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SITE-GROWTH RELATIONSHIP OF DIFFERENT SHORT-ROTATION COPPICE TREE SPECIES IN SOUTHWESTERN GERMANY FOUR YEARS AFTER ESTABLISHMENT

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Abstract

NERLICH KRISTIN, GAUDER MARTIN, SEIDL FRIEDER, MASTEL KLAUS, MÖHRING JENS, CLAUPEIN WILHELM, GRAEFF-HÖNNINGER SIMONE. Site-growth relationship of different short-rotation coppice tree species in southwestern Germany four years after establishment. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis,* 64(4): 1219–1232.

Due to lack of detailed information on the suitability of short rotation coppice (SRC) species for different climatic regions, over four years this study investigated tree growth and susceptibility to pests and diseases of willow (*Salix* spp.) and poplar (*Populus* spp.) clones and other tree species like *Alnus* spp. and *Robinia pseudoacacia* at four sites located in southwestern Germany. The study was undertaken in order to deduce the kind of tree species recommended for the various site conditions. In 2009, field trials were established at four sites which differ in climate and soil characteristics (Forchheim, Kupferzell, Marbach and Aulendorf).
At all tested locations, a high survival rate (>90 %) was observed for almost all willow and poplar clones and little infestations with leaf rust (*Melampsora*) and minor leaf damages caused by the poplar leaf beetle (*Chrysomela populi*) had occurred. The survival of the other tree species varied from 22 to 97 % depending on the site and species.
Across all tree species and locations, results indicated that willow clones can be recommended for cold sites and poplars generally seem to require higher temperatures. The *Alnus* spp. seems to be favorable for both cold and warm conditions while *Robinia pseudoacacia* can be recommended for warm sites. Due to its chilling sensitivity, *Paulownia tomentosa* seems to be rather unsuitable for cultivation in southwestern Germany. For all tested sites, it appears that those with heavy soils and dry conditions are inappropriate for establishing SRC species.

Keywords: short rotation coppice, *Salix* spp., *Populus* spp., *Alnus* spp., *Robinia pseudoacacia*, bioenergy, fast growing trees

INTRODUCTION

Short Rotation Coppice (SRC) plantations are established with fast-growing trees which have the ability to resprout from the stump after harvest (Dimitriou and Rosenqvist 2011).

In temperate climate, typically willow (*Salix* spp.) or poplars (*Populus* spp.) are cultivated on arable land, because of their rapid growth rate (Aylott *et al.* 2008). To enlarge the species spectrum and to cover a broad range of different growing conditions, other tree species like *Alnus* spp. and *Robinia pseudoacacia*, which are both able to fix nitrogen from the atmosphere (Danso *et al.* 1995, Benson 1982), as well as *Paulownia tomentosa* and Acer spp., are considered nowadays for SRC. All these species are characterized by their fast growing capability, and their capacity to re-grow from rootstocks or stools (Baum *et al.* 2009,

Rahman *et al.* 2013, Aosaar *et al.* 2012, Vande Walle *et al.* 2007). Due to the lack of detailed information on the suitability of different tree species for different sites and regions, it is highly beneficial to be able to give farmers a clear recommendation on which species will grow most appropriately under a specific farmer's site condition. Therefore, the aim of this study was to examine the growth behavior of SRC willow and poplar clones as well as alternative tree species according to different site conditions in southwestern Germany with a focus on maximizing biomass production.

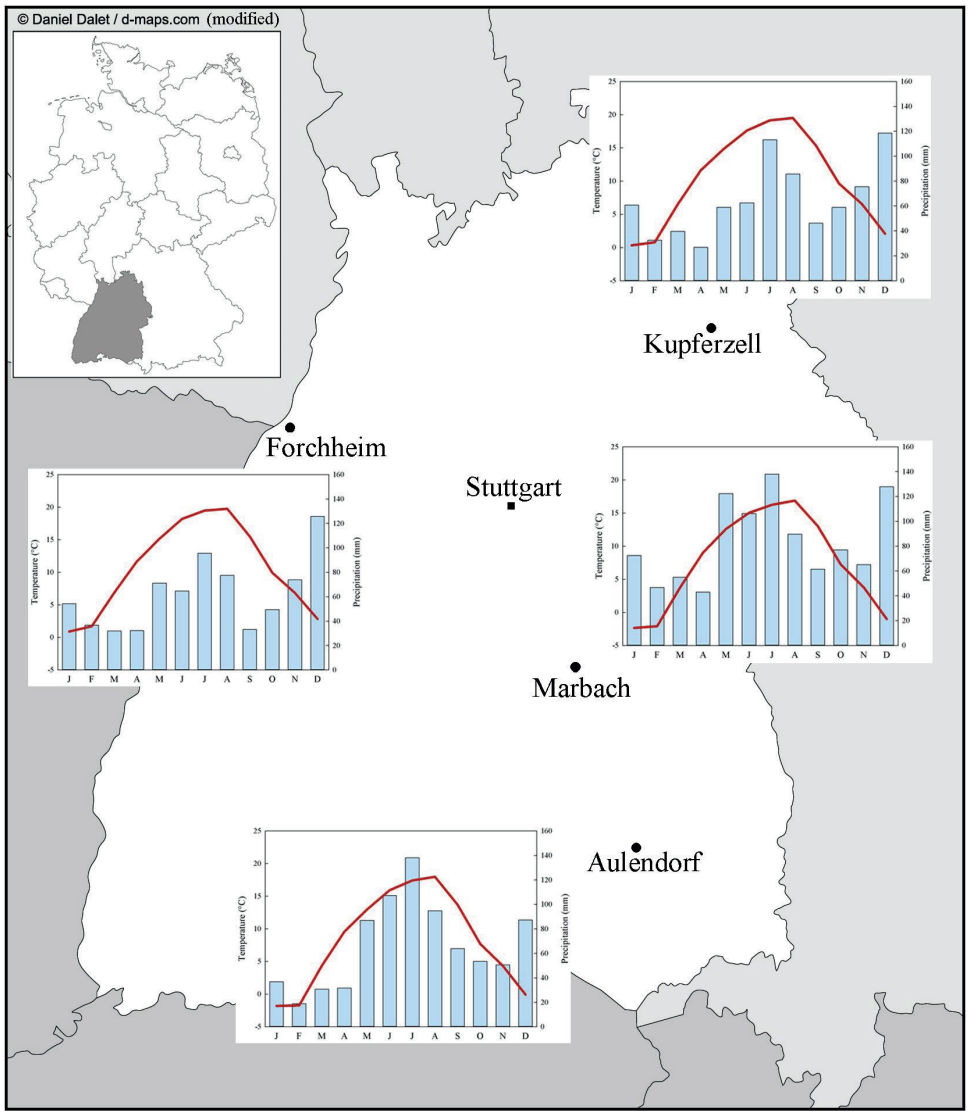
MATERIALS AND METHODS

Experimental sites and plant material

The field experiments were conducted at four different pedo-climatic sites in southwestern Germany (Fig. 1). The experimental design was a split-plot design with main plots being the group of willow, poplar and other species and the sub plots being the genotypes. On each site of the trial, two replicate plots of the different genotypes were established.

Table I describes the experimental sites in detail. The site at Forchheim is characterized by a warm and dry climate (9.9 °C, 855 mm) with having typical arable farming conditions and the option of temporary irrigation. While Kupferzell and Aulendorf have moderate temperatures (9.1 °C, 7.6 °C), Marbach is in a much cooler region (5.8 °C). The locations of Kupferzell and Marbach are characterized by an annual rainfall of about 900 mm, whereas Aulendorf is a typical grassland site and has a significantly higher annual precipitation of 1,013 mm. With the exception of Aulendorf, all sites were formerly used for arable crop production.

For the trial sites in Kupferzell and Marbach, 34 tree species and clones were selected consisting



1: *Location of experimental sites Forchheim, Kupferzell, Marbach and Aulendorf in southwestern Germany and the mean temperature (°C; lines) and precipitation (mm; bars) over the four experimental years (Source: (DALET, D. 2007) modified).*

I: *Description of the four experimental sites in southwestern Germany.*

	Experimental site			
	Forchheim	**Kupferzell**	**Marbach**	**Aulendorf**
Elevation (m asl)	117	350	720	550
Yearly mean temperature (°C)*	9.9	9.1	5.8	7.6
Average annual precipitation (mm)*	855	903	901	1013
Soil types	loamy sand	loamy clay	clay loam / silty loam	half-boggy / bog
Previous use	arable farming	arable farming	arable farming	grassland
Geographic coordinates	48°96' N, 8°33' E	49°22' N, 9°69' E	48°39' N, 9°41'E	47o96' N, 9o64' E

*means of the years 1961-1990

of eight willow, thirteen poplar and 15 further species like *Paulownia tomentosa*, *Robinia pseudoacacia* or *Alnus incana*. At Forchheim *Ailanthus altissima* and *Juglans mandschurica* were tested in addition to these 34 species and clones. Due to a lack of space in Aulendorf only willow and poplar species and *Paulownia tomentosa* were planted. Table II provides an overview of the tree species and clones.

The plots were established in the year 2009 between end of March (Forchheim) and April (Kupferzell, Marbach, Aulendorf) with a size of 8 m × 12 m in which four rows of trees were planted by hand. Willows were planted with a spacing of 2 m × 0.5 m and poplars with 2 m × 0.7 m. Both species were planted as 20 cm unrooted cuttings. The other tree species were planted as bare rooted seedlings with a space consisting of a 2 m × 1 m design.

At Forchheim and Marbach, primary tillage was carried out before planting with a moldboard plow to a depth of 25–30 cm. In addition, the soil at these two sites was loosened with a harrow. At Kupferzell, a chisel plough (15 cm depth) was used for soil preparation.

The cuttings were placed one day in water before planting. At the experimental sites Forchheim and Kupferzell, a mixture of two soil herbicides (Terano and Stomp Aqua) with the active ingredients of metosulam, flufenacet and pendimethalin, and at the Marbach site one soil herbicide (Bacara) with the active ingredients of diflufenican and flurtamone were applied just before or directly after planting. Due to the site at Aulendorf being a former grassland, no large-scale soil cultivation was carried out because of ecological reasons. The planting strips were prepared by band spraying with a non-selective herbicide (active ingredient: glyphosat). The grass between the planting strips was mulched. During the growing season further weed control was needed at all sites. In all field trials no fertilization or irrigation was applied.

Growth and vitality measurements

All measurements were performed on the trees within the central two rows of each plot. Therefore, 32 willows, 22 poplars, and 16 plants of the other tree species were examined per plot. The survival of the different tree species was controlled during the summer season (mostly August). In addition, by walking along the tree rows in summer, the trees were visually checked for pests and diseases. The incidence of leaf rust of single trees were evaluated by randomly taking ten leaves in the mid area of the tree, then the level of infestation was evaluated by estimating the mean infected area of each leaf in categories of 0 %, 1–25 %, 26–50 % etc.

All growth parameters were measured after leaf fall during the winter rating on every vital tree in the years 2009–2012. On the main stem the tree height was measured with a level rod. Using a caliper rule the root neck diameter at 0.1 m height (D0.1) above the ground surface was recorded. The total number of shoots per tree was counted.

Statistical analysis

The data was analyzed using a mixed model. To reach model requirements, survival rate data were logit transformed and height data were square root transformed. Estimated means were back transformed for presentation only. Estimated standard errors were back transformed using the delta method. Single tree data were analyzed using a mixed model approach assuming genotype (G) and genotype*year (G*Y) effects as fixed and all other effects as random. Because of limited available information for estimating the variance component of years (Y), sites (S), and replicates (R), these effects are formally taken as fixed. The model is given by

$$Y+S+R+G+G\cdot Y:Y\cdot S+Y\cdot S\cdot R+S\cdot R\cdot Gt+Y\cdot S\cdot R\cdot MP+Y\cdot S\cdot R\cdot MP\cdot SP$$

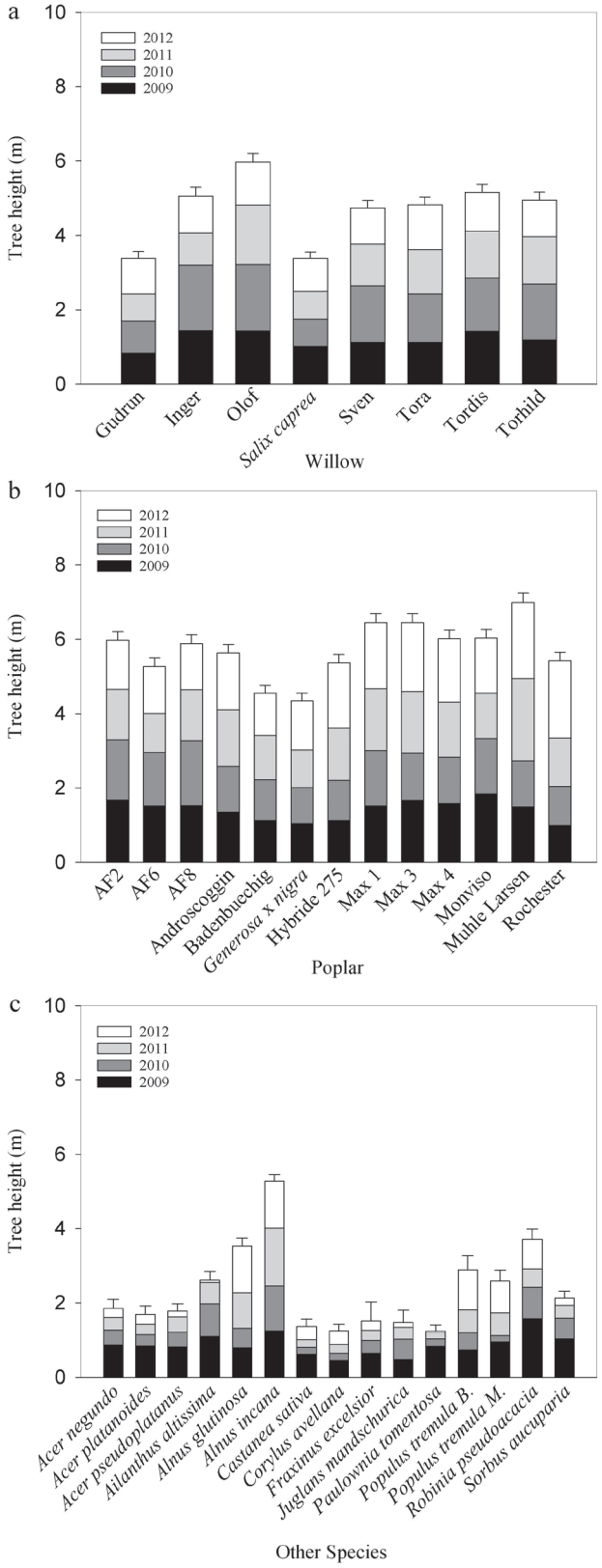
where fixed effects are given before the colon. All fixed effects were highly significant. MP and SP denote the main and sub plot effect. Interactions are denoted by dots between the corresponding main effects. Additionally, site specific error and plot variances were fitted. It was further assumed, that errors between years are correlated with year specific variances. Least square means were calculated for G and G*Y. To get estimates for each

II: *Tree species, sections and clones studied at the four sites: Forchheim, Kupferzell, Marbach and Aulendorf.*

Species	Clones	Section
Willow (*Salix* spp.)		
Salix caprea		
S. dasyclados	Gudrun	
S. triandra × *S. viminalis*	Inger	
S. viminalis × (*S. viminalis* × *S. schwerinii*)	Olof	
S. viminalis × (*S. viminalis* × *S. schwerinii*)	Sven	
S. schwerinii × *S. viminalis*	Tora	
(*S. schwerinii* × *S. viminalis*) × *S. viminalis*	Tordis	
(*S. schwerinii* × *S. viminalis*) × *S. viminalis*	Torhild	
Poplar (*Populus* spp.)		
P. deltoides × *P. nigra*	AF2	*Aigeiros*
P. generosa × *P. nigra*	AF6	*Aigeiros*
(*P. deltoides* × *P. trichocarpa*) × *P. trichocarpa*	AF8	Intersectional Hybrid
P. maximowiczii × *P. trichocarpa*	Androscoggin	*Tacamahaca*
P. deltoides × *P. nigra*	Badenbuechig	*Aigeiros*
P. generosa × *P. nigra*	Generosa × nigra	Intersectional Hybrid
P. maximowiczii × *P. trichocarpa*	Hybride 275	*Tacamahaca*
P. nigra × *P. maximowiczii*	Max 1	Intersectional Hybrid
P. nigra × *P. maximowiczii*	Max 3	Intersectional Hybrid
P. nigra × *P. maximowiczii*	Max 4	Intersectional Hybrid
(*P. trichocarpa* × *P. deltoides*) × *P. nigra*	Monviso	*Aigeiros*
P. trichocarpa × *P. trichocarpa*	Muhle Larsen	*Tacamahaca*
P. nigra × *P. maximowiczii*	Rochester	Intersectional Hybrid
Other species		
Acer negundo		
Acer platanoides		
Acer pseudoplatanus		
Ailanthus altissima		
Alnus glutinosa		
Alnus incana		
Castanea sativa		
Corylus avellana		
Fraxinus excelsior		
Juglans mandschurica		
Paulownia tomentosa		
Populus tremula	Byalistok	
Populus tremula	Marcali	
Robinia pseudoacacia	Nyirsegi	
Sorbus aucuparia		

III: *Survival rate (%) four years after establishment (Std - Standard deviation).*

	Forchheim		Kupferzell		Marbach		Aulendorf	
Willow	**%**	**Std**	**%**	**Std**	**%**	**Std**	**%**	**Std**
Gudrun	91	(0.06)	93	(0.05)	86	(0.10)	59	(0.27)
Inger	59	(0.20)	97	(0.02)	65	(0.18)	0	
Olof	83	(0.12)	95	(0.04)	93	(0.05)	71	(0.23)
Salix caprea	91	(0.07)	85	(0.10)	68	(0.18)	71	(0.23)
Sven	82	(0.12)	85	(0.10)	91	(0.06)	87	(0.13)
Tora	97	(0.02)	86	(0.10)	89	(0.08)	82	(0.17)
Tordis	85	(0.10)	95	(0.04)	93	(0.05)	59	(0.17)
Torhild	89	(0.08)	91	(0.07)	92	(0.06)	82	(0.17)
mean	85		91		85		64	
Poplar								
AF2	98	(0.02)	98	(0.02)	98	(0.02)	90	(0.07)
AF6	93	(0.05)	92	(0.06)	83	(0.12)	73	(0.16)
AF8	98	(0.02)	98	(0.02)	96	(0.03)	87	(0.09)
Androscoggin	98	(0.02)	98	(0.02)	95	(0.04)	95	(0.04)
Badenbuechig	93	(0.05)	96	(0.03)	90	(0.07)	23	(0.14)
Generosa × nigra	88	(0.08)	98	(0.02)	92	(0.06)	70	(0.17)
Hybride 275	95	(0.04)	96	(0.03)	96	(0.03)	85	(0.10)
Max 1	98	(0.02)	98	(0.02)	96	(0.03)	90	(0.07)
Max 3	96	(0.03)	98	(0.02)	93	(0.05)	80	(0.13)
Max 4	98	(0.02)	98	(0.02)	93	(0.05)	83	(0.11)
Monviso	96	(0.03)	98	(0.02)	98	(0.02)	84	(0.11)
Muhle Larsen	93	(0.05)	98	(0.02)	98	(0.02)	96	(0.03)
Rochester	93	(0.05)	98	(0.02)	93	(0.05)	80	(0.13)
mean	95		97		94		80	
Other species								
Acer negundo	89	(0.08)	65	(0.18)	83	(0.12)	-	
Acer platanoides	97	(0.02)	71	(0.17)	80	(0.13)	-	
Acer pseudoplatanus	95	(0.04)	80	(0.13)	57	(0.20)	-	
Ailanthus altissima	86	(0.10)	-		-		-	
Alnus glutinosa	95	(0.04)	93	(0.05)	89	(0.08)	-	
Alnus incana	97	(0.02)	68	(0.18)	97	(0.02)	-	
Castanea sativa	97	(0.02)	44	(0.20)	14	(0.10)	-	
Corylus avellana	97	(0.02)	35	(0.18)	75	(0.15)	-	
Fraxinus excelsior	89	(0.08)	59	(0.19)	61	(0.19)	-	
Juglans mandschurica	97	(0.02)	-		-		-	
Paulownia tomentosa	47	(0.20)	0		0		0	
Populus tremula B.	80	(0.13)	85	(0.10)	84	(0.11)	-	
Populus tremula M.	74	(0.15)	85	(0.10)	93	(0.05)	-	
Robinia pseudoacacia	85	(0.10)	50	(0.20)	22	(0.14)	-	
Sorbus aucuparia	95	(0.04)	64	(0.19)	78	(0.14)	-	



2: *Tree height (m) of the tested willow (a), poplar (b) and the other tree species (c) averaged over all sites for the years 2009–2012. Standard deviations are shown by vertical bars.*

IV: *Mean tree height (m), number of shoots (#) and root neck diameter (D0.1, mm) of willow and poplar species at the study sites Forchheim, Kupferzell, Marbach and Aulendorf four years after establishment ± standard error..*

	Forchheim			**Kupferzell**			**Marbach**			**Aulendorf**		
Willow	**Height (m)**	**Shoots (#)**	**D0.1 (mm)**	**Height (m)**	**Shoots (#)**	**D0.1 (mm)**	**Height (m)**	**Shoots (#)**	**D0.1 (mm)**	**Height (m)**	**Shoots (#)**	**D0.1 (mm)**
Gudrun	3.09 (0.56)	2.41 (0.24)	28.75 (4.63)	1.47 (0.52)	2.00 (0.25)	17.29 (3.61)	4.81 (0.95)	2.62 (0.33)	41.93 (8.67)	2.35 (0.71)	1.58 (0.22)	23.01 (5.21)
Inger	4.81 (0.70)	2.18 (0.23)	33.14 (5.42)	2.25 (0.65)	1.94 (0.25)	14.48 (3.04)	6.69 (1.12)	2.19 (0.28)	37.95 (7.10)	4.22 (0.96)	1.54 (0.21)	27.99 (6.40)
Olof	5.90 (0.77)	1.59 (0.16)	37.98 (6.07)	2.71 (0.71)	1.42 (0.18)	16.30 (3.38)	8.53 (1.25)	1.70 (0.21)	45.40 (9.32)	4.48 (0.98)	1.19 (0.16)	27.71 (6.23)
Salix caprea	3.01 (0.55)	1.63 (0.16)	32.15 (5.14)	1.93 (059.)	1.40 (0.17)	20.92 (4.33)	4.05 (0.86)	1.43 (0.18)	34.88 (7.16)	2.43 (0.72)	1.17 (0.16)	24.98 (5.61)
Sven	4.45 (0.67)	1.75 (0.17)	28.82 (4.59)	2.25 (0.64)	1.26 (0.16)	16.95 (3.51)	6.33 (1.08)	1.73 (0.22)	35.39 (7.24)	3.69 (0.89)	1.19 (0.16)	25.42 (5.70)
Tora	4.62 (0.68)	1.68 (0.17)	34.83 (5.54)	2.34 (0.65)	1.34 (0.17)	18.56 (3.84)	6.68 (1.11)	1.52 (0.19)	42.73 (8.74)	3.47 (0.86)	1.02 (0.14)	25.03 (5.62)
Tordis	4.55 (0.68)	1.96 (0.20)	28.41 (4.53)	2.31 (0.65)	1.97 (0.24)	14.81 (3.07)	7.39 (1.17)	2.11 (0.26)	42.32 (8.68)	4.22 (0.95)	1.63 (0.22)	25.55 (5.74)
Torhild	4.52 (0.67)	1.69 (0.17)	29.12 (4.64)	2.41 (0.67)	1.36 (0.17)	15.76 (3.27)	6.74 (1.12)	1.58 (0.20)	34.69 (7.12)	3.87 (0.91)	1.16 (0.16)	25.64 (5.76)
mean	*4.37*	*1.826*	*31.65*	*2.21*	*1.59*	*16.88*	*6.40*	*1.86*	*39.41*	*3.59*	*1.31*	*25.67*
Poplar												
AF2	6.14 (0.78)	1.18 (0.10)	49.76 (7.78)	2.99 (0.74)	0.95 (0.11)	27.56 (5.66)	5.84 (1.04)	1.09 (0.12)	48.51 (9.90)	6.21 (1.15)	0.99 (0.12)	55.64 (12.36)
AF6	5.27 (0.72)	1.08 (0.09)	42.28 (6.62)	2.73 (0.71)	1.15 (0.13)	25.34 (5.21)	5.43 (1.00)	1.27 (0.14)	48.05 (9.83)	5.05 (1.04)	1.02 (0.12)	44.02 (9.80)
AF8	6.45 (0.80)	1.14 (0.10)	50.26 (7.85)	3.47 (0.80)	0.98 (0.11)	29.56 (6.07)	5.77 (1.03)	1.26 (0.14)	44.70 (9.13)	5.01 (1.03)	1.01 (0.12)	39.52 (8.78)
Andro-scoggin	6.04 (0.77)	1.10 (0.09)	49.00 (7.65)	3.44 (0.79)	0.93 (0.10)	29.91 (6.13)	5.47 (1.01)	1.06 (0.12)	42.72 (8.72)	4.75 (1.00)	0.86 (0.10)	34.86 (7.74)
Baden-buechig	4.71 (0.68)	1.32 (0.11)	37.14 (5.85)	2.68 (0.70)	1.00 (0.11)	23.25 (4.79)	4.42 (0.90)	1.14 (0.12)	35.32 (7.24)	3.84 (0.90)	1.06 (0.13)	28.74 (6.43)
Generosa × nigra	5.12 (0.71)	1.13 (0.10)	44.48 (6.97)	2.17 (0.63)	1.05 (0.12)	22.78 (4.68)	3.82 (0.84)	1.01 (0.11)	36.35 (7.43)	3.94 (0.91)	0.98 (0.12)	35.39 (7.87)
Hybride 275	6.08 (0.78)	1.43 (0.12)	51.82 (8.10)	2.81 (0.72)	1.17 (0.13)	24.63 (5.05)	5.33 (0.99)	1.25 (0.14)	48.43 (9.89)	4.65 (0.99)	0.91 (0.11)	36.28 (8.06)
Max1	6.73 (0.82)	1.18 (0.10)	51.73 (8.08)	3.54 (0.80)	1.05 (0.11)	28.78 (5.90)	6.41 (1.09)	1.08 (0.12)	51.90 (10.60)	6.18 (1.15)	0.96 (0.12)	51.13 (11.36)
Max3	7.02 (0.83)	1.18 (0.10)	53.49 (8.36)	3.60 (0.81)	1.06 (0.12)	30.04 (6.17)	6.41 (1.09)	1.26 (0.14)	52.03 (10.63)	5.83 (1.11)	0.95 (0.12)	50.72 (11.27)
Max4	6.23 (0.79)	1.17 (0.10)	50.70 (7.93)	3.03 (0.74)	1.03 (0.11)	26.70 (5.48)	6.24 (1.07)	1.04 (0.11)	49.79 (10.17)	5.84 (1.11)	0.96 (0.12)	44.83 (9.96)
Monviso	6.27 (0.79)	1.47 (0.12)	50.11 (7.83)	3.07 (0.74)	1.24 (0.14)	26.59 (5.46)	5.94 (1.05)	1.57 (0.17)	47.65 (9.73)	6.10 (1.14)	1.21 (0.15)	51.37 (11.42)
Muhle Larsen	6.79 (0.82)	0.98 (0.08)	49.87 (7.80)	4.40 (0.90)	0.96 (0.11)	32.51 (6.67)	6.97 (1.13)	0.92 (0.10)	53.11 (10.84)	6.61 (1.18)	0.90 (0.11)	48.31 (10.73)
Rochester	6.05 (0.77)	1.02 (0.09)	51.03 (8.02)	3.04 (0.75)	0.97 (0.11)	24.83 (5.13)	5.35 (1.00)	0.94 (0.10)	42.87 (8.78)	4.57 (0.99)	0.82 (0.10)	36.71 (8.21)
mean	*6.07*	*1.18*	*48.59*	*3.15*	*1.04*	*27.11*	*5.65*	*1.15*	*46.26*	*5.28*	*0.97*	*42.89*

	Forchheim			Kupferzell			Marbach			Aulendorf		
Other species	**Height (m)**	**Shoots (#)**	**D0.1 (mm)**	**Height (m)**	**Shoots (#)**	**D0.1 (mm)**	**Height (m)**	**Shoots (#)**	**D0.1 (mm)**	**Height (m)**	**Shoots (#)**	**D0.1 (mm)**
A. negundo	2.20 (0.50)	1.03 (0.12)	29.82 (5.24)	0.5 (0.32)	0.96 (0.13)	8.23 (1.82)	1.93 (0.62)	1.23 (0.17)	27.70 (6.07)	1.42 (0.61)	0.86 (0.13)	20.30 (5.27)
A. platanoides	1.82 (0.46)	0.90 (0.10)	26.49 (4.64)	0.51 (0.32)	0.87 (0.12)	11.45 (2.53)	1.79 (0.60)	0.87 (0.12)	25.75 (5.63)	1.28 (0.57)	0.71 (0.11)	21.26 (5.51)
A. pseudo-platanus	2.11 (0.49)	1.15 (0.13)	30.78 (5.42)	0.5 (0.31)	1.01 (0.14)	11.30 (2.50)	1.83 (0.60)	1.23 (0.17)	27.21 (5.97)	1.36 (0.59)	0.91 (0.14)	22.67 (5.89)
A. altissima	2.90 (0.78)	1.03 (0.18)	44.7 (10.69)	1.09 (0.57)	0.92 (0.17)	18.69 (5.14)	2.59 (0.88)	1.04 (0.20)	42.90 (11.74)	2.10 (0.84)	0.80 (0.16)	35.33 (10.37)
A. glutinosa	3.86 (0.66)	1.59 (0.19)	51.03 (8.92)	1.93 (0.62)	1.36 (0.19)	28.08 (6.18)	3.20 (0.80)	1.47 (0.20)	40.72 (8.89)	2.93 (0.87)	1.18 (0.19)	41.56 (10.76)
A. incana	5.41 (0.79)	1.17 (0.14)	61.32 (10.8)	2.97 (0.77)	1.03 (0.14)	28.32 (6.28)	5.49 (1.05)	1.01 (0.14)	59.07 (12.99)	4.53 (1.08)	0.86 (0.13)	50.16 (13.03)
C. sativa	1.80 (0.46)	1.24 (0.14)	33.99 (6.28)	0.48 (0.31)	0.87 (0.12)	11.27 (2.57)	0.96 (0.44)	1.24 (0.17)	22.04 (5.04)	1.01 (0.51)	0.89 (0.14)	21.82 (5.77)
C. avellana	1.43 (0.40)	0.95 (0.11)		0.41 (0.29)	0.69 (0.10)		1.02 (0.45)	0.84 (0.12)		0.90 (0.48)	0.66 (0.11)	
F. excelsior	1.54 (0.42)	0.98 (0.11)	24.29 (4.28)	0.53 (0.32)	0.96 (0.13)	12.36 (2.74)	1.50 (0.55)	1.14 (0.16)	29.07 (6.38)	1.13 (0.54)	0.82 (0.13)	22.06 (5.73)
J. mandschu-rica	1.69 (0.59)	0.99 (0.17)	36.92 (8.80)	0.41 (0.35)	0.88 (0.17)	15.44 (4.24)	1.45 (0.66)	1.00 (0.19)	35.43 (9.68)	1.09 (0.60)	0.77 (0.15)	29.18 (8.55)
P. tomentosa	1.60 (0.48)	0.99 (0.16)	45.72 (9.34)	0.28 (0.25)	0.91 (0.16)	16.72 (4.10)	1.10 (0.5)	1.16 (0.20)	40.76 (9.91)	0.91 (0.50)	0.81 (0.15)	36.11 (9.72)
P. tremula B.	3.02 (0.59)	0.90 (0.1)	29.37 (5.16)	1.29 (0.51)	0.86 (0.12)	12.87 (2.85)	3.00 (0.77)	0.96 (0.13)	34.30 (7.51)	2.35 (0.78)	0.73 (0.11)	25.17 (6.53)
P. tremula M.	3.29 (0.61)	0.89 (0.1)	39.77 (7.00)	1.10 (0.47)	0.88 (0.12)	13.06 (2.89)	2.15 (0.65)	0.88 (0.12)	26.94 (5.90)	2.08 (0.73)	0.71 (0.11)	25.82 (6.70)
R. pseudo-acacia	4.39 (0.72)	0.92 (0.11)	49.19 (8.83)	1.34 (0.52)	0.88 (0.12)	19.33 (4.33)	4.12 (0.91)	0.89 (0.12)	50.76 (11.3)	3.09 (0.90)	0.72 (0.11)	39.01 (10.21)
S. aucuparia	1.91 (0.47)	1.28 (0.15)	19.95 (3.51)	0.77 (0.39)	1.10 (0.15)	11.19 (2.47)	2.64 (0.73)	1.21 (0.17)	29.51 (6.48)	1.67 (0.66)	0.96 (0.15)	20.09 (5.22)
mean	*2.60*	*1.07*	*37.38*	*0.94*	*0.95*	*15.59*	*2.32*	*1.08*	*35.15*	*1.86*	*0.83*	*29.32*

location the solution of G*S and G*Y*S effects is added to the corresponding least square mean of G and G*Y.

To identify relationships between the parameters tree height, number of shoots and root neck diameter, the Pearson rank correlation between estimated least square means was calculated and tested.

All data were analyzed by using ASREML 3 (Gilmour *et al.* 2009) and SAS 9.3 (SAS Institute, Cary, NC, USA) using the procedures PROC CORR.

RESULTS

Survival rate four years after establishment

Four years after establishment at the sites Forchheim, Kupferzell and Marbach, the survival rate of most poplar clones was above 95 % and for most willow clones above 85 % (Tab. III). A lower survival rate was observed for 'Inger' at Forchheim (59 %) and Marbach (65 %) and for *Salix caprea* also at Marbach (68 %). Due to the infestation of voles at Aulendorf in winter 2011/12 larger parts of the trial were destroyed. The survival rate was on average 80 % for poplar and 64 % for willow species. Major losses of 77 % were observed for the poplar clone 'Badenbuechig' and the willow clone 'Inger' which was destroyed completely (Tab. III).

The average survival rate for the other tree species was highest at Forchheim with 88 %. At the site Kupferzell and Marbach, the survival rate was between 61 and 64 %. The species *Paulownia tomentosa* died in Kupferzell, Marbach and Aulendorf due to frost, and only 47 % survived in Forchheim. Lower survival rates were also observed for *Castanea sativa, Corylus avellana* and *Robinia pseudoacacia* in Kupferzell and Marbach. In average, the survival rate decreased over time with the largest decrease in the first year. But the decrease rate varied between the species.

Pests and diseases

During the experimental period (2009-2012) only light leaf rust (*Melampsora*) infestations (max. 25 %) occurred on most varieties, especially on the poplar clones 'Max 3', 'Max 4', 'Hybride 275' and 'Rochester' and on the willow clones 'Tordis', 'Sven' and 'Tora'. Stronger infestations were observed on the poplar clones 'AF6' (26-50 %), 'AF8', 'Monviso' and '*Generosa* × *nigra*' and the willow clones 'Inger', 'Olof' and '*Salix caprea*'. Only the clone 'Gudrun' (willow) was completely free of leaf rust. The infestation level was slightly higher at Forchheim and Marbach than in Aulendorf and Kupferzell.

Feeding damage on leaves caused by the poplar leaf beetle (*Chrysomela populi*) could be observed on all willow and poplar varieties, particularly on the clones 'AF2', 'AF8', 'Hybride 275' and 'Rochester' (all mentioned are poplar species) and on the willow species Inger. Leaf damage did not seem to have negative effects on the species growth.

At the experimental site in Forchheim, an infestation with the white peach scale (*Pseudaulacaspis pentagona*) was observed on many willow and few poplar species at the end of August in the year 2011. Therefore, the infested trees were initially cleaned using brushes and in spring (2012) the trees were treated with lime sulfur. In autumn 2012, a slight re-infestation was found, which was mechanically removed.

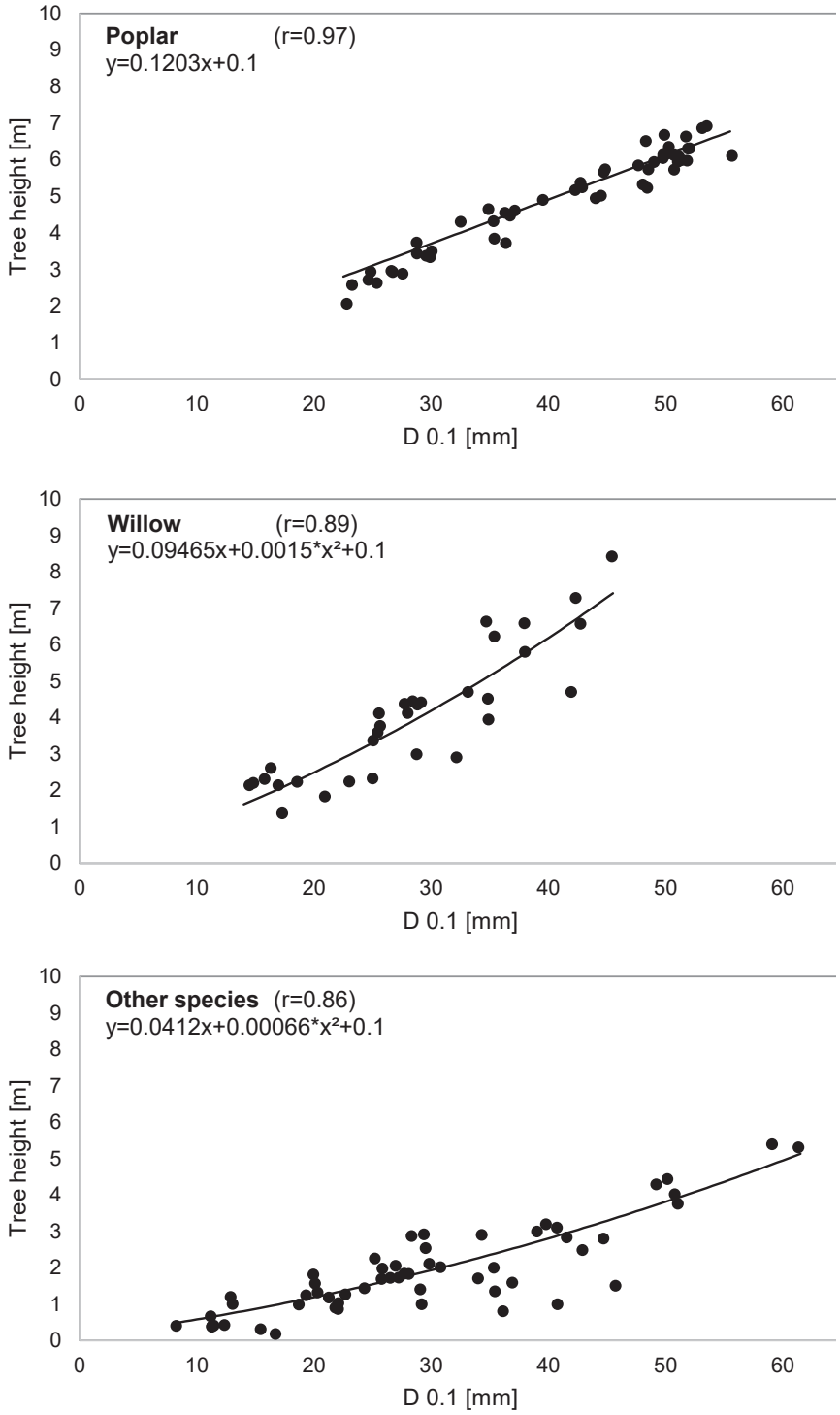
Tree height

Across all sites, the willow clones 'Tordis' and 'Olof' achieved on average with 5.2 m and 6.0 m their maximum heights. The lowest average height was observed for the clones 'Gudrun' and *Salix caprea* (both 3.4 m). The poplar clones 'Max 1' and 'Max 3' and 'Muhle Larsen' were the tallest at 6.4 m and 7.0 m, and the smallest were the clones *Generosa* × *nigra* (4.3 m) and 'Badenbuechig' (4.6 m). Of the other tree species, *Alnus incana* had the best growth potential (5.3 m), followed by *Robinia pseudoacacia* (3.7 m) and *Alnus glutinosa* (3.5 m), whilst the lowest were *Corylus avellana* (1.2 m), *Castanea sativa* (1.4 m) and *Paulownia tomentosa* (2.6 m). Table IV lists the results for the parameter 'tree height' of all tested varieties at each site and Figure 2 shows the average across all sites for the years 2009–2012.

The experimental site Kupferzell was found to have the lowest tree heights which may be explained by the rather dry conditions that eventuated during the growing season. In comparison to the other sites, Marbach (cold climate) had on average the maximum tree height and this was measured for the willow clones 'Tordis' (7.4 m) and 'Olof' (8.5 m). The maximum tree heights of poplars, 'Muhle Larsen' (6.80 m) and 'Max 3' (7.0 m), and the other tree species, *Robinia pseudoacacia* (4.4 m) and *Alnus incana* (5.4 m), were observed at the warm and dry site of Forchheim.

Total number of shoots

Amongst species, willows had on average 34 % more shoots than poplars and more than 41 % compared to the other tree species. Table 4 shows the number of shoots for the four trial sites. Dead plants were not counted. Shoot numbers with slightly less than one result from adjusting means for main plot effects; when all plants of one cultivar had exactly one shoot and were grown in relatively better main plots the outcome of the model was close to one but not exactly one. At all experimental sites, 'Inger' and 'Gudrun' (both willows) achieved with 2.20 and 2.40 shoots per tree the most shoot numbers. The clones 'Hybride 275' (1.33) and 'Monviso' (1.55) had the highest number of shoots for the poplars, and *Sorbus aucuparia* (1.28) and *Alnus glutinosa* (1.58) had the highest number of shoots amongst the other tree species.



3: *Significant correlation between tree height [m] and root neck diameter [mm] for poplar, willow and the other tree species (r - correlation coefficient).*

V: *Correlation coefficient (r) between tree height, number of shoots and root neck diameter (D 0.1) for willow, poplar and the other tree species.*

	Willow		Poplar		Other tree species	
	Tree height	**D 0.1**	**Tree height**	**D 0.1**	**Tree height**	**D 0.1**
Shoot number	0.25	0.34	0.22	0.27	0.27	0.15
Tree height		0.89 ***		0.97 ***		0.86 ***

*** $p < 0.001$

Root neck diameter

The average root neck diameter for the willow clones ranged from around 32.60 mm, compared to around 48.37 mm for the poplar clones and around 33.44 mm for the other tree species. The biggest diameters for the poplars were measured in 'Muhle Larsen' (54.47) and 'Max 3' (54.73). 'Olof' and 'Inger', which had the biggest of the root neck diameters amongst the willow clones, showed a 35 % lower root neck diameter than the poplars. Root neck diameters of *Alnus glutinosa* (47.60 mm) and *Alnus incana* (57.44 mm) were in the range of poplars. The lowest diameter could be observed for the clones 'Sven' and 'Torhild' (both willows), *Generosa × nigra* and 'Badenbuechig' (both poplars) and the species *Acer negundo* and *Sorbus aucuparia*. The maximum root neck diameters for willows were measured in Marbach, but for poplars and the alternative tree species the maximum diameters were measured in Forchheim. The lowest diameters for all tested species were identified in Kupferzell. The results of the several experimental sites can be viewed in detail in Table IV.

Correlations

A strong correlation was found between tree height and root neck diameter especially for poplars with $r = 0.97$ ($p < 0.001$ ***). As the root neck diameter is measured at a height of 0.1 m, the constant value was fixed to 0.1. For willow the correlation coefficient was $r = 0.89$ ($p < 0.001$ ***) and for the other tree species $r = 0.85$ ($p < 0.001$ ***) (Fig. 3), again with a constant of 0.1. In contrast, between tree height and number of shoots, and between number of shoots and root neck diameter no significant correlations were determined. The correlation coefficient ranged between 0.15 and 0.34 (Tab. V) indicating that tree height is proportional to the root neck diameter.

DISCUSSION

In order to get the legal status of a SRC (which is handled similar to agricultural standards and subsidies) tree species in Germany must be listed on a "white list". Eligible genera are currently *Salix, Poplar, Robinia, Betula, Alnus, Fraxinus* and *Quercus*. In these genera most of the species are eligible (for further details see Michalk 2015). However, other genera and species will be possibly get allowance to be grown on agricultural sites if trials suggest their viability. With a life cycle of approximately 20 years, a high survival rate is of high importance for SRC species to achieve high yields (Rosso *et al.* 2013). At all experimental sites, poplar clones showed on average a higher survival rate than willow clones. The highest survival of willow (91 %) and poplar (97 %) clones was observed at Kupferzell followed by Forchheim and Marbach. The low survival rate of the willow clones at Aulendorf (64 %) is related to the occurrence of voles, which resulted in major losses of willows. Before the establishment of the SRC, Aulendorf was used as a grassland. The grass between the tree rows was only mulched during the experimental time and no herbicides were applied. According to Campbell *et al.* (2012), voles' infestations can mainly be found in areas with abundant understory vegetation, and this may explain their infestation during this experiment at the Aulendorf site. Additionally, a further factor for consideration could have been due to the lack of tillage at this site.

The survival rate of the other tree species was not as high as for willows and poplars, especially for *Paulownia tomentosa*. This tree species is a thermophile tree and is susceptible to cold temperatures (Florea-Octavian 2009). Under optimal growing conditions, the tree height can increase 5-6 m in the first growing season and the tree-trunk diameter by 3-4 cm annually (El-Showk and El-Showk 2014). Additionally, *Paulownia tomentosa* can grow on a wide range of different soil types. However, due to strong winters at the experimental sites Kupferzell, Marbach and Aulendorf, *Paulownia tomentosa* died. The temperatures at Forchheim during winter were not as low as for the other sites, but nevertheless only 47 % survived. Therefore, this species can only be recommended for warm sites without a frost hazard.

Fungi, bacteria and viruses can cause disease infestations on short growing tree species whose impact can vary depending on the clone. The poplar species are especially threatened by rust fungus. In the case of pests leaf beetles play an important role (Liebhard 2007).

On the experimental sites, most clones had minor infestations with leaf rust as well as with the poplar leaf beetle. The highest infestations with leaf rust were determined for the poplar clone 'AF6', which is no longer available on the market. The willow clone 'Gudrun' was the only one which showed no infestation by leaf rust. However, compared to the other clones, 'Gudrun' tended to show the slowest growth. Feeding damage caused by the poplar leaf beetle was particularly observed on poplar clones. Nevertheless, the minor infestations on the tested

species by leaf rust and the poplar leaf beetle had no negative effect on growth.

SRC require appropriate site conditions to achieve an economically rewarding biomass production (Petzold *et al.* 2010). Dickmann (2006) pointed out that in the north-temperate climates, willow and poplar species demonstrated the fastest growth rate, which is comparable to the results of this study. The other tested tree species, with the exception of *Alnus* spp. and *Robinia pseudoacacia*, were not comparable to willows and poplars.

The maximum tree height was measured for the willow species in Marbach, especially the clones 'Tordis' and 'Olof' reached heights of up to 7.40 m and 8.50 m. Marbach is characterized by its cold climate and sufficient water. In Sweden, the water availability for willows was analyzed by Lindroth and Båth (1999). They pointed out that water availability is crucial to achieve high yields. Furthermore, Labrecque and Teodorescu (2001) studied the biomass production of willow clones in Canada and observed that willow growth is mainly promoted by adequate precipitation and cool temperatures.

In contrast, poplars prefer warmer temperatures (Stanturf *et al.* 2001) like in Forchheim, where the poplars measured for all species 6.10 m compared to a height of 4.40 m on average for all willow species. The tallest poplars were determined for the clone 'Max 3' (7.00 m). Liebhard (2007) described that this clone has a high productivity at warm and dry sites. However, at the coolest site (Marbach) within this study, poplars were approximately 10 % smaller. Although at Marbach, some clones behaved quite similarly to those at Forchheim, for example, 'Muhle Larsen' had an average height of 6.95 m. 'Muhle Larsen' belongs to the section *Tacamahaca* (balsam poplars), which is characterized by a rapid juvenile growth, and when compared to the section *Aigeiros (cottonwoods) it has a lower demand on the tempera*ture (Liebhard 2007). Benetka *et al.* (2014) demonstrated that different poplar clones can show a good growth performance even on marginal sites.

Alnus spp. is able to fix nitrogen (N2) by root nodules formed by *Frankia* actinomycetes (Benson 1982). This is one reason why *Alnus* spp. can be suitable for SRC. Another reason is that it has fast biomass growth (Aosaar *et al.* 2012). Due to the ability of *Alnus* spp. to produce rapid biomass growth in SRC, this species is ranked behind Salix spp. and *Populus* spp. (Ranney 1985). Danso *et al.* (1995) observed that *Robinia pseudoacacia* also has a high potential for N2 fixation from the atmosphere. In addition, this species is characterized by its drought tolerance (Gruenewald *et al.* 2009). The potential of *Alnus incana, Alnus glutinosa* and *Robinia pseudoacacia* to fix N2 could explain why these species demonstrated a good growth compared to the other tested tree species excluding willows and poplars, as all sites were unfertilized. Additionally like *Robinia pseudoacacia*, *Alnus incana* tolerates a wide range of soil conditions and is adapted to moist and dry sites (Johansson 1999; Kurokochi 2015). This species also survives droughts and winter frost and is resistant to most pests (Facciotto *et al.* 2009, Rockwood *et al.* 2004).

Willow and poplar clones and the other alternative tree species showed different growth behavior. At all experimental sites willow clones developed with a maximum of 2.40 ('Gudrun') number of shoots. On the contrary, the thickest root neck diameter was measured on average for *Alnus incana* (57.40 mm) and for the poplars with diameters between 36.90 mm and 54.70 mm. These results are consistent with a study examining the field performance and biomass production of twelve willow and poplar clones in Canada by Labrecque and Teodorescu (2005). The poplar clones had a single trunk with a larger diameter and a greater height than the willows which developed several thinner shoots. Although the diameter of the willow stem was smaller, the higher number of shoots led to comparable yields to that of the poplar clones. It could be shown that tree height and root neck diameter were correlated. When taking into account that a high bark content leads to inferior burning qualities of the wood (Jacob *et al.* 2013; Manzone *et al.* 2014), it can be assumed that tree species with a superior tree height and larger root neck diameter are the most profitable species. However root neck diameter is not often measured in SRC field trials (Kneifl *et al.* 2015).

CONCLUSION

Based on the above mentioned results, the willow clone 'Olof' and *Alnus* spp., especially *Alnus incana*, are considered to be suitable for most sites in southwestern Germany. The results further indicate that willow tree species seem to be adequate for cooler sites and poplars for warmer locations. The poplar clone 'Max 3' is recommended for sites with a warm and dry climate, for cooler sites 'Muhle Larsen' is recommended and for sites with moderate temperatures and rainfall in summer the clone 'AF2' should be chosen. *Paulownia tomentosa*, which is also characterized by its rapid growth, is only recommended for very warm areas without frost. The results at Kupferzell showed that low rainfall during the growing season (May–September) and heavy soil conditions are not favorable for the cultivation of fast-growing tree species.

In order to give final recommendations for the several tested clones and tree species, the re-growth and post-harvest growth should further be examined.

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