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Hybrid Willow Cultivation: Maximising Yields through Variable Spacing and Coppice Managements

Aman Mahajan[1*], J.P. Sharma[2]* and Bill Nelson Paul[1]
[1]*ICFRE- Forest Research Institute Dehradun-248 006, India*
[2]*Dr. Y. S. Parmar University of Horticulture and Forestry, Nauni, Solan-173 230, India*
*Corresponding Author Email: jaiuhfrajgarh@rediffmail.com

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***Abstract*:** The study was conducted in an experimental field at Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan, to assess the effect of spacing and clones on the growth and yield of hybrid willow. The experiment was set up in a factorial randomized block design with three hybrid clones (J-799, Kashmiri and J-194) planted at three spacings, 1 × 1 m, 1 × 2 m and 1 × 3 m. The highest survivability was observed for J-194 at 1 × 3 m spacing (86.04%), but the effects of spacing and clones were not significant. Spacing has a significant impact on the growth parameters of both trees and coppices. Kashmiri at 1 × 1 m spacing had the highest individual tree height (6.59 m) and the highest per hectare volume (189 m^3/ha), while J-194 at 1 × 2 m spacing recorded highest mean tree volume (2275.00 cm^3) and J-799 at 1 × 3 m largest mean diameter (6.94 cm). In coppice J-799 at 1 × 3 m spacing the highest collar diameter (3.03 cm), diameter at breast height (2.70 cm) and mean stem volume (2583.49 cm^3) were observed. Kashmiri at 1 × 1 m spacing showed highest leading coppice height (4.21 m) and J-799 at 1 × 1 m spacing the highest per-hectare volume (20.85 m^3/ha). The study shows that lower planting density favoured more lateral growth and individual volume production, whereas denser spacing was more favourable for height and volume per hectare.

Keywords: *Salix*, Willow, Coppice, Clones, Hybrid, Spacing.

1. INTRODUCTION

The genus *Salix*, in the family Salicaceae, contains 450-520 species worldwide (Wu et al., 2015). These are primarily deciduous trees and shrubs that thrive in moist soils across the Northern Hemisphere's temperate zones. Common names include 'willow', with specific narrow-leaved shrubs called 'osier' and broad-leaved species known as 'sallow'. In India, 33 willow species have been documented in the northern regions, of which 24 are explicitly found in the Indian Himalayan region. Willows exhibit remarkable adaptability, capable of growing in a wide range of soil conditions, including compacted, swampy, alkaline, or acidic soils, provided adequate moisture is available (Baum et al., 2009). Willows are highly versatile, fast-growing and extensively used in plantations worldwide (Chaudhary et al., 2013) and are good coppicers, frequently yielding 20 or 25 shoots from a single coppice stool (Anchal et al., 2022). They are notable for their rapid growth, excellent regenerative capabilities and high productivity within short rotation cycles and are widely used in wood and biomass production (Hernea et al., 2015).

Spacing is a crucial factor in project planning and execution in production forestry. Effective stand management requires careful control of growing stock spacing, plays vital role in resource availability and affects growth and yield (Stolarski et al., 2019). Moreover, spacing has significant silvicultural, economic and technological consequences, impacting productivity, costs and management practices (Moulin et al., 2015; Brito et al., 2019; Resquinet et al., 2019). Furthermore, spacing can alter wood properties by influencing tree growth and morphology (Hebert et al., 2016, Rocha et al., 2016). Optimum spacing is determined by the ability to produce the maximum yield with the desired size, shape and quality. However, it varies depending on the plant species, cultivars, site conditions and the genetic potential of the reproductive material used (Li et al., 2014; Brito et al., 2019; Huijuan et al., 2020; Fernandes et al., 2023). Numerous genetic improvement efforts have been undertaken in willow to develop improved clones for different end uses, such as bioenergy production, erosion control and phytoremediation (Larsen et al., 2014; Fehrenz et al., 2024). Willows can be grown at high densities and managed as short rotation coppice (SRC) due to their high coppicing ability. They are cultivated as an energy crop for

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biomass production and utilised as a renewable source of bioenergy (Fischer et al., 2015; Srivastava et al., 2025). In this context, the effect of spacing on the growth parameters and productivity of 3 clones and their coppice shoots formed after harvest was studied.

2. MATERIALS AND METHODS

The study was carried out at an experimental farm in Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan (H.P.), located at 30°51'05.0"N and 77°11'12.7"E with an altitude of 1060 metres above mean sea level. This site is situated within the mid-hill zone of Himachal Pradesh, India. The local climate is sub-temperate and sub-humid, with moderate summers and cool winters; May and June are the hottest months, while January and February are the coldest. Meteorological data, including rainfall, mean temperature and relative humidity, were recorded from January 2017 to December 2020 at the Meteorological Observatory of the Department of Environmental Science, Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan (H.P.) (Figure 1). The prevailing weather conditions during the experimental period were favourable for willow growth. Yearly average meteorological data and averages during the growing period (March-October) are provided in Table 1.

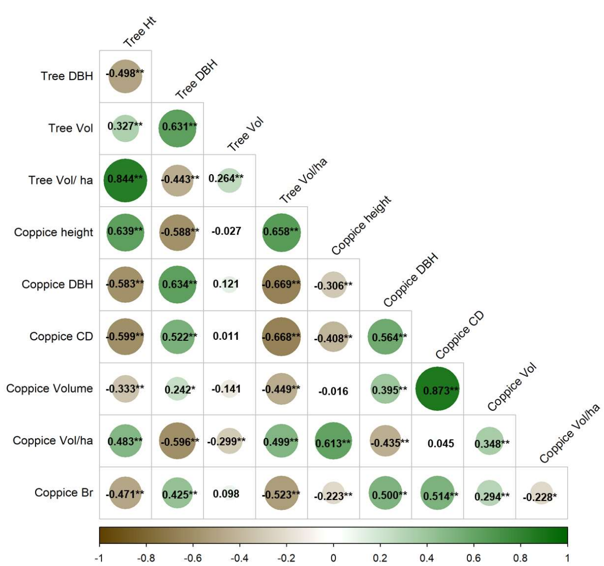

Figure 1. Correlation heat map of tree and coppice growth parameters

The soil depth at the site varies from very deep (>120 cm) to shallow (<20 cm), with the majority being moderately deep (50-80 cm). The soil at the experimental site was clay loam, with moderate fertility. The topsoil consists of clay (50%), silt (44-47%) and humus (3-6%). The experiment was set up in a factorial randomized block design with three clones, spacings and replications, with 18 trees for each combination (Table 2). After a growing period of three years, the survivability percentage (SV%) was calculated. The growth parameters of the surviving trees were measured and the trees were harvested, 15 cm from the base, to facilitate the growth of coppices on the stumps. The height of the tree (Tree height) was measured using a clinometer. Diameter at breast height (Tree DBH) of the trees was measured with the help of a tree caliper. Volume for each tree (Tree Vol) was calculated (Mahendran et al., 2018) and volume/hectare (Tree Vol/ha) was derived from it.

Leading coppices were selected from each stump and the remaining coppices were removed 2 months after harvest. The height of the coppice (Cop Ht) was measured with a measuring stick from the leading tip to ground level and the branches (Cop Br) were counted. The collar diameter (Cop CD) and diameter at breast height (Cop DBH) of the coppice shoot were measured with the help of a digital calliper. Volume for each coppice shoot (Cop Vol) was calculated similarly to that of the trees and coppice volume/hectare (Cop Vol/ha) was derived from it. The effects of the three spacings and clones on the growth parameters of trees and coppices were studied.

2.1. Data Analysis

Data were presented as means and all tests were statistically analysed using SPSS 21.0 (SPSS Inc., Chicago, IL, USA). The primary and interactive influences of spacing

Table 1. Annual average of meteorological data and average of meteorological data during the growing period

Year	Annual			Growing period		
	Ppt (mm)	M T (°C)	RH (%)	Ppt (mm)	M T (°C)	RH (%)
2017	97.37	12.45	60.00	131.36	21.44	61.59
2018	40.27	18.13	61.08	46.91	21.28	64.37
2019	87.80	18.08	62.28	101.51	21.49	63.30
2020	87.21	19.05	61.25	98.46	21.75	63.25

Ppt (mm): Precipitation, M T (°C): Mean Temperature, RH (%): Relative Humidity design and clones on growth parameters of trees and coppice shoots were determined using analysis of variance. Karl Pearson's correlations were calculated to determine the significance and strength of relationships among all variables.

3. RESULTS AND DISCUSSION

3.1 Survivability

After a period of 3 years of growth, the mean survivability (SV %) of the entire experiment was 67.79%, ranging from 50% for C1S2 to 86.04% for C3S3 (Table 3). Kirongo et al. (2013) had observed that wide spacing (2.5 x 2.5 m) gave significantly better survivals than closer spacing (1 x 1 m). Similar observations have been made in Douglas-fir (Curtis et al., 2016). The highest survivability was observed for C3 with the widest spacing (S3) in the current study. However, there were no significant differences among the spacings or clones.

3.2. Tree Growth Parameters

3.2.1. Height growth: The highest average tree height was observed in the C2 clone planted at S1, reaching 6.59 m. Conversely, the C1 clone at S3 exhibited the lowest average height, measuring 3.73 m (Table 3). The variation in tree height was significant among the three spacings and a progressive decrease in mean tree height was observed as planting spacing increased (S1 > S2 > S3). Among clones, tree height varied significantly only between C3 and C2 and between C2 and C1. Spacing has a profound influence on the form, growth and productivity of young plantations (Tun et al., 2018) by altering the resources each tree can access (Thomas et al., 2009). The mean tree height was higher in plots with closer plant spacing (S1) and decreased with increasing spacing. This phenomenon is a classic silvicultural response, where denser planting (S1) intensifies inter-tree competition for light. This competition promotes vertical growth, as trees grow faster to capture available sunlight, often at the expense of radial expansion. Similar observations were recorded in *Acacia mearnsii* (Amanuel et al., 2025) and in Teak (Kainyande et al., 2023). However, this effect of spacing on height might not be evident in the very early stages of growth and in some cases, spacing reduction can negatively affect height growth (Kirongo et al., 2012).

3.2.2. Lateral growth: The variation in tree DBH among the three spacings was significant, but the variations among the clones were not significant. The largest average tree DBH at breast height was in the C1 clone at S3, with a mean of 6.94 cm, whereas the C2 clone at S1 exhibited the smallest average tree DBH, at 5.32 cm (Table 3). In a direct and inverse relationship to tree height, tree DBH demonstrated an increase with wider planting spacing (S1 < S2 < S3). The results agree with Kirongo et al. (2012), Tun et al. (2018) and Kainyande et al. (2023) who observed that increasing spacing led to a subsequent increase in lateral growth. This can be attributed to the reduced competition for resources

Table 2. Spacing and clones used in the study

Spacing	Abbreviation	Clones	Abbreviation	Parents
1 × 1 m	S1	J-799	C1	*Salix matsudana × S. alba*
1 × 2 m	S2	Kashmiri	C2	*Salix alba* cv. *caerulea*
1 × 3 m	S3	J-194	C3	*Salix matsudana × S. arbutifolia × S. matsudana*

Table 3. Mean growth parameters of different clones planted at three spacings (Mean)

Clone	Spacing	Sv (%)	Tree height (m)	Tree DBH (cm)	Tree Vol (cm^3)	Tree Vol/ha (m^3/ha)
C1	S1	67.99	5.872^{b}	5.44^{c}	1707.98^{bc}	170.8^{ab}
C1	S2	55.36	4.817^{c}	6.24^{b}	1859.16^{bc}	97.61^{c}
C1	S3	73.54	3.732^{d}	6.94^{a}	1799.12^{bc}	59.96^{d}
C2	S1	74.34	6.589^{a}	5.32^{c}	1899.73^{bc}	189.97^{a}
C2	S2	50.00	5.045^{c}	6.23^{b}	1981.03^{ab}	99.05^{c}
C2	S3	60.74	4.204^{d}	6.83^{a}	1959.79^{abc}	65.32^{d}
C3	S1	77.31	5.201^{c}	5.56^{c}	1618.9^{c}	161.89^{b}
C3	S2	64.81	5.192^{c}	6.53^{ab}	2275^{a}	113.75^{c}
C3	S3	86.04	3.855^{d}	6.71^{a}	1757.38^{bc}	58.57^{d}

SV- Survivability percentage, Tree DBH- Tree Diameter at Breast height, Tree Vol- Tree volume, Tree Vol/ha- Tree Volume per hectare

with the stocking reduction (Đodan et al., 2024). Lower stocking allows greater resource availability per individual; trees can allocate more photosynthates to radial growth, resulting in thicker stems (Li et al., 2023).

3.2.3. Stem and stand volume: Tree volume varied significantly between spacings S1 and S2, and between S2 and S3. Among clones, tree volume varied significantly only between C2 and C1. The highest mean individual tree volume was observed for C3 at S2 (2275.00 cm^3) and the lowest was for the same clone at the densest spacing (S1), at 1618 cm^3 (Table 3). Consistently higher individual tree volumes for all clones were observed for the intermediate spacing S2. Reducing stocking has been observed to have a positive impact on individual tree volume (Héber et al., 2016). Similar observations were made by Zhang et al. (2020) and Stape et al. (2022) reported that the highest individual tree volumes occurred in stands with the largest spacing. However, this pattern is not evident in the current study, which might be due to the contributions of height and diameter towards volume and their inverse correlation among the different planting densities. Tree volume per hectare varied significantly among all the spacings. However, among clones, tree volume per hectare varied significantly only between C2 and C1. The highest mean tree volume per hectare was observed for the C2 clone at S1, reaching about 189 m^3/ha, while the lowest was for C3 at S3 (58.57 m^3/ha). C2 consistently outperformed the other clones in terms of Tree volume per hectare, across all spacings.Volume production per unit area is of paramount importance in commercial forestry, as it directly reflects the overall productivity of the stand. The consistent trend was observed where tree volume per hectare is generally highest at the densest spacing (S1) and progressively decreases with wider spacing (S3). The higher per-hectare volume has been observed in previous studies for younger or short-rotation stands with high stocking (Sang et al., 2021; Stape et al., 2022). There is a distinct and critical trade-off between individual tree volume and volume per hectare as planting spacing changes. This is primarily because, despite individual trees being smaller in denser stands, the significantly greater number of trees per hectare more than compensates, leading to a higher cumulative volume in younger stands.

3.3. Coppice Growth Parameters

3.3.1. Leading coppice height: Coppice height varied significantly between spacings S1 and S2 and between S1 and S3, but there was no significant difference among the clones. The maximum mean coppice height was observed for the C2 clone at S1, reaching 4.21 m and the C3 clone at S3 exhibited the least mean coppice height, at 2.68 m (Table 4). The trend for coppice height largely mirrors that of initial Tree height. i.e., denser initial spacing (S1) generally leads to taller coppice shoots. This is likely due to the competition for light among the coppice shoots of individual stools, along with the smaller initial spacing, which promotes vertical growth. However, studies with contradictory results have been reported. Ogunwande et al. (2022) reported that the leading coppice formed after cutting six-month-old *Albizia lebbeck* were tallest in the field with the least density (2 x 2 m). Intense competition can be deleterious to the overall growth when the stocking is very high (Berbec and Matyka 2020).

3.3.2. Lateral growth: The variation in coppice collar diameter and diameter at breast height among the three

Table 4. Growth parameters of the leading coppice shoots

Clone	Spacing	Cop Ht (m)	Cop DBH (cm)	Cop CD (cm)	Cop Vol (cm^3)	Cop Vol/ha (m^3ha^{-1})	Cop Br
C1	S1	3.92^{ab}	1.77^{de}	1.85^{cde}	2084.52^{abc}	20.85^{a}	20^{d}
C1	S2	3.28^{bc}	2.22^{bcd}	1.78^{cde}	1868.41^{bc}	9.34^{cd}	26^{bcd}
C1	S3	2.81^{c}	2.7^{a}	1.95^{a}	2583.49^{a}	8.61^{cd}	28^{bcd}
C2	S1	4.21^{a}	1.48^{e}	2.37^{e}	1508.77^{c}	14.71^{bc}	19^{d}
C2	S2	3.48^{c}	2.22^{abcd}	2.27^{bcd}	1819.14^{bc}	8.73^{d}	29^{abc}
C2	S3	3.03^{c}	2.64^{ab}	2.56^{ab}	2471.4^{ab}	8.24^{d}	34^{a}
C3	S1	3.51^{abc}	1.75^{cd}	3.03^{de}	1703.47^{bc}	16.81^{b}	22^{cd}
C3	S2	2.99^{bc}	2.31^{abc}	2.74^{bcd}	2128.57^{bc}	10.1^{cd}	29^{ab}
C3	S3	2.64^{c}	2.56^{a}	2.88^{abc}	2256.07^{abc}	7.52^{d}	29^{ab}

Cop Ht- Coppice height, Cop DBH- Coppice diameter at breast Height, Cop CD- Coppice collar diameter, Cop Vol- Coppice volume, Cop vol/ha- Coppice volume per hectare, Cop Br- Coppice branches

spacings was significant, while among the clones, coppice DBH varied significantly between C3 and C2. However, variation in coppice collar diameter among clones was not significant. The C1 clone at S3 had the largest mean collar diameter (3.03 cm; Table 4) and the highest mean coppice DBH (2.70 cm). Conversely, the C2 clone at S1 exhibited the smallest average Coppice collar diameter and coppice DBH at 1.78 cm and 1.48 cm, respectively. Plants with the widest spacing were observed to have the largest stem diameter, followed by intermediate spacing and the smallest diameter was observed in plants with the closest spacing (Ogunwande et al., 2022; Pradhan et al., 2023). This aligns with the results of this study. This trend of higher spacing producing coppices with larger stem diameter follows the pattern seen in tree DBH.

3.3.3. Stem and stand volume: Coppice volume had a significant difference only between the spacings S1 and S3, while coppice volume/ha varied significantly between the spacings S1, S2 and S1, S3. Among the clones, significant variation was observed between C3 and C1 and between C2 and C1 for coppice volume. The highest average coppice volume was for the C1 clone at S3, with 2583.49 cm^3 (Table 4). Conversely, the C2 clone at S1 exhibited the lowest average Coppice volume, at 1508.77 cm^3. Coppice volume generally increased with the spacing of the initial planting, except for C1, which showed a non-significant decrease from S1 to S2. Higher individual stem volumes have been reported in stands with lower density (Hébertet al., 2016; Huijuan et al., 2020; Sang et al., 2021). The coppice volume/ha varied significantly between C3 and C1 and between C2 and C1. The highest mean coppice volume per hectare was recorded for the C1 clone at S1, at 20.85 m^3/ha. C3 clone at S3 exhibited the lowest mean coppice volume/ha, at 7.52 m^3/ha. Similarly, to tree volume/ha, coppice volume/ha decreased with increasing initial planting spacing (S1>S2>S3). The C1 clone performed better for individual coppice volume and per-hectare volume production across most spacings. The contribution of stem number, due to higher planting density, is often greater than the individual stem volumes when calculating stand volume (Chane et al., 2022).

3.3.4. Branch number: Coppice branch number varied significantly between S1 and S3 and between S1 and S2; for clones, significant variation was observed only between C3 and C1. The maximum mean coppice branch number was recorded for the C2 clone at S3, reaching 34. This indicates that C2, when initially planted at the widest spacing, subsequently produced coppice shoots with the largest number of branches. Conversely, the C2 at S1 exhibited the lowest average number of 19 branches (Table 4). Similar to coppice DBH, coppice volume and coppice collar diameter, the number of branches generally shows an increasing trend with wider initial planting spacing (S1 < S2 < S3). This may be due to the lesser competition during the initial growth phase, resulting in larger and more vigorous stumps, which subsequently enable more robust basal shoot development upon coppicing. In line with this study's results, the number of branches and their size were reported to increase with reduced stocking (West and Smith 2020). With the increase in spacing, biomass accumulation has been reported to increase in the branches (Hébert et al., 2016)

3.4. Correlation Studies

The correlation coefficient reflects the level of correlation between the tree growth parameters and coppice growth parameters (Figure 1). Tree height and diameter at breast height (DBH) showed strong positive correlations with tree volume and tree volume/ha, indicating their direct contribution to volume. However, tree height and tree DBH were significantly negatively correlated. This is primarily due to the spacing effect, in which closer spacing promotes greater height growth than lateral growth and vice versa with increased spacing. Another notable effect is the strong negative correlation of tree diameter at breast height and coppice collar diameter with tree volume/ha and coppice volume/ha. This suggests that even though tree DBH and coppice collar diameter are contributing factors for volume estimation, the effect of the number of trees per hectare had a higher contribution to tree volume/ha. This has been observed in previous spacing studies, especially in short rotation crops (Sang et al., 2021; Chane et al., 2022). The coppice height showed significant positive correlations with tree height, tree volume and coppice volume/ha and significant negative correlations with tree and coppice DBH, collar diameter and branches. Unlike the significant positive correlation of tree height and volume, coppice height did not show any significant correlation with coppice volume. This might be due to the lateral growth in the leading coppice shoots after removing competing shoots from the stump. Regarding the efficacy of predictor variables, the analysis highlights that for coppice volume estimation, diameter-based measurements were far superior predictors than coppice height. DBH and collar diameter had a significant positive correlation with each other and also showed a significant positive correlation with tree DBH and coppice volume branch number. Furthermore, the size of individual coppice shoots was not a strong predictor of stand-level coppice volume/ha, suggesting that density is more influential for volume production at the stand level, at least at younger ages.

4. CONCLUSION

The study concludes spacing has a significant effect on growth parameters of 3-year-old hybrid willow clones and their coppices. The denser stocking has been shown to improve vertical growth, higher stocking density restricts lateral growth. Conversely, reducing planting density promotes lateral growth but reduces height growth. For higher stand volume, high-density stocking is recommended; wider spacing can be considered if higher-diameter growth is required. In general, Kashmiri clone consistently maintained higher volume per unit area across various spacings in trees compared to other clones; conversely. J799 clone performed better in most growth parameters across all spacings in coppice.

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Authors' Contributions

All authors contributed significantly to the development of this work. AM contributed to field data collection, data curation and the writing of the original draft. JPS contributed to the conceptualization, study design, methodology, supervision and validation. All authors (AM, JPS and BNP) contributed to the writing, review and editing of the manuscript, as well as to data analysis and interpretation.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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