, the most critical time for SRC is the establishment phase, later weed control is less important since the plants have already established root systems, therefore grow faster and are able to shade out weeds at the point of canopy closure.

There are three main mechanisms of weed control carried out within modern agronomic practice, either in combination, or occasionally singularly when a particular criterion must be fulfilled: Mechanical weed control, chemical weed control and "Passive methods".

Mechanical weed control includes all physical disturbances of the weeds such as tilling, mowing and rotovating. This type of weed control is a common practice to manage the conflict of weed control balanced with the avoidance of chemicals. For mechanical weed control the planting density must be adjusted to suit management operations since damage to resprouting stools can occur. Mechanical weed control can be considered as being environmentally friendly but more labour intensive and thus more expensive per unit area, besides the effect on weeds is short-lived. Mowing for example, is described as a method of weed control but weeds quickly re-establish over time, such a method has virtually no effect on below ground competition. Furthermore, small mammals that have the potential to cause damage to the crop may use the resulting mulch as cover [1].

Chemical weed control covers the usage of a broad range of different herbicides that are currently commercially available but not currently licensed for SRC application in Germany (an exemption is required by German Law). They can be classified in manifold ways, for example by their persistence (long/short), selectiveness (selective/non-selective), mode of action (contact/systemic/soil sterilant) or application type (pre-emergence/post-emergence). The use of herbicides is on the one hand less labour intensive and has a longer lasting effect on the weeds while on the other hand non-targeted plants and animals can be affected.

"Passive methods" include the planting of companion crops to outcompete the weeds. This method is an environmentally friendly approach, but importantly during the critical first months post establishment the companion crops are also competing with the SRC in the upper soil layers for nutrient, water and light. One study found utilising ten different cover crops that were tested with five poplar clones kept weeds within acceptable levels, but concurrently retarded the growth of hybrid poplars [13]. A further "passive method" is the use of mulch material to cover the soil such practice prevents the existing weed seed bank from germinating. The success of mulching is depending on the type of mulch material, pre-existing ground conditions [6] and the size of area around the trees that is covered it has been suggested this should cover an area of approximately 1 m^2 without the support of any form of herbicide application [14]. Mulches can include natural materials such as straw, composted material, bark, or wood chips; recycled materials such as newspaper or fibre slurries; or can utilise specialist material fit for purpose such as biodegradable (starch based) or conventional plastic "poly" mulch sheets. The use of which is much depending on the quality of the site and the intensity of the accompanying management operations [15].

Most research agrees that the use of herbicides and pesticides should be limited [16–18], the culture of poplar or willow SRC itself requires less artificial input than conventional arable cropping systems [10]. From an ecological point of view the most intensive use of herbicide still means a more extensive approach for the environment than the standard application regime employed for annual crops. Typical herbicide prescriptions within SRC utilise both pre- and post-emergence herbicides occasionally with additional herbicides or mechanical weeding to the point of canopy closure, at which point the crop is able to sufficiently suppress weed growth independently. A sustainable approach to the control of weeds is that of integrated weed management (IWM). Within such a framework the control of weeds within a cropping system is not reliant on one method of control, but rather a targeted combination of chemical, mechanical and cultural methods to reduce weed competition to an acceptable level. This approach is not indiscriminate and relies on the practitioner specifically targeting certain weed species at a point in time when vulnerability is greatest (young weed plants) or in a precautionary way to prevent further spread (before weed seed is formed and distributed), while simultaneously minimising risk of damage to the crop and the environment. The core message being that prevention is better than control. To obtain a targeted approach information is needed regarding the critical period of weed control *i.e.*, when growth is most affected by weed competition, hence when control is most needed, a key component of IWM [19]. Such course of action is already common practice within agriculture and applied within several different cropping systems [20–23].

2. Materials and Methods

2.1. Description of the Experimental Plot

2.1.1. Soil

The 1.74 ha research plot is located on abandoned agricultural land previously stocked with wheat in north-western Baden-Württemberg, Germany (Latitude: 49°10'52.62"; Longitude: 8°46'17.15") at an elevation of 161 m above sea level. The underlying geology is typical of the Germanic Trias Group, consisting of the Keuper strata (dolostone, shales and claystones) with sandstone over shell bearing limestone further overlying bunter sandstone [24]. The site, situated in a shallow valley, is dominated by brown riparian soils with gley components and riparian pararendzinas derived from periglacial loess deposits. Soil types and their freely-available nutrient composition are shown in Table 1.

Table 1. Research plot soil types, pH, organic matter and N, P, K composition.

Tillage system	**Sample depth** (cm)	**Soil type**	**pH**	**Organic matter** (%)	**Nitrogen N** (g kg^{-1})	**Phosphorus P** (mg kg^{-1})	**Potassium K** (mg kg^{-1})
A	0–30	silt loam	7.5	1.8	1.3	6.5	5.8
Ploughing &	30–60	silt loam	7.4	2.1	1.4	7.9	6.6
harrowing	60–90	silt loam	7.6	0.8	0.7	1.3	1.7
B	0–30	silt loam	7.2	2.3	1.5	7.0	8.3
Cultivation	30–60	silt loam	7.4	1.4	1.1	4.4	2.5
with ley crop	60–90	silt loam	7.5	0.6	0.6	0.9	1.7
C	0–30	silt loam	7.3	2.3	1.5	6.5	11.6
No tillage	30–60	silt loam	7.4	1.8	1.4	7.0	5.8
	60–90	silt loam	7.3	1.0	0.8	1.3	1.7

Soil analysis values represent the mean of all analysed samples taken post-planting early in the establishment year from each of the three different management types and repetition blocks, analysed in accordance with established methodologies [25]. Site soil conditions were found to be consistent across the plot with no significant difference between blocks or management units. Site conditions can be considered favourable for the culture of SRC poplar [7].

2.1.2. Climate

The region has a climate dominated by warm summers and mild winters. Mean annual precipitation amounts to 819 mm (May–Sept.: 377 mm). Mean annual air temperature is 9.4 °C (May–Sept.: 16.1 °C) distributed between an average minimum air temperature of −0.7 °C and a maximum of 18.8 °C. Monthly based means of air temperature and precipitation sum based on the 1961 to 1990 Climate Normals and actual monthly climatic conditions for the years 2010 to 2012 were obtained from interpolated gridded data with a resolution of 1 km × 1 km [26], as shown in Figure 1.

Figure 1. Climate data for the Stifterhof Research Plot 2010 to 2012.

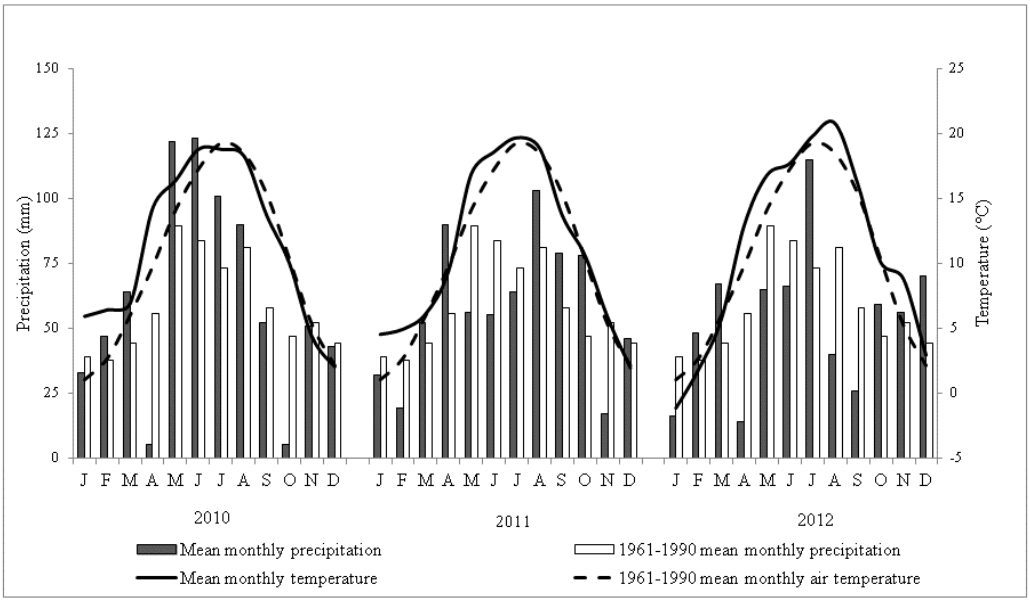


Figure 1 reveals a very dry April in 2010 in comparison with the 1961–1990 Normals. This can be considered a critical period, important for the successful establishment of a poplar crop, such a situation however, was short lived and was followed by a wet summer negating any water deficit accrued earlier in the year. The air temperature during the three year growing period was slightly above the recorded 1961–1990 Climate Normals, meanwhile, precipitation during these years was dryer than the average with the exception of single months, markedly April to July 2011 and April to June, August and September 2012.

2.2. Plantation Design

The plot was planted at the end of March 2010 utilising the Poplar variety "AF2" (*Populus deltoides* × *P. nigra*). 20 cm long cuttings were placed vertically in the ground in single rows at a spacing of 2.0 m × 0.7 m, thus reflecting a stocking density of 7143 cuttings ha^{-1}. Plantation design was set out as given in Figure 2 as a split plot design with blocking [27]. The research plot consists of three tillage systems (A, B, C) constituting the whole plots or blocks, each including eight distinct weed treatments representing the sub-plots. This provided a total of 24 parcels, one parcel for each distinct variant, with three replicates, totalling in 72 parcels. An additional row was planted at the outer edge of each sub-plot (e.g., "B8" and "B7" block 1) if not adjoined by another.

In total nine different herbicides have been used for the trial. They can be grouped in three different categories being *Selective residual pre-emergence herbicides*, *Non-selective post-emergence herbicides* and *Selective systemic post-emergence herbicides*. In Table 2 the trade names, active ingredients, target and the application rates of the herbicides are displayed. Details towards each variant are given in Table 3. Three tillage systems were utilised, providing variation between purely mechanical (A), purely chemical (C) and a combination of chemical and mechanical (B) tillage.

Additionally four groups of weed treatments were applied. Group I using a broadcast application of herbicide defined as the treatment of the whole subplot area (weed treatments "1–3"), group II using a band spray application of herbicides within the poplar rows only (weed treatments "4–6"), group III being the ecological variant using mulch mats (weed treatment "7") and group IV constituting the control without any weed treatment (weed treatment "8").

Initial chemical treatment utilised glyphosate with the target species and rate given in Table 2, spraying was carried out one week before planting. Herbicide application method (*i.e.*, total area or band spraying within the rows) was further defined by the specific weed treatment variant "1" to "6". If no herbicide treatment was prescribed within a specific weed treatment variant (e.g., variant "7" and "8") none was applied. Eight variants of weed treatment were used within each tillage system type. Weed treatment consisted of a predefined non-selective treatment as outlined above plus the application of a pre- and post-emergent herbicide as defined in Table 3. In most cases a combination of products was utilised as permitted by the product label. Furthermore, variants "7" and "8" exploited non-chemical control methods, the former utilising a compostable starch based mulch sheet and the latter no weed treatment at all, thus constituting the control treatment. Additional to any herbicide application a number of weed treatment variants prescribed the cutting (mulching) of weed or cultivation between rows. Spraying was carried out using a tractor mounted boom sprayer while for weed treatment variant "6", a herbicide contact roller ("Rotowiper") was utilised for the application of glyphosate. Specific timings of the main agronomic practices are shown in Table 4.

Figure 2. Plantation design showing the nine sub-plots consisting of three different tillage systems (A, B, C) and eight different weed treatments (1–8) within a three block replication.

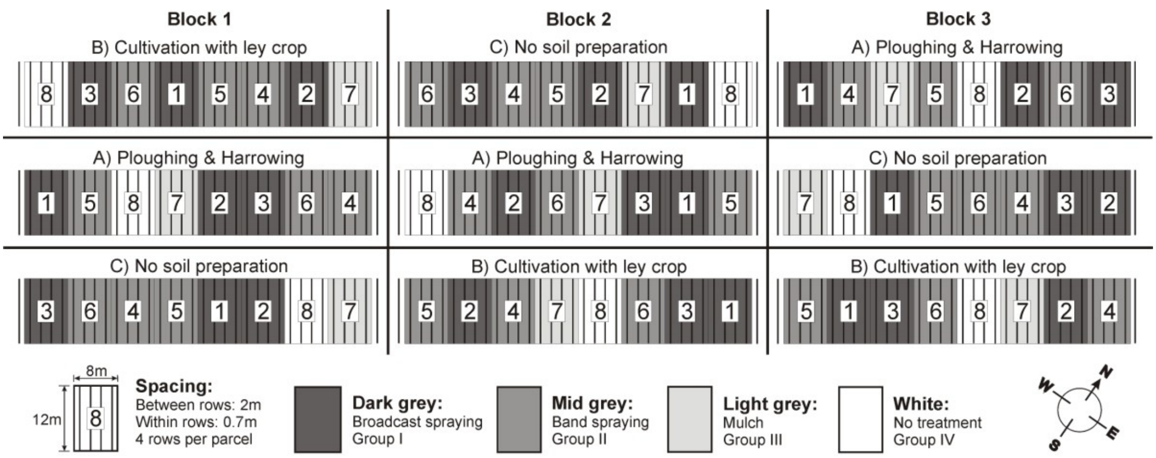


Table 2. Herbicides and their active ingredients used in this study.

Trade name (Company)	Active Ingredient	Target	Application rate
Selective residual pre-emergence herbicides			
Stomp® Aqua *(BASF SE, Ludwigshafen, DE)*	Pendimethalin 455 g/L	●■	2.5l ha^{-1}
Terano® *(Bayer CropScience AG, Monheim am Rhein, DE)*	Metosulam 25 g/kg Flufenacet 600 g/kg	●■	1.0 kg ha^{-1}
Sencor® WG *(Bayer CropScience AG, Monheim am Rhein, DE)*	Metribuzin 700 g/kg	●■	750 g ha^{-1}
Non-selective post-emergence herbicides			
Glyfos® *(Cheminova GmbH & Co KG, Stade, DE)*	Glyphosate 480 g/L [*N*-(phosphonomethyl)glycine]	●■◆	5.0 l ha^{-1}
Roundup® UltraMax *(Monsanto Europe S.A., Antwerp, BE)*	Glyphosate 480 g/L [*N*-(phosphonomethyl)glycine]	●■◆	33% solution *
Selective systemic post-emergence herbicides			
Lontrel 100™ *(Dow AgroSciences GmbH, Munich, DE)*	Clopyralid 100 g/L	●	1.2 l ha^{-1}
Fusilade Max™ *(Syngenta Agro GmbH, Maintal, DE)*	Fluazifop-*p*-butyl 125 g/L	■	2.0 l ha^{-1}
Katana® *(ISK Biosciences Europe N.V., Diegem, BE)*	Flazasulfuron 250 g/kg	●■	200 g ha^{-1}
Kontakt® 320 SC *(Feinchemie Schwebda GmbH, Cologne, DE)*	Phenmedipham 320 g/L	●	3.0 l ha^{-1}

● = Annual Broadleaf Weeds, ■ = Annual and Perennial Grasses, ◆ = Woody Species, * application using weed wiper equipment (coverage per hectare undeterminable).

Table 3. Tillage systems specifying herbicide and/or mechanical weed treatment combinations for each variant.

			Tillage system		
		Weed treatment	**A** **Ploughed in autumn, harrowed in spring**	**B** **Soil cultivation with ley crop (*Lolium perenne* 'Kabota')**	**C** **No tillage**
I	**1**	Broadcast[1]	---	Glyfos	Glyfos
		Broadcast Pre-emergent	Terano/ Stomp	Terano/ Stomp	Terano/ Stomp
		Broadcast Post-emergent	F. Max/ Lon. 100	F. Max/ Lon. 100	F. Max/ Lon. 100
	2	Broadcast[1]	---	Glyfos	Glyfos
		Broadcast Pre-emergent	Terano/ Stomp	Terano/ Stomp	Terano/ Stomp
		Broadcast Post-emergent	Katana	Katana	Katana
	3	Broadcast[1]	---	Glyfos	Glyfos
		Broadcast Pre-emergent	Sencor WG	Sencor WG	Sencor WG
		Broadcast Post-emergent	Kontakt 320 SC	Kontakt 320 SC	Kontakt 320 SC

Table 3. *Cont.*

		Weed treatment	Tillage system: A Ploughed in autumn, harrowed in spring	B Soil cultivation with ley crop (*Lolium perenne* 'Kabota')	C No tillage
II	4	Band spray [1]	---	Glyfos	Glyfos
		Between Rows	Mowing	Mowing	Mowing
		Band spray Pre-emergent	Terano/ Stomp	Terano/ Stomp	Terano/ Stomp
		Band spray Post-emergent	F. Max/ Lon.100	F. Max/ Lon. 100	F. Max/ Lon. 100
	5	Band spray [1]	---	Glyfos	Glyfos
		Between Rows	Rotivation	Rotivation	Rotivation
		Band spray Pre-emergent	Terano/ Stomp	Terano/ Stomp	Terano/ Stomp
		Band spray Post-emergent	F. Max/ Lon.100	F. Max/ Lon. 100	F. Max/ Lon. 100
	6	Band spray [1]	---	Glyfos	Glyfos
		Between Rows(Rotowiper)	---	Round-up	Round-up
		Band spray Pre-emergent	Terano/ Stomp	Terano/ Stomp	Terano/ Stomp
		Band spray Post-emergent	F. Max/ Lon.100	F. Max/ Lon. 100	F. Max/ Lon. 100
III	7	Within Rows[1]	Mulchmat	---	---
		Between Rows	Mowing	Mowing	Mowing
IV	8	No weed treatment (Control)	---	---	---

Note: [1] = Pre-planting application.

Table 4. Main agronomic practices carried out on plantation.

Operation	Date/Timeframe
Soil preparation	Autumn/Winter 2009/2010
Glyphosate application	March 2010 (1 week before planting)
Planting	March 2010
Pre- emergence herbicide application	March 2010 (4 days after planting)
Mulching, cultivation & weed wiping between the rows	May & August 2010
Post- emergence herbicide application	June & August 2010 *
Harvest	January 2013

* supplementary application of "Katana" to variants "1–6", to suppress excessive growth of field bindweed (*Convolvulus arvensis* L.).

2.3. Sampling

After the third growing season (end of first rotation, January 2013) DBH measurements (stem diameter measurement at 1.3 m above ground) were taken from the two inner rows of each variant parcel (22 trees) with a three tree buffer at the end of each row to negate any edge effect, totalling 1056 trees across two tillage systems and eight weed treatment variants. DBH was measured using digital callipers in two directions perpendicular to each other. It must be noted that the tillage system "C" which employed no mechanical intervention displayed greater than 80% mortality at an early stage within the investigation and therefore was excluded from further studies. Additionally, during measurement dead or missing trees were noted allowing for an assessment of mortality between the variants.

It was assumed that individual tree architecture would remain the same between treatments as all trees were of the same age, species, variety and were planted at the same stocking density. A total of 50 trees were destructively sampled across tillage systems and weed treatments chosen to represent the spread of DBH found within the plot. For each sample tree DBH measurements were taken and the tree was weighed in the field using a scale with a given accuracy of ± 0.05 kg. As the trees were felled during the period of winter dormancy, biomass refers to leafless above ground biomass.

Chipped samples from mixed tillage system and weed treatment variables, amounting to approximately 4 kg were taken from the field to calculate a fresh/dry weight conversion factor. Samples were dried in an oven at 105 °C until of a constant weight.

2.4. Data Analysis

Statistical data analysis was carried out using SPSS for Windows 20.0 software [28]. The level of significance was set at $p = 0.05$ for all analyses. Normality was ensured by means of a Shapiro-Wilk test. Weight data for oven dry above ground leafless biomass and DBH measurements were natural log transformed to determine the model to be fitted, a common practice within biomass estimation procedures [29–33]. It is common to use allometric biomass equations as a method of relating an easily measurable parameter to that of a less obtainable dependent factor such as dry tree weight. DBH and height are frequently used as predictor variables, both have been demonstrated to be strongly indicative of dry above ground woody biomass [34–36]. The log transformed data on both x and y axis followed a linear relationship thus denoting that an allometric power model provides the best fit to the data [37]. The least-squares method of linear regression was carried out utilising the log transformed data providing the model as given in Equation 1 where B (biomass) is the dependent variable, DBH the predictor variable, while a and b are the regression coefficients.

$$\mathrm{Ln}(B) = a + b\ \mathrm{Ln}(\mathrm{DBH}) \tag{1}$$

By utilising the model given in Equation 1 ($R^2 = 0.98$, $F(1,53) = 2427.0$, $p = < 0.001$), residuals were analysed for homoscedasiticity and a normal distribution. A Durbin-Watson test was conducted to assess whether there was any autocorrelation between residuals, and thus signifying whether or not they are independent. A retransformation procedure was carried out using the regression coefficients deduced from the general linear function (Equation 1) applied to Equation 2. Since the use of natural log transformed data shows a tendency to slightly under-predict the dependent variable [38] a correction factor (β) was applied (Equation 3) where S_e (0.2) is the standard error of the regression.

$$B = \exp(-7.243 + \beta)\ \mathrm{DBH}^{2.133} \tag{2}$$

$$\beta = 0.5\ S_e^2 \tag{3}$$

The derived model as given in Equation 2 was applied to the DBH measurements taken from the inner parcels of each tillage system and weed treatment variant. This provided an estimate of whole tree dry above ground leafless biomass for each tree within each sub-plot. Furthermore, estimated figures for sub-plot mortality were made. A two way ANOVA (Analysis of Variance) was conducted to assess differences between the main effects of tillage system and weed treatments as well as the combined interaction of both main effects (tillage system*weed treatment). Biomass yields per hectare and year were determined at the end of the first rotation (after three growing seasons) between tillage systems and weed treatments. This was carried out to reflect the influence of effective weed management prescriptions over the whole rotation and to obtain realistic values for biomass production for comparison with other biomass studies.

3. Results

Using DBH as the predictor variable (β = 0.99, p = < 0.001) for dry biomass in combination with mortality determined the mean estimated biomass after the third growing season. The samples taken for the determination of a conversion factor from fresh to dry weight revealed an oven dry weight that was 44.2% of fresh sample weight. In Table 5 the mean estimated dry biomass per tree can be found to cover a range from 0.70 kg for variant "A8" (control) to a biomass of 4.63 kg for variant "A2". The mortality rate ranged from 0% (A2) to 27.3% (B6). Since the mortality has a direct influence on the biomass production on a hectare basis "A2" resulted in the highest biomass production of all variants 11.0 odt $ha^{-1}yr^{-1}$ and "B6" resulted in the lowest biomass production of all amounting to 2.2 odt $ha^{-1}yr^{-1}$, with the exception of the control variant (A8).

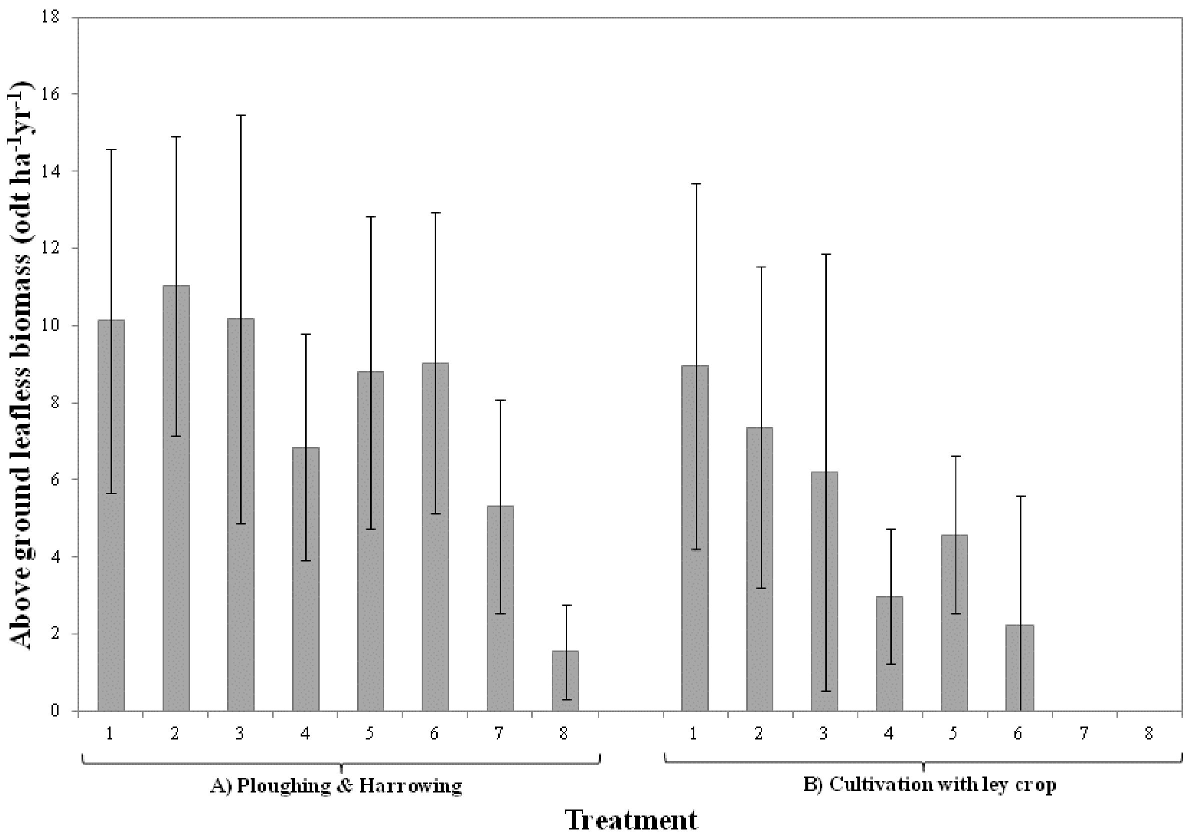
Table 5. Mean DBH, mortality, mean biomass per tree and per hectare and year by weed treatment plot.

Tillage System	Weed treatment groups*	Weed treatment*	Mean estimated biomass per tree	Mortality	Mean estimated biomass yield
			(kg)	(%)	(odt $ha^{-1}yr^{-1}$)
A	I	1	4.39 $_a$	3.0	10.1
		2	4.63 $_a$	0.0	11.0
		3	4.48 $_a$	4.5	10.2
	II	4	3.06 $_{bc}$	6.1	6.8
		5	3.81 $_{ab}$	3.0	8.8
		6	3.85 $_{ab}$	1.5	9.0
	III	7	2.33 $_c$	4.5	5.3
	IV	8	0.70 $_d$	7.6	1.5
B	I	1	4.00 $_e$	6.1	8.9
		2	3.40 $_{ef}$	9.1	7.4
		3	2.96 $_f$	12.1	6.2
	II	4	1.35 $_g$	7.6	3.0
		5	1.95 $_g$	1.5	4.6
		6	1.29 $_g$	27.3	2.2
	III	7	---	>80	---
	IV	8	---	>80	---
C	I-IV	1-8	---	>80	---

* Refer to Table 3 for detailed description. Mean values within columns followed by the same letter are not significantly different according to Tukey HSD test (sig level $p < 0.05$, p-values: a = 0.62, b = 0.80, c = 0.14, d = 1.00, e = 0.22, f = 0.62, g = 0.12).

The Tukey HSD post hoc test showed that all three tillage systems were significantly different (significance level $p < 0.05$, p-values: a = 1.00, b = 1.00, c = 1.00). In addition, the test showed a clear tendency to group the same weed treatments prescriptions together within both tillage systems "A" and "B" as can be seen in Table 5. In terms of above ground woody biomass production the weed treatment variant groups can be seen to rank: Group I: Broadcast application (variants 1–3) > Group II: Band application (variants 4–6) > Group III: mulching (variant 7) > Group IV: control (variant 8).Choice of tillage system and weed treatment shows a substantial impact on biomass production as seen in Figure 3. Variant "A" produced higher biomass for the area spraying (Group I) for band spraying (Group II) and provided results within Groups III and IV where the other tillage system variants failed. The control variant "A8" produced a low biomass yield amounting to 1.5 odt $ha^{-1}yr^{-1}$, this can be considered to be in direct contrast with the other control variants "B8" and "C8" where mortality was observed to be greater than 80%.

Figure 3. Biomass production per hectare and year (± SD). The x-axis shows tillage system and weed treatments as explained in Table 3. (Figure exclusive of tillage system "C" due to an excessive rate of first year mortality).



By means of a two-way ANOVA [27,39] the main effect of the applied tillage system was found to be significant, as was the main effect of applied weed treatment. The interaction of both factors (tillage system*weed treatment) was also highly significant the results of the analysis can be seen in Table 6. Furthermore, the replicate blocks were found to be not significantly different, meaning the site conditions can be considered homogeneous.

Table 6. Analysis of variance for the split plot design.

	Sum of Squares	df	Mean Square	F	*p*-Value
Blocks	7.77	2	3.89	2.9	0.05
Tillage System	3073.99	2	1537.00	1154.1	<0.01
Blocks*Tillage system	68.60	4	17.15	12.9	<0.01
Weed Treatment	1155.69	7	165.10	124.0	<0.01
Blocks*Weed Treatment	89.04	14	6.36	4.8	<0.01
Tillage System*Weed Treatment	708.19	14	50.59	38.0	<0.01
Blocks*Tillage System*Weed Treatment	146.11	28	5.22	3.9	<0.01

4. Discussion

4.1. General Biomass Production

Within this investigation the highest yielding tillage system/ weed treatment variant combinations provided approximately 10–11 odt $ha^{-1}yr^{-1}$. This corresponds with other published studies utilising the same hybrid poplar variety “AF2”. Yields of 11 odt $ha^{-1}yr^{-1}$ were reported, calculated as a mean value for two stocking densities (7140 and 10,360 cuttings ha^{-1}) within a two year rotation following cutback (roots being three years old), integrating ploughing, post-emergent herbicide application, and fertilisation [40]. Yields of 5.6 odt $ha^{-1}yr^{-1}$ and 9.3 odt $ha^{-1}yr^{-1}$ within a biannual rotation at 5900 cuttings ha^{-1} were described in Italy for the same hybrid poplar variety on poor and average sites respectively, here the plots were unfertilised and weeds were controlled mechanically with an application of the pre-emergent herbicide pendimethalin [41]. Finally, utilising a pre-emergence herbicide and mechanical weed treatment, yields of 6.0 odt $ha^{-1}yr^{-1}$ after two years were also found in Italy, calculated as a mean of two distinct stocking densities namely 5500 and 11,000 cuttings ha^{-1} for the “AF2” variety [42].

4.2. Mortality Rate

Utilising both efficient and modern weed control methodology, mortality rates are expected to remain below 20% [8,43,44]. Mortality statistics as given within this study show that most variants fell below this value, with the majority below 10%. For treatment combinations where mortality occurred above the 20% upper threshold, subplot mortality was seen to be higher than 80% and was thus considered a failure. This was with one exception within variant “B6”, where approximately a quarter of all cutting died by the end of the third year. Mortality in all cases can be attributed to increased competition for nutrient, water and light.

4.3. Tillage Systems

Between tillage systems utilised within this investigation it was found that biomass yields can be ranked as follows: ploughing and harrowing > cultivation with ley crop > no tillage. These findings confirm previous suggestions that tillage systems generally provide better results than non-tillage systems when utilised within SRC poplar culture [43].

Variants that experienced the tillage system “A” consisting of an autumn ploughing operation followed by harrowing in spring performed better than any other employed tillage system, reaching dry above ground biomass production values of up to 11.0 odt $ha^{-1}yr^{-1}$. This can be considered an excellent yield without irrigation and fertilisation inputs within southern Germany. Tillage relies on the mechanical disruption of a weed’s growth habit, either by complete burial, the exposure of roots to frost or dehydration or by causing physical injury resulting in bacterial or fungal infection further leading to the weakening or death of the weed. The use of mechanised site preparation methods allows for the deep preparation of the soil. Ploughing (inversion tillage) turns weeds deep into the soil recycling nutrients and resulting in the deep burial of seeds, preventing germination. The inversion of soil and reincorporation of plant matter can be clearly see within Table 1, where percentage values for organic matter are inverted in comparison with other tillage systems between differing soil depths. Harrowing creates a flat weed free surface with a finer texture for rapid early growth of cuttings, ease of water penetration and facilitation of further management operations.

Within tillage system “B” the site was cultivated during the autumn and then seeded with a ley crop of perennial ryegrass (*Lolium perenne* “Kabota”), that remained *in situ* over the winter months. Maximal production yields were calculated to be 8.9 odt $ha^{-1}yr^{-1}$, yields were only realised with a comprehensive input of herbicides specifically targeting grass species, while passive weed treatments failed. Given the non-selective systemic mode of action presented by glyphosate, it can be assumed that its application was sufficient to control all weed species present in the sward at the time, with the inclusion of the ley crop. Meanwhile it can be presupposed that the previous mechanical cultivation treatment, a form of non-inversion tillage was not comprehensive enough to sufficiently bury seeds within the seed bank preventing germination. It has previously been stated that non-inversion tillage leaves greater amount of weed seed at the surface with the potential to germinate [45]. Dead ryegrass on the soil surface following glyphosate application may have created a barrier for further herbicide applications. Without further mechanical cultivation after treatment with glyphosate such pre-emergent herbicide applications may have been rendered inefficient, similarly as concluded by a recent study where the pre-emergent was viewed to not have reached its full potential due to a lack of incorporation with the soil matrix post application [18].

By the end of the first growing season more than 80% of plants within tillage system “C” had died. “C” was effectively a non-tillage system utilising only herbicides with the exception of Groups III and IV (see Table 3). The use of chemical treatment alone is evidently not sufficient in controlling weed growth. This concurs with previous research [46]. A pre-planting application of glyphosate effectively controls all evident weed species given its broad target spectrum, especially problematic perennial weed species [16]. However, glyphosate does not prevent seed germination [18]. For this reason later in the first season, or during the second season the bare site is open for a rapid recolonisation by weed species germinating from the seedbank. If these are not effectively controlled by a pre-emergent herbicide or the additional application of a post-emergent herbicide, any advantage of a weed free site attained in the establishment phase is lost before canopy closure. Weed growth within this tillage system was seen to be most vigorous with high pressure on cuttings by field bindweed (*Convolvulus arvensis L.*). The growth habit of this species allows the weed to spiral around cutting shoots and bend them towards the ground because of the increased weight. The shoots then become susceptible to herbivory by slugs and snails or infection by fungi, bacteria or plant pathogens.

Such a weed is difficult to control chemically given its climbing growth habit [47], but also mechanically regarding its ability to resprout from root portions [48]. A mechanical treatment will only provide a short term release of competition pressure ultimately only exacerbating the problem. Furthermore its seeds have been reported to be persistent within the seed bank for 20–50 years [49,50]. One herbicide reportedly providing the greatest potential for field bindweed control is 2,4D [51], untested within this study.

4.4. Weed Treatments

Broadcast (whole plot area) herbicide applications provided a better success rate for the control of weed species. The effect on biomass production can be seen between tillage systems where mean yields of 10.7 odt $ha^{-1}yr^{-1}$ and 8.5 odt $ha^{-1}yr^{-1}$ were produced under tillage system "A" and mean yields of 8.2 odt $ha^{-1}yr^{-1}$ and 3.6 odt $ha^{-1}yr^{-1}$ under the "B" regime, respectively for broadcast herbicide application (Group I) and band spraying (Group II) within the rows in both cases. Broadcast application can be considered to have a greater potential for weed suppression than an application of the same herbicide through band spraying. This can be attributed to the fact that weeds are eradicated across the whole area rather than only being controlled within the rows where there is direct competition with the cuttings. As competition for nutrients and water can be considered being more critical than light [17,18,52], the control of below ground competition is most critical. The roots of those weeds that remain uncontrolled between the rows in the band spraying variants are able to encroach within the rows under the poplar, thus challenging for resources. To be most effective, weed control must remove root competition [6]. The use of pre- and post-emergent herbicides is considered good practice, a combination will reduce the weed cover within such a plantation providing increased biomass yields [18,46]. However, care should be taken as to the timing and the controlled application of the herbicide chosen and the impact its application has on biomass yield [16,17], this is particularly critical when considering a post-emergent application of herbicide over an emerged crop [16]. Treatment utilising a rotowiper (rotary weed wiper) retains the core principle of IWM. Using this equipment in combination with a broad-spectrum non-selective post-emergence herbicide such as glyphosate the chemical is only applied to the weed species that it comes into contact with, providing a physical selectivity. This can be considered especially useful in the suppression of tall, vigorous weeds that compete with poplar cuttings for resources.

The utilisation of mechanical weed treatments within this study showed that their employment has a potential to effectively manage weed growth. Two alternative methods were employed mowing and rotovation, the latter attaining higher biomass yields in both tillage systems at the end of the third year, (see Table 5). This can be explained by the method of control. When weed management is carried out utilising a mowing operation, the weeds are not removed from site, rather just cut and are able to rapidly resprout. The underground competition remains, and thus to a degree reduces the growth of the poplar crop. A mowing treatment is only effective if utilised repeatedly, depleting the weed of food resources ultimately causing death. The application of a mowing treatment will delay the formation of seed heads within the weed species, thus allowing the poplar crop more time to achieve canopy closure an integral part of an IWM approach. Meanwhile the employment of a rotovation treatment provides the opportunity for total disturbance of the weeds between rows. Roots are exposed and damaged. This operation must be carried out with care post crop emergence as such soil disturbance has the potential to damage the poplar's roots as well. Additionally, with rotation of the soil, fresh seed from the weed seed bank has a renewed chance to grow.

The mulch variant utilised within this investigation was unsuccessful producing yield of only 5.3 odt $ha^{-1}yr^{-1}$, an insufficient yield to be considered economically viable [10], especially when the high price of mulch material is accounted for. It has been previously reported that the primary advantage of utilising mulch within SRC poplar culture is the reduction in initial mortality [18], the employment of a natural or artificial barrier such as the compostable starch based membrane as used within this study provides a short term barrier to emerging and low-level pre-existing weed species. This results in higher biomass production yields than implementing no treatment at all, which is supported by previous research [53,54]. Within this study mulch foil was located only within the row, a whole area covering is considered commercially uneconomical given the high price of mulching materials. Between the rows mowing operations were carried out (variant A7). Improvement on this variation could include the application of a pre-/post-emergent herbicide to control weeds between the rows. The control of weed species prior to installation of mulch materials is not considered necessary [55] although it is unclear if any improvement may have been seen.

The control variant represents a treatment without herbicide application, relying purely on tillage to suppress weed growth. This weed treatment variant was adopted in the field trial to simulate the establishment of SRC under grassland conditions. A ley crop with minimal tillage and no additional treatment is not sufficient as a method of weed suppression, weed growth was competitive enough to cause complete crop failure. Ploughing and harrowing with no further treatment was the only surviving variant, yielding an uneconomical return of 1.5 odt $ha^{-1}yr^{-1}$, this is in agreement with previous research [8,18]. Nevertheless, there are contradicting opinions to this, suggesting that tillage without any form of herbicide application has the potential to produce acceptable results [46]. The results of this study suggest, that the establishment of SRC on grasslands is difficult, if no consequent weed control with herbicides that provide an effect on monocotyledonous weeds or grasses is applied. Nevertheless, the change of use of permanent grasslands is restricted by EU regulation and furthermore, prohibited in some federal states of Germany.

5. Conclusions

It has been shown that the tillage systems and weed control treatments utilised within this study have an effect on biomass production over the whole rotation. Within the 24 tillage and weed treatment combinations investigated within this study a number of conclusions can be drawn with respect to total above ground dry leafless biomass production for the hybrid poplar clone "AF2". Autumn ploughing followed by spring harrowing followed by the application of a number of currently marketed pre- and post-emergent herbicides, produced a biomass of up to 11.0 odt $ha^{-1}yr^{-1}$. These results are in accordance with current poplar plantation establishment recommendations [7,46]. Techniques used in other permanent crops such as band spraying combined with rotivation between rows could help with successful establishment of SRC while reducing herbicide application. The treatments explored within this investigation were limited to the first growing season, thus considered to be the most critical within the lifecycle of a SRC poplar plantation. Further treatments maybe required in subsequent years or during the spring after harvesting operations until canopy closure is achieved by the crop, a factor largely determined by site conditions, choice of hybrid variety and initial stocking density. Although, in view of less fertile sites where more intensive operations for the culture of annual crops would be necessary, a contrast in input requirements in comparison with SRC becomes more pronounced. Comparing the management of SRC as described above with modern common agronomic practice, low levels of soil tillage and low input of herbicide are an important benefit provided by this system. This can be coupled with a sensitive IWM approach, including a better awareness of weed-crop relationships, a greater familiarity with methods of weed control, weed growth habits and seed bank dynamics. This can lead to the development of optimal weed control procedures with an efficient and targeted use of herbicides. Ultimately this offers the chance to provide economical and ecological benefits to the grower, the product end-user and the wider population.

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Conflicts of Interest

The authors declare no conflict of interest.

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