Range Management and Agroforestry 45 (2) : 211-217, 2024
ISSN 0971-2070 (Print); 2249-5231 (Online)
https://doi.org/10.59515/rma.2024.v45.i2.04

Research article

Precision silviculture: optimization of water and nutrient scheduling for high-density tree plantation of *Dalbergia sissoo*

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Received: 21st November, 2023 Accepted: 25th October, 2024

Abstract

The study was conducted by applying the principles of precision silviculture to standardize optimal water and nutrient requirements. It also evaluated effects of balanced fertilization on tree physiology and analyzed distribution of nutrients in soil sub-surface using GIS technology, specifically SURFER 7 software in high density *Dalbergia sissoo* tree plantation. The plantation was given spacing of 3 x 2 meters in split plot design with three levels of irrigation *viz.*, 100% pan evaporation (PE), 125% PE and 150% PE in main plots and three levels of fertigation regimes in subplots which consisted humic acid @ 62.5 l ha^{-1}, 150:100:100 kg N, P_2O_5, K_2O ha^{-1} and humic acid @ 62.5 l ha^{-1} + 75:50:50 kg N, P_2O_5, K_2O ha^{-1}. The study revealed that higher height (5.28 m), basal diameter (51.19 mm) and volume index were found in the treatment that received irrigation @ 125% PE and fertigation with the fertilizer dose of 150:100:100 kg N, P_2O_5, K_2O ha^{-1} (I_2F_2). I2F2 Recorded improved photosynthetic rate (7.73 µ $mol.m^{-2}$ s^{-1}), transpiration rate (8.83 m $mol.m^{-2}$ s^{-1}) and stomatal conductance (0.16 µ $mol.m^{-2}$ s^{-1}). Maximum available nitrogen (190 kg ha^{-1}), phosphorus (19.2 kg ha^{-1}) and potassium (346 kg ha^{-1}) were recorded at 30 cm lateral distance and the corresponding values were 188, 12.80, 362 kg ha^{-1} at 0 to 30 cm sub-surface soil at 7 months after plantation (MAP). The SURFER maps showed that the mobility of nutrient concentration in the sub-soil surface decreased as the distance from the plant increased. A significant increase in N P and K in soil was recorded in I2F2 as compared to fertigation with humic acid 62.5 l ha^{-1} and irrigation level @150% PE (I_1F_1).

Keywords: Biometric parameters, Drip fertigation, Nutrient distribution, Physiological traits, Precision silviculture

Introduction

Precision silviculture is an advanced and emerging approach in plantation forestry, integrating modern technologies to address the growing industrial demand for wood while ensuring sustainable supply and reducing pressure on natural forests. Many countries are now focusing on plantation forestry and wood-based industries as vital components of their regional and national economic development strategies (Nambiar *et al*., 2004). Additionally, plantation forestry plays a crucial role in carbon sequestration and climate change mitigation through various afforestation practices (Roy, 2016; Chaturvedi *et al*., 2016). In India, the Green India Mission 2014 emphasizes agroforestry to achieve a 33% green cover by planting commercial tree species on farmlands. However, the increasing demand and low productivity of tree plantations pose significant challenges for wood-based industries. Precision forestry, inspired by precision agriculture, relies on information-based decision-making systems designed to optimize each step of the agricultural process to maximize the production and sustainability of natural resources (Rasher, 2009). By using improved planting materials and location-specific silvicultural technologies, precision silviculture aims to enhance plantation productivity (Kovacsova and Antalova, 2010). In Tamil Nadu, with an average annual rainfall of 961.8 mm distributed over 40 to 45 rainy days, rainfall alone is insufficient to meet irrigation needs. Traditional irrigation systems require substantial water and manpower. Water stress impairs a plant's ability to resist biotic stress, leading to increased susceptibility to biotic stressors (Sateesh Kumar *et al*., 2022). The micro-irrigation system, known for its high water use efficiency (80–90%), such as drip irrigation, addresses these challenges effectively (Madhok, 2020). These limitations can be mitigated through the use of a combination of inorganic and organic fertilizers, which enhances soil fertility and reduces moisture loss *via* drip fertigation. *Dalbergia sissoo*, commonly known as shisham or Indian rosewood, belongs to the Fabaceae family and is native to countries like Afghanistan, Bangladesh, Bhutan, India, Malaysia, and Pakistan, which is used for different purposes, including as a fodder tree. However, the successful regeneration of *D. sissoo* relies on abundant moisture and minimal competition, typically found in riverine environments with ample sunlight and moisture, often alongside species such as *Pinus roxburghii*, *Acacia catechu*, and *Shorea robusta*. Therefore, the present study aimed to standardize water and nutrient requirements for high-density plantations of *D. sissoo* and to record the effects of balanced fertilization on species' growth and physiology, including soil nutrient distribution.

Materials and Methods

Study site: A field trial was conducted in E Block of the Farm Unit at Forest College and Research Institute, Mettupalayam. The site is situated at 11°19′ N latitude and 77°56′ E longitude, with an altitude of 300 meters above mean sea level. The experimental field's soil belongs to the Illupanatham soil series. It was classified as loamy sand in texture, well-drained, slightly alkaline (pH 7.87), and non-saline (EC 0.20 dSm^{-1}). Initial soil fertility assessments revealed low levels of available nitrogen (154 kg ha^{-1}) and available phosphorus (5.50 kg ha^{-1}), while available potassium was at a medium level (223 kg ha^{-1}). The surface soil exhibited a low organic carbon content (0.45%).

Field layout: The experiment was laid out in a split-plot design of plot size 42 x 54 m which consisted of main plots for irrigation treatments and sub-plots for fertigation levels (Table 1). The seedlings were planted in a high-density plantation configuration with a spacing of 3 x 2 meters. Irrigation treatments were allocated to main plots, designated as I_1, I_2, and I_3. Fertigation treatments were assigned to sub-plots labeled F_1, F_2, and F_3. These fertigation treatments included application of humic acid at 62.5 liters per hectare (F_1), a fertilizer mixture of 150:100:100 kg N, P_2O_5 and K_2O per hectare (F_2), and a combination of humic acid at 62.5 liters per hectare plus a reduced fertilizer mix of 75:50:50 kg N, P_2O_5 and K_2O per hectare (F_3).

Table 1. The details of treatments imposed in the study

Main plot: Irrigation water level		Subplot: Fertilizers level	
I_1	100% PE	F_1	Humic acid (62.5 l ha^{-1})
I_2	125% PE	F_2	150:100:100 kg N, P, K ha^{-1}
I_3	150% PE	F_3	Humic acid (62.5 l ha^{-1}) + 75: 50: 50 kg N, P, K ha^{-1}

Water requirement was calculated by using pan evaporation (PE) data; Water requirement (liter $tree^{-1}$ day^{-1}) = Pe X Kp X Kc X A X Wp – Re; where Pe = Pan evaporation rate (mm day^{-1}), Kp = Pan coefficient (0.70), Kc = Crop coefficient (1.00), Wp = Wetted percentage (0.50) and Re = Effective rainfall (mm). The duration of irrigation through micro irrigation system was also computed using the formula: Irrigation duration = [W/ (N x D)], where W = Water requirement per plant, N = Number of drippers per plant and D = Discharge rate (liter h^{-1}).

Biometric parameters: Biometric parameters were recorded at 1 month after planting (MAP), 4 MAP, 7 MAP and 9 MAP for seedlings under each treatment and replication. The mean value for each parameter was subsequently calculated. The total height of the trees was measured from ground level to the leading terminal tip using a standard scale, with measurements expressed in meters. Basal diameter was measured at the collar using a digital vernier caliper and expressed in millimeters. Finally volume index (VI) was obtained ($VI = D^2 \times H$), based on basal diameter (D) and height (H) (Rubilar *et al*., 2008).

Ecophysiological attributes: Ecophysiological attributes, including photosynthetic rate, stomatal conductance and transpiration rate, were measured using a portable photosynthesis system (PPS, Model LC pro+ Photosynthesis System CO_2 Gas Analyzer, UK). Measurements were conducted on fully matured leaves (5–6 leaves per bud) at 4 months after planting (MAP) and 8 MAP, during sunny days between 10:00 AM and 11:00 AM to ensure consistent light and temperature conditions. The PPS, utilizing an Infrared Gas Analyzer (IRGA), quantified CO_2 uptake and estimated photosynthetic productivity. These parameters were expressed as (µ mol m^{-2} s^{-1}) for photosynthetic rate, (m mol m^{-2} s^{-1}) for stomatal conductance and (m mol m^{-2} s^{-1}) for transpiration rate to evaluate the impact of fertigation on the physiology of tree species.

Soil nutrient dynamics: Soil nutrient dynamics were assessed by analyzing available nitrogen, phosphorus and potassium contents in soil. Soil sampling was conducted horizontally at distances of 30, 60 and 90 cm, as well as at vertical depths of 0 to 30 cm and 30 to 60 cm from the lateral drip pipe. Distribution of nutrients (N, P and K) in sub-soil at these horizontal distances and vertical depths from the plant was also determined using standard soil analytical procedures (Subbiah and Asija, 1956; Olsen *et al.*, 1954; Stanford and English, 1949). Data were then processed using the GIS application SURFER (Golden Software) to create contour and 3D maps illustrating the spatial distribution of N, P and K in soil. This comprehensive analysis allowed a better understanding of nutrient availability and its implications for plant growth and soil management practices.

Statistical analysis: Data collected/generated were statistically analyzed using a split-plot design. For treatments that showed significant effects, critical differences (CD) were calculated at 5% probability level.

Results and Discussion

Biometric parameters: The irrigation and fertigation regimes had a significant impact on biometric parameters from 1 MAP to 9 MAP. The irrigation at 125% pan evaporation (PE) and fertigation with inorganic fertilizers @ 150:100:100 kg of N, P, K ha^{-1} (I_2F_2) and irrigation at 100% PE and fertigation with inorganic fertilizers @ 150:100:100 kg of N, P, K ha^{-1} (I_1F_2) recorded the highest biometric values. Among the various treatments, the highest height was achieved with I_2F_2 treatment, which utilized irrigation at 125% of the pan evaporation (PE) along with fertigation using 150:100:100 kg of N, P, and K per hectare, resulting in a height of 3.55 meters. Additionally, the highest basal diameter was recorded with I_1F_1 treatment, which involved irrigation at 100% PE and application of humic acid at 62.5 liters per hectare, leading to a basal diameter of 22.33 mm. Furthermore, the highest volume index was also observed with I_2F_2 treatment. Conversely, the lowest values for these biometric parameters were observed in treatment combinations I_2F_3 and I_3F_1, with the I_2F_3 treatment resulting in a height of 2.62 meters and a basal diameter of 15.13 mm (Table 2; Fig 1). Earlier, Samuelson *et al.* (2008, 2009) observed similar findings, indicating that fertigation resulted in increased basal area and stem biomass in loblolly pine (*Pinus taeda* L.), along with enhanced foliar nitrogen concentration and foliage biomass. Additionally, the study found that in a six-year-old loblolly pine plantation, stands receiving inorganic fertilization exhibited significantly greater height, diameter at breast height (DBH), and basal area compared to non-fertilized stands.

Ecophysiological attributes: Understanding the effects of different irrigation and fertigation regimes on physiological parameters is essential for optimizing growth and productivity in plantation systems. The highest physiological performance was observed under I_2F_2 treatment. This regime resulted in photosynthetic rates of 7.73 and 8.30 μ mol m^{-2} s^{-1}, transpiration rates of 7.56 and 8.83 m mol m^{-2} s^{-1}, and stomatal conductance of 0.16 and 0.14 m mol m^{-2} s^{-1}, measured at 4 and 8 MAP, respectively. Thus, I_2F_2 treatment was found to be the optimal schedule for enhancing plantation growth. In contrast, the lowest values for these parameters were recorded under I_3F_3, I_1F_1, and I_3F_1 treatments, which yielded 7.12 μ mol m^{-2} s^{-1} for photosynthetic rate, 6.54 m mol m^{-2} s^{-1} for transpiration rate, and 0.10 m mol m^{-2} s^{-1} for stomatal conductance (Table 3). Optimal irrigation and targeted fertigation often enhance photosynthetic rates and overall plant health, while inadequate or excessive treatments could lead to suboptimal growth and reduced efficiency. Ricardo *et al.* (2001) similarly found that *Swietenia macrophylla* demonstrated a higher photosynthetic rate under ambient conditions compared to stress conditions. Additionally, Hyun-Seok *et al.*

Table 2. Biometric parameters of *Dalbergia sissoo* under high density plantation

Irrigation/ Fertigation regimes	Basal diameter (mm)				Height (m)				Volume index (m^3)			
	1 MAP	4 MAP	7 MAP	9 MAP	1 MAP	4 MAP	7 MAP	9 MAP	1 MAP	4 MAP	7 MAP	9 MAP
I_1	12.52	22.19	31.57	44.77	1.32	2.54	3.23	4.27	0.0002	0.0013	0.0032	0.0086
I_2	9.93	17.94	27.35	46.42	1.13	2.24	3	4.37	0.0001	0.0007	0.0022	0.0094
I_3	9.09	17.04	26.57	42.71	1.12	2.07	2.81	4.08	0.0001	0.0006	0.0020	0.0074
CD ($p < 0.05$)	1.81**	2.94**	3.56*	2.65*	0.16*	0.46	0.23*	0.3	0.00005**	0.0003**	0.0013	0.0014
SE	0.74**	1.20**	1.45*	1.08*	0.06*	0.19	0.09*	0.12	0.00002**	0.0001**	0.0005	0.0006
F_1	10.79	19.64	27.53	41.38	1.23	2.21	2.93	3.76	0.0001	0.0009	0.0022	0.0064
F_2	11.23	19.9	31.51	49.58	1.27	2.57	3.35	5.1	0.0002	0.0010	0.0033	0.0125
F_3	9.52	17.63	26.45	42.94	1.07	2.08	2.75	3.85	0.0001	0.0006	0.0019	0.0071
CD ($p < 0.05$)	1.43	1.84**	1.21**	2.59**	0.13**	0.18**	0.14**	0.34**	0.00005*	0.0002	0.0008**	0.0013**
SE	0.68	0.88**	0.58**	1.23**	0.06**	0.86**	0.7**	0.16**	0.00002*	0.0001	0.0004**	0.0006**

CD: Critical difference; SE: Standard error; *($p < 0.05$); **($p < 0.01$)

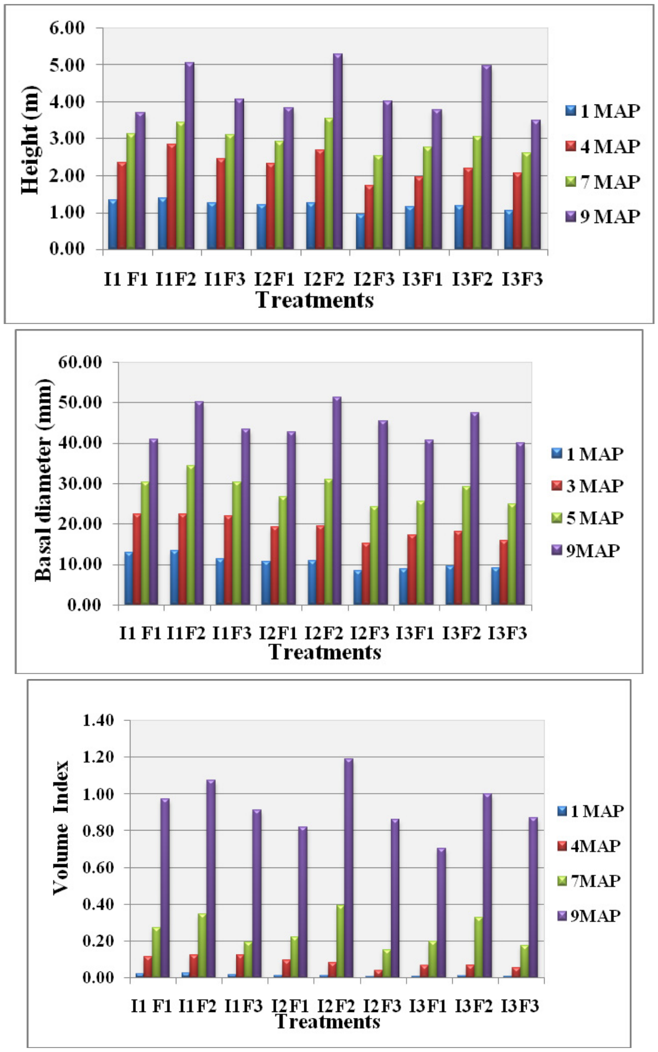

Fig 1. Influence of irrigation and fertigation regimes on height and basal diameter in *D. sissoo*

(2008) noted that optimizing biomass production in *Populus trichocarpa* and *P. deltoides* with drip irrigation necessitates 70% more water and resulted in a 27% reduction in water use efficiency.

Soil nutrient dynamics: Different irrigation and fertigation regimes can significantly alter the spatial distribution of nutrients, impacting their availability to plants. The soil nutrients were analyzed at 7 MAP across lateral distances of 30, 60, and 90 cm, and vertical depths of 0 to 30 cm and 30 to 60 cm from the sub-soil surface. Contour and wireframe maps were developed to illustrate nutrient distribution relative to these distances (Figs 2-3). The analysis revealed that different irrigation and fertigation regimes significantly affected soil nutrient dynamics. The I_2F_2 treatment (irrigation at 125% PE and fertigation with inorganic fertilizers @ 150:100:100 kg of N, P, K ha^{-1}) recorded the highest concentrations of available soil nutrients, with nitrogen at 181 kg ha^{-1}, phosphorus at 17.10 kg ha^{-1}, and potassium at 326 kg ha^{-1}, predominantly at a lateral distance of 30 cm from the plant.

Additionally, at the vertical depth of 0 to 30 cm, I_2F_2 treatment showed maximum concentrations of available soil nitrogen (174 kg ha^{-1}), phosphorus (335 kg ha^{-1}), and potassium (11.18 kg ha^{-1}) (Tables 4 and 5). Similar results were reported by Anitta and Muthukrishnan (2013) in which nitrogen concentrations were highest in 15 to 30 cm depth layer and at a distance of 20 cm from the plant, while phosphorus tended to accumulate near the application point, with limited downward leaching or lateral movement. Achakzai *et al*. (2012) further reported that urea, due to its relative mobility and weak adsorption by soil colloids, distributed down the soil profile, with the maximum nitrogen concentration observed immediately below the emitter, extending laterally up to 30 cm and vertically up to 0 to 30 cm before declining.

Table 3. Physiological parameters of *D. sissoo* under high density plantation

	Photosynthetic rate (μ mol.m^{-2} s^{-1})		**Transpiration rate (m mol. m^{-2} s^{-1})**		**Stomatal conductance (m mol. m^{-2} s^{-1})**	
Irrigation /Fertigation regimes	**4MAP**	**8MAP**	**4MAP**	**8MAP**	**4MAP**	**8MAP**
I_1	7.53	8.17	5.12	7.11	0.12	0.12
I_2	7.42	8.18	5.44	7.53	0.12	0.12
I_3	7.20	8.16	4.82	6.54	0.12	0.12
CD (*p* <0.05)	0.3	0.17	0.18**	0.20**	0.005*	0.01
SE	0.11	0.06	0.06**	0.07**	0.001*	0.01
F_1	7.18	8.13	4.09	5.75	0.10	0.10
F_2	7.66	8.25	6.57	8.57	0.14	0.15
F_3	7.31	8.13	4.73	6.87	0.12	0.12
CD (*p* <0.05)	0.22**	0.24*	0.17**	0.21**	0.003**	0.003**
SE	0.1**	0.11*	008**	0.09**	0.001**	0.001**

Table 4. Nitrogen, phosphorus and potassium dynamics at lateral distances under drip fertigated *D. sissoo* plantation (7 MAP)

	Available nitrogen (kg ha^{-1})			Available phosphorus (kg ha^{-1})			Available potassium (kg ha^{-1})		
Irrigation /Fertigation regimes	**30 cm**	**60 cm**	**90 cm**	**30 cm**	**60 cm**	**90 cm**	**30 cm**	**60 cm**	**90 cm**
I_1	161	140	125	13.2	11.2	8.9	311	283	295
I_2	180	155	143	12.9	10	7.6	326	298	281
I_3	169	155	127	12.1	9.7	8.1	283	269	254
CD ($p < 0.05$)	11.09*	15.72	19.64	7.05	2.4	2.16	13.46**	12.27**	12.41**
SE	3.99*	5.66	7.07	2.54	0.86	0.77	4.89**	4.42**	4.47**
F_1	166	142	127	10.8	8.3	6.9	295	266	248
F_2	181	161	139	17.1	13.7	10.5	322	311	301
F_3	163	148	129	10.3	8.9	7.2	304	273	281
CD ($p < 0.05$)	9.04**	9.40**	6.75**	4.21**	2.08*	1.31*	9.49**	8.86**	8.61**
SE	4.14**	4.31**	3.09**	1.93**	0.95*	0.60*	4.35**	4.06**	3.95**

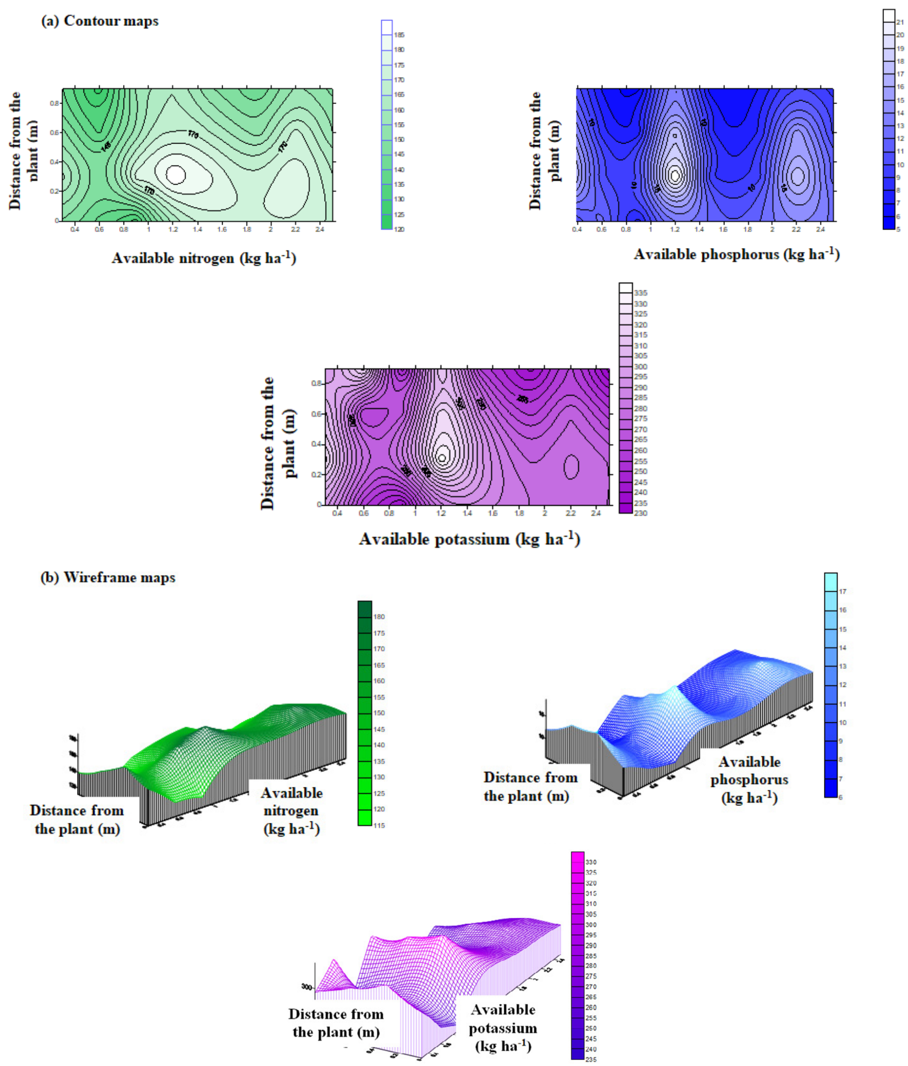

Fig 2. Contour maps (a) and wireframe maps (b) of nitrogen, phosphorus and potassium at lateral distances (30, 60, 90 cm; 7 MAP)

Table 5. Nitrogen, phosphorus and potassium dynamics at vertical depth under drip fertigated *D. sissoo* plantation (7 MAP)

	Available nitrogen (kg ha^{-1})		Available phosphorus (kg ha^{-1})		Available potassium (kg ha^{-1})	
Irrigation/ Fertigation regimes	**30 cm**	**60 cm**	**30 cm**	**60 cm**	**30 cm**	**60 cm**
I_1	150	132	8.28	6.55	285	299
I_2	168	146	9.56	7.55	326	319
I_3	153	141	7.36	5.78	290	278
CD (*p* <0.05)	6.93**	6.18**	0.39**	0.33**	13.24**	13.40**
SE	2.49**	2.22**	0.14**	0.11**	4.77**	4.82**
F_1	135	123	6.07	4.92	267	274
F_2	174	155	11.18	9.26	335	329
F_3	161	141	7.96	5.7	300	294
CD (*p* <0.05)	4.93**	4.21**	0.27**	0.22**	9.59**	9.33**
SE	2.26**	1.93**	0.12**	0.10**	4.40**	4.28**

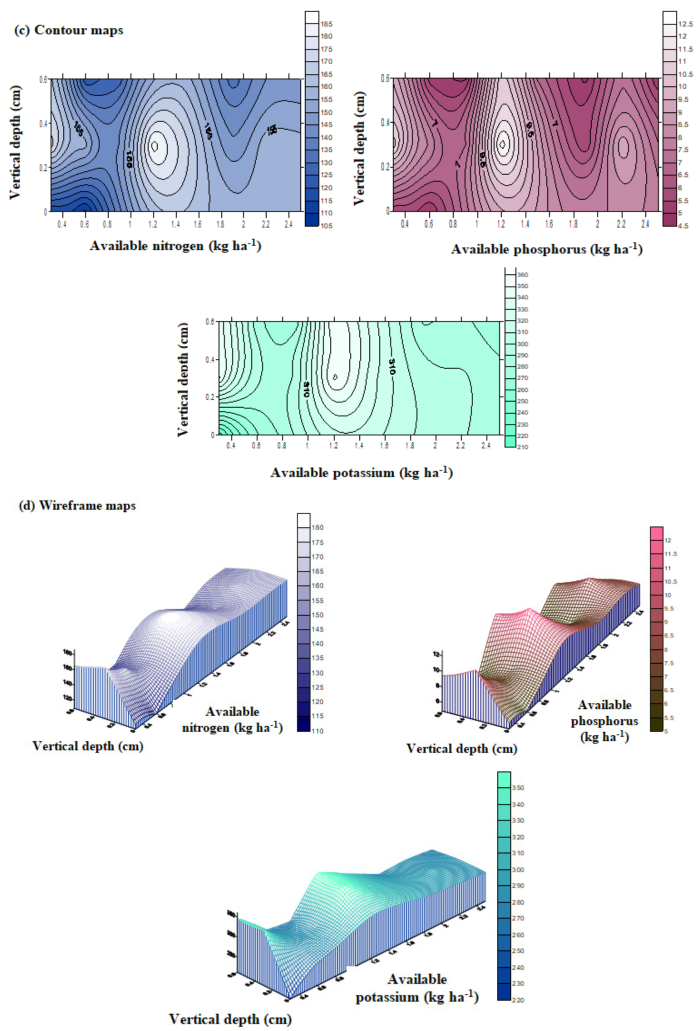

Fig 3. Contour maps (c) and wireframe maps (d) of nitrogen, phosphorus and potassium at vertical depths (0–30, 30–60 cm; 7 MAP)

The contour maps and wireframe maps developed using the GIS application SURFER software showed that the distribution of available soil nutrients, *i.e.*, nitrogen, phosphorus and potassium kilogram per hectare, was found to be maximum at 30 to 60 cm lateral distance and at 0 to 30 cm vertical depth. The nutrient distribution under drip fertigation using SURFER software indicated that the highest available phosphorus in soil was confined to 0 to 15 cm of soil layer under all fertigation levels (Anitta and Muthukrishnan, 2013). It was found that the nutrient concentration decreased when the distance from the plant was increased.

Conclusion

Overall results from the investigation revealed that irrigation through a micro irrigation system at 125% PE (I_2) and fertigation with inorganic fertilizers @ 150:100:100 kg N, P and K ha^{-1} (F_2) enhanced the growth parameters *viz.,* height, basal diameter and volume index; ecophysiological parameters *viz.,* photosynthetic rate, stomatal conductance and transpiration rate. Similarly, nutrient distribution dynamics revealed that irrigation level at 125% PE (I_2) along with inorganic fertilizers @ 150:100:100 kg N, P and K ha^{-1} (F_2) recorded the highest soil N, P and K status at 30 cm lateral distance and horizontal depth of 0 to 30 cm. The findings of this study optimized irrigation and fertigation strategy through micro irrigation system for enhancing biomass production in high-density tree plantation of *D. sissoo* and sustaining soil productivity.

Acknowledgment

The authors would like to thank the Department of Silviculture, Forest College and Research Institute, Mettupalayam, Tamil Nadu Agricultural University, Coimbatore, for funding the research project.

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