Productivity of wheat (*Triticum aestivum* L.) and soil fertility with poplar (*Populus deltoides*) agroforestry system in the semi-arid ecosystem of Haryana, India

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The diverse and multi-component nature of traditional agroforestry systems (AFS) provides them a unique edge over monoculture cropping, particularly in arid and semi-arid ecosystems due to their role in providing several ecosystem services (ES) in addition to their prime role in agricultural production. Appropriate selection of components and their management practices results in reduced competition for resources among the components and maximum capitalization of the interactions. Poplar-based AFS adopted in a big way by farmers in the Indo-Gangetic region of India has improved their economic status due to its high industrial value. The present study discusses the effect *Populus deltoides* as windbreak on yield of wheat as intercrop and soil nutrient status. We considered winter wheat varieties (WH-1105, WH-542, HD-2967, HD-943 and DPW-621-50) during two consecutive years (2013–15) delimited by a row of poplar trees in the east–west and north–south directions. Whereas effects on crop produce were limited for all wheat varieties with increasing distance from the tree line, considerable yield reductions were found near the tree line (treatments T_1 and T_2) for all the wheat varieties. The highest available soil N (365.2 kg ha^{-1}), P (19.7 kg ha^{-1}) and K (357.3 kg ha^{-1}) were recorded near the tree line at a distance of 2 m. To optimize the provisioning service of poplar windbreak AFS, the cultivation of highly shade-tolerant wheat variety HD-2967 may be advisable over other varieties towards the end of the rotation of mature poplar trees.

Keywords: Agroforestry, crop growth and yield, *Populus deltoides*, tree-based intercropping, wheat.

THE research advances in agricultural sciences have been successful in feeding about 7.8 billion people in the world, mainly depending upon development of high-yielding crop cultivars and increased use of fertilizers and pesticides[1]. The Green Revolution in India triggered land degradation and environmental security due to increase in atmospheric carbon dioxide (CO_2), reduction in soil fertility, enhanced soil erosion and loss of biodiversity[2]. It has been predicted by many researchers that climate change and its variability will have a negative effect on agricultural production in the near future[3]. In this context, climate-smart integrated land-use system such as the agroforestry system (AFS) is an viable option to mitigate the potential effects of climate variability on agricultural productivity[4].

Agroforestry has been recognized as a more sustainable and profitable agricultural practice compared to monoculture of crops and has received considerable attention due to the resultant environmental and profitable benefits such as potential for enhanced carbon sequestration, amelioration of microclimate and reduced soil erosion[5].

In this scenario, there is tremendous scope to diversify the existing farming systems with suitable agroforestry models[6,7]. Several studies revealed that availability of natural resources such as moisture, sunlight, soil organic matter and the availability of nutrients are the major limiting factors resulting in interactions between trees and agricultural crops[8,9]. The suitable design and management practices of AFS are associated with the existing ecological conditions and the field locality. Moreover, it has been observed that when fast growing trees were planted as boundary plantation, they decreased the wind effect and protected soil erosion in addition to reduced evapotranspiration and ultimately conserving soil moisture[10]. Organic matter in the form of litterfall from trees is decomposed in the soil and improves its physico-chemical properties, thus sustainably increasing fertility[11]. Windbreak AFS improves the ecosystem services (ES) through better utilization of available natural resources on a sustainable basis[12], whereas fast-growing trees provide additional income to the farmers from woody biomass along

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with regular yield from agricultural crops[13]. Among various fast-growing tree species, *Populus deltoides* has emerged as important due to its deciduous nature and huge demand from wood-based industry, resulting in a large share of 270,000 ha plantation in the Indo-Gangetic regions of India to prevent land degradation and obtain biological production on a sustainable basis[14]. Poplars are the most preferred agroforestry tree species by farmers of the northwestern region of India since 1980s, due to their fast growth, less competition with associated crops and tolerance to pruning, high economic returns in short rotation, i.e. 6–8 years and easy availability of bank loans. A recent study reported about 0.276 m ha area in Punjab and 0.205 m ha in Haryana under poplar-based agroforestry[15]. Farmers can easily cultivate agricultural crops throughout the harvesting period and poplar acts as an assured wealth for their future needs, without affecting intercrops due to its growth characteristics. Poplar-based agroforestry has been found to give better economic returns than sole annual crops[16]. Poplar being deciduous in nature is more favourable as a winter crop due to comparatively less shading effect on intercrops.

Wheat (*Triticum aestivum* L.) is one of the most important winter crops of the poplar-growing regions in North India and can be successfully grown under boundary plantation of poplar throughout its rotation age. Wheat–poplar intercropping has been extensively studied earlier, but focused emphasis on specific issues was initiated from the 1980s on need-based aspects, viz. geometry, crop varieties/tree clones, fertility, tending, crop quality, productivity, carbon sequestration, economics, etc. Studies have shown that wheat yield reduction (10–46%) varying with age of the poplar plantation (1–6 years) has been compensated by poplar trees, both in terms of productivity and economic returns at the end of the rotation. In addition, adoption of AFS takes care of crop failure risks due to compensation of returns from the tree component[17].

In semi-arid regions of North India, in spite of poplar–wheat being the most preferred system, information on the evaluation of different wheat varieties under windbreaks of poplar-based AFS is lacking[18]. Therefore, the present study was done with the objective to determine the viability of using mature poplar windbreak as a means to uphold sustainable food production intercropped with wheat varieties. A considerable variation in shade tolerance ability of wheat varieties has been reported in the past by different researchers in India. Thus, there is a need to screen shade-tolerant wheat varieties with higher productivity, which can perform better under tree shade compared to existing wheat varieties grown by the farmers. Therefore, to address this critical issue, the performance of different wheat varieties intercropped with poplar windbreak AFS was evaluated. The present study was conducted with the aim to determine wheat productivity in relation to increasing distance from the poplar tree base, resulting in identifying the most suitable wheat variety under these conditions. The results will be useful for large-scale adoption of this system for sustainable crop production to enhance food security and higher economic returns to the farmers.

Materials and methods

Experimental site

The study was conducted during 2013–14 and 2014–15 in an experimental farm of the Forestry Department in the CCS Haryana Agricultural University, Hisar, Haryana (29°09′N lat. and 75°43′E long., situated 215 m amsl) in northwestern India, with characteristics features of a semi-arid ecosystem. The region has subtropical–monsoonic climate with 350–400 mm of mean annual rainfall mainly restricted to July to September (accounting for 70–80% of total annual rainfall). The maximum temperature is in the range 40–45°C observed during May and June, whereas during winter the lowest temperature observed is as low as 0°C in January. During 2014–15, a total of 447.9 mm rainfall was received and the weekly mean values for observed weather parameters were recorded at the site during the study period. The experiment was laid out in factorial randomized block design with three replications. Poplar trees were planted in the site during 2007, and prior to which the site was under mono wheat cropping.

Soil sampling to determine soil nutrient status

In the present study four random soil samples were collected in the east–west and north–south windbreaks of poplar at an interval of 2 m each at 2–10 m from the poplar tree base, in addition to control site. The samples were evaluated for soil organic carbon (%), available nitrogen (N; kg ha^{-1}), phosphorus (P; kg ha^{-1}) and potassium (K; kg ha^{-1}) at a depth of 0–15 cm in three replications. Sampling was done twice during 2013–14 and 2014–15, i.e. during both years of study, i.e. first prior to sowing (October) and second after harvesting of wheat crop (April). The air-dried samples were ground and sieved using a 2 mm sieve before storing for further analysis. The alkaline permanganate method was used for determining available N, partial oxidation method for organic carbon (%), sodium bicarbonate method for available P and neutral normal ammonium acetate method for available K[19–22].

Layout and design of the experiment

The east–west and north–south poplar windbreak-based agroforestry system was laid out in randomized block design with six treatments at various distances from the poplar tree line, viz. T_1: 2 m (sowing of all five wheat varieties at 2 m distance from the poplar tree line) T_2: 4 m (sowing of all five wheat varieties at 4 m distance from the poplar tree line); T_3: 6 m (sowing of all five wheat varieties at 6 m distance from the poplar tree line), T_4: 8 m (sowing of all five wheat varieties at 8 m distance from the poplar tree line), T_5: 10 m (sowing of all five wheat varieties at 10 m distance from the poplar tree line) and T_6: sole crop (all five wheat varieties without poplar) and three replications.

Growth studies of wheat crop

During the first week of November in 2013 and 2014 five wheat varieties, viz. WH-1105, HD-2967, WH-542, DPW-621-50 and HD-943 were sown with a 22.5 cm row-to-row distance and 100 kg/ha seed rate. The same set of wheat varieties with similar row-to-row distance and seed rate was simultaneously sown in the control treatment (without trees). The fertilizer dose (150 kg N, 60 kg P_2O_5 and 60 kg K_2O ha^{-1}) was applied according to the recommendation for these varieties. At the time of sowing, half the amount of N and the whole amount of P and K were applied, followed by top dressing at the crown root initiation (CRI) stage with the remaining N through urea. The same procedure was repeated in the next year (2014–15).

Crop yield

Wheat crop was estimated in terms of grain yield by quadrate method at a time of harvest at increasing distances of 2–10 m at intervals of 2 m from the base of poplar tree line. After taking all the growth and yield parameters of wheat crop, the samples which have been taken from 1 sq. m quadrant were sun dried and after that the produce of net plot was threshed by hand and then weighed to determine grain yield and total aboveground biomass (kg per net plot) reported as grain yield tonne ha^{-1} and straw yield tonne ha^{-1} using appropriate conversion factor.

Tree growth

The tree height and DBH of all the trees were taken during dormancy once in year during both years (December, 2013 and 2014) of the study with the help of Multimeter and measuring tape respectively. The CAI of the trees was also calculated. The tree growth data taken for both the tree planting directions, i.e. east–west and north–south. To study the effect of shade on intercrop, light intensity was measured by Luxmeter at crop surface to study the shade effect of tree on crop. The reading was taken at monthly interval under agroforestry system and in open area during the study period. The data were recorded at 7.00 am, 9.00 am, 11.00 am, 1.00 pm, 3.00 pm and 5.00 pm.

Statistical analysis

Data obtained during the course of this investigation were subjected to analysis of variance using SPSS 23.0 statistical software and it showed that the data were normally distributed and can be used for analysis of variance (ANOVA). After validating the normal distribution and homogeneity of variances, ANOVA was performed and subsequently the means were compared by using Duncan's Multiple Range Test (DMRT) $P < 0.05$.

Results and discussion

Organic carbon and available N, P and K

The increasing status of soil organic carbon (SOC), available nitrogen, phosphorus and potassium were found near the poplar tree line during both the years under this study (Figures 1–4). However sole cropping exhibited lower nutrient concentration compared to poplar windbreak AFS. North–south direction of poplar windbreak significantly affects soil organic carbon and it decreases as the distance increased from poplar tree (Figure 1). In both the aspects of north–south poplar windbreak, significantly higher organic carbon (0.74% and 0.72%) were observed in western aspect compared to eastern aspect (0.70% and 0.68%) up to 4 m distance from poplar tree in 2014–15 when values were recorded after crop harvesting. The minimum SOC was recorded when the distance was 10 m away from poplar tree in comparison to all other distance treatments in the study. The lowest SOC (0.38%) was exhibited by sole cropping plot prior to sowing of crop in 2013–14, which was significantly lower than other treatments.

The available soil N for different distances was higher than sole crop (control) for both the years under study (Figure 2). In poplar windbreak, the available N was observed to be significantly higher (365.2, 357.3 and 352.1 kg ha^{-1}) in western aspect up to 6 m distance from tree base when compared with eastern aspect after wheat crop harvesting. Available N was significantly less between 8 m and 10 m distances from tree base at both aspects of poplar windbreak during both years but was significantly more over control. The trend was same for available P as well as K at both aspects of North–South direction of poplar windbreak (Figures 3 and 4). Significantly higher availability of P as well as K content was observed under poplar windbreak AFS than the sole crop (control). The increasing status of soil organic carbon (SOC), available N, P and K were also found near the poplar tree line. In general, slightly higher organic carbon content value was recorded after harvesting of the wheat crop compared to the initial values recorded before crop sowing for both the years in poplar windbreak. The soil organic matter contains nutrients, seize organic carbon and increases the

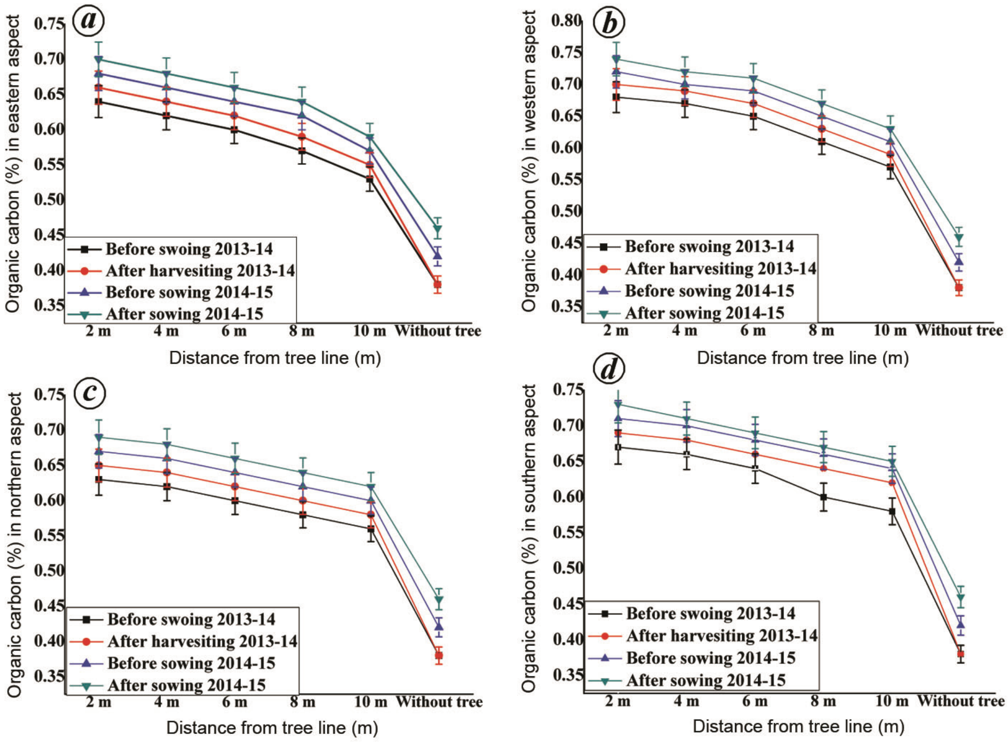

Figure 1. ***a–d***, Soil organic carbon (%) before sowing and after harvesting of winter wheat varieties (WH-1105, WH-542, HD-2967, HD-943 and DPW-621-50) during two consecutive years (2013–15) delimited by a row of deciduous poplar trees (7- and 8-year-old) in the east–west and north–south directions. (The E–W tree line divides the farmlands into two aspects, i.e. northern and southern whereas the N–S tree line divides them into the eastern and western aspects.) Error bars are ± standard error (SE).

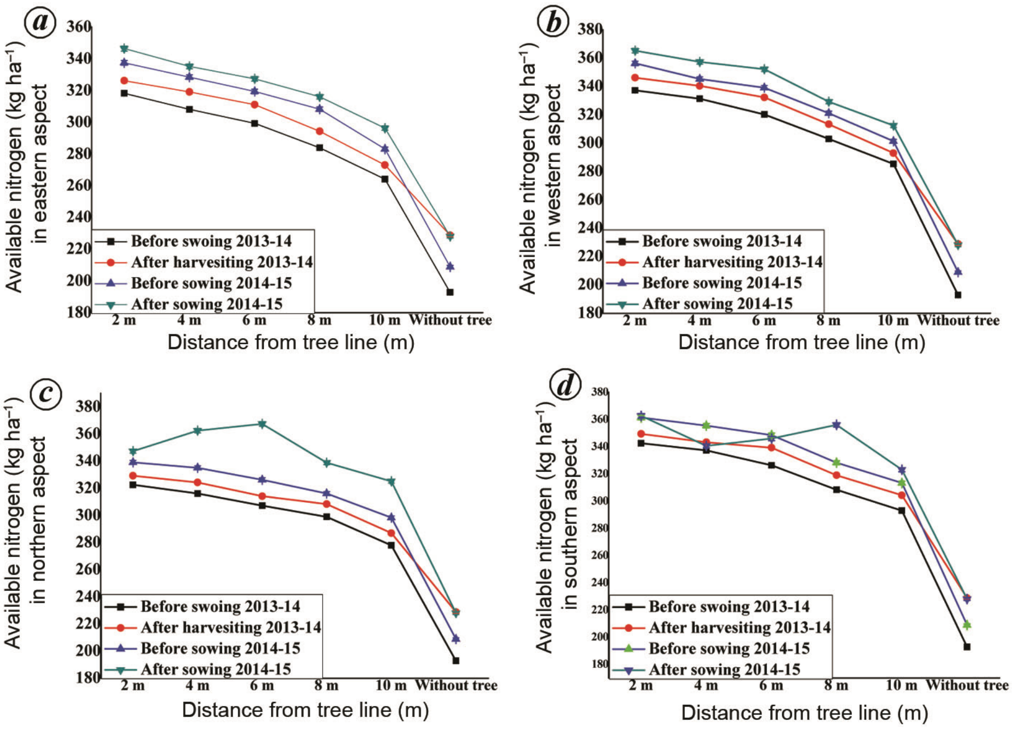

Figure 2. ***a–d***, Available N (kg ha^{-1}) before sowing and after harvesting of winter wheat varieties (WH-1105, WH-542, HD-2967, HD-943 and DPW-621-50) during two consecutive years (2013–15) delimited by a row of deciduous poplar trees (7- and 8-year-old) in the east–west and north–south directions.

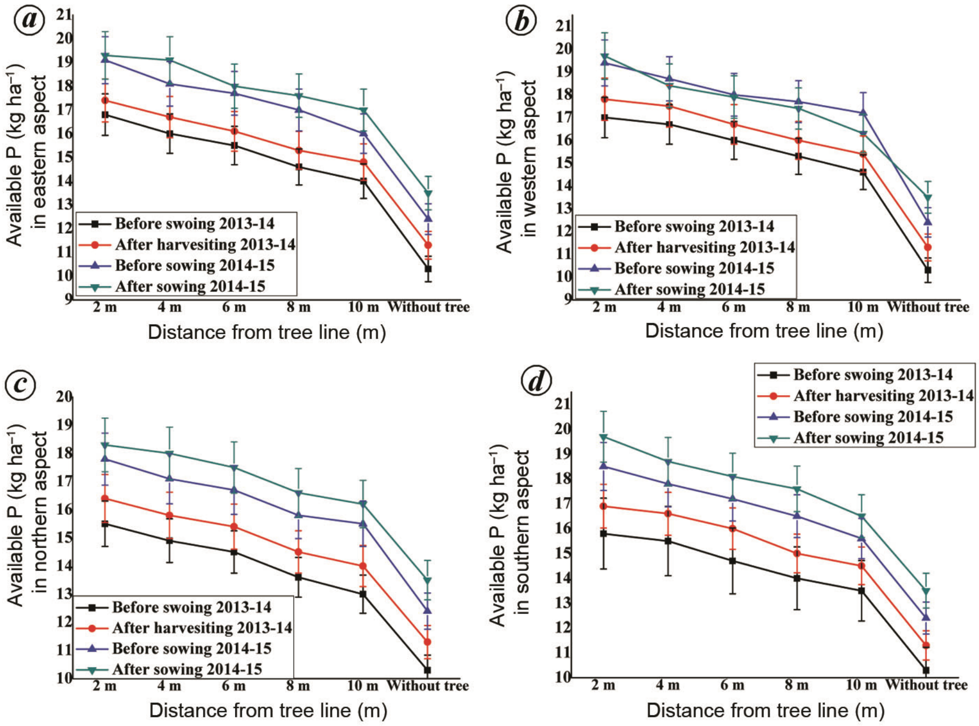

Figure 3. ***a–d***, Available P (kg ha^{-1}) before sowing and after harvesting of winter wheat varieties (WH-1105, WH-542, HD-2967, HD-943 and DPW-621-50) during two consecutive years (2013–15) delimited by a row of deciduous poplar trees (7 and 8 year old) in the east–west and north–south directions.

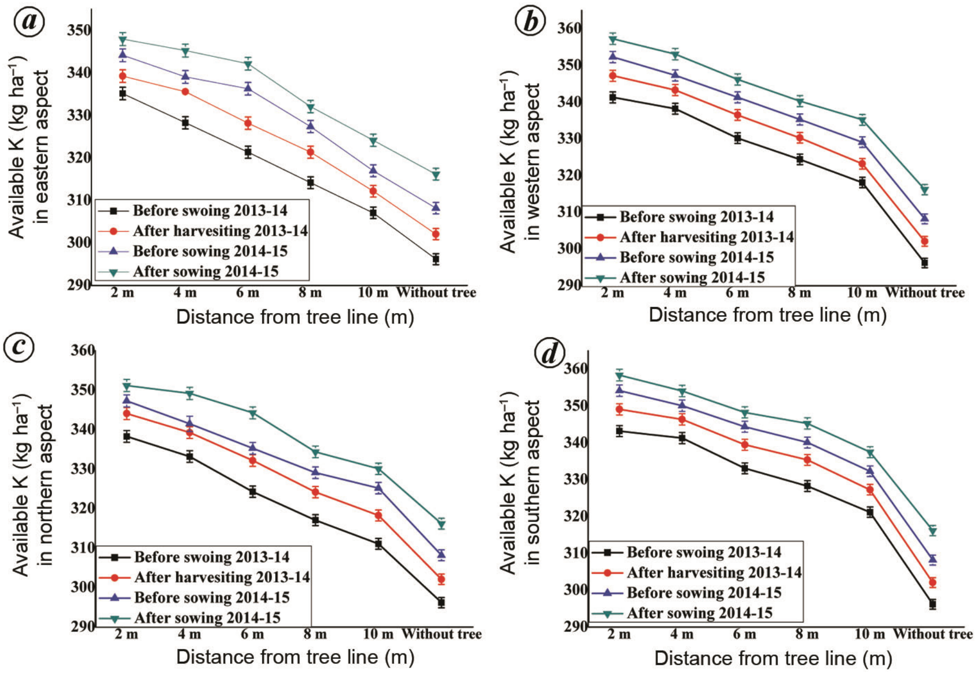

Figure 4. ***a–d***, Available K (kg ha^{-1}) before sowing and after harvesting of winter wheat varieties (WH-1105, WH-542, HD-2967, HD-943 and DPW-621-50) during two consecutive years (2013–15) delimited by a row of deciduous poplar trees (7- and 8-year-old) in the east–west and north–south directions.

activation of microorganisms which improve the soil fertility status[23]. The addition of litter due to leaf fall, twigs and fine tree roots decomposition may be the reason for higher soil organic carbon build-up near the tree base as reported earlier[24].

The planting of poplar trees in a row in north–south direction on farm boundary resulted in a significantly higher amount of available soil N, P and K from 2 m (near the tree line) to 6 m distance. This trend has also been observed in poplar based AFS[11], however, the total

N value and the available P and K values (kg ha^{-1}) for the soil were higher in the upper layer but decreases with an increase in soil depth and further reported non-significant but slightly higher values for available P as well as K with increasing distance from the tree base in comparison to control plot[25]. The nutrient capture is one of the important factors in intercropping studies. The factors attributing towards soil fertility improvement under agroforestry system could be ascribed to more favourable microclimatic conditions under trees resulting in higher soil moisture and favourbale soil temperature in addition to nutrient released through leaf litter and *in situ* root decomposition and higher microbial activity also reported[26]. Physico-chemical properties of soil are the most significant undermined forces in tree based intercropping system, predominantly during the phase of following disturbances such as ploughing, weeding and other cultural practices. During this period, the tree based intercropping system increase total biomass and nutrients in the soil for the reformation of ecological development on sustainable basis[27].

Yield attributes

Grain yield: Overall, treatments and years had variable effects on grain yield (tonne/ha) of all the wheat varieties in east–west and north–south poplar windbreak (Figures 5 and 6). Grain yield of wheat varieties exhibited significant differences between all the aspects in poplar-wheat system. Significant grain yield reduction in wheat was observed when intercropped with different treatments in windbreak of poplar compared to sole crop (Figures 5 and 6). The north–south row direction of poplar wind break has more influence on the grain yield of all wheat varieties. In this direction of poplar wind break, variety HD-2967 recorded maximum grain yield (3.77 tonne ha^{-1}) for western aspect and was statistically at par with eastern aspect in treatment T5 ($P < 0.05$). Both eastern and western aspects of north to south poplar windbreak plantation recorded higher grain yield of all varieties during both the consecutive years of study. The grain yield significantly declined up to a distance of 4 m from tree base (treatments T_1 and T_2) in both the aspects. In eastern aspect of poplar windbreak, the grain yield of all the wheat varieties HD-2967, WH-542, DPW-621-50, HD-943 and WH-1105 had significantly ($P < 0.05$) affected with treatment T_1 and T_6: sole crop (Figure 5 *a*). Wheat varieties HD-2967, WH-542, DPW-621-50, HD-943 and WH-1105 were found non-significant with each other in treatments T_2, T_3, T_4 and T_5 in eastern aspect (Figure 5 *a*). Variety WH-1105 recorded maximum decrease in grain yield over control (86%) close to the tree base (2 m, treatment T_1) in eastern aspect and minimum reduction in grain yield was observed for variety HD-2967 (58.1%) under similar conditions. Whereas, treatment T_6 recorded highest grain yield in WH-1105 variety (5.00 and 4.70 tonne ha^{-1}) for both years followed by variety WH-542 (4.70 and 4.30 tonne ha^{-1}). The data revealed that micro-site amelioration caused by favourable environment due to shade and leaf litter addition resulted in variable effect of wind break directions on the yield of the crop in different aspects. Western aspect had also exhibited the similar effect as that of eastern aspect on the grain yield of all the wheat varieties under this study (Figure 5 *b*). A considerable increase in grain yield of all the wheat varieties was recorded in treatment T_2 to onwards treatment T_5 in both the aspects of north–south poplar windbreak (Figure 5 *a* and *b*). Whereas, in east–west windbreak of poplar, treatment T_1 had significantly ($P < 0.05$) affected the grain yield of all the wheat varieties, i.e. HD-2967, WH-542, DPW-621-50, HD-943 and WH-1105 (Figure 5 *c* and *d*). Non-significant difference was observed in treatment T_2 with T_1, treatment T_3 with T_2, treatment T_4 with T_3 and treatment T_5 with T_4 in both the aspects (northern and southern) of east–west poplar windbreak. Similar trend was also exhibited during the next successive growing season of wheat crop in east–west and north–south poplar windbreak (Figure 6 *a*–*d*). Our results indicated that both tree row direction and the distance from tree base (treatments T_1, T_2, T_3, T_4 and T_5) are the major factors which determine the effect of tree canopy on wheat yield intercropped along with tree wind break. The least negative effects of presence of poplar boundary plantation on crop yield were observed for various varieties of wheat at varying distances from tree base. This is in line with the earlier observations that *Rabi* (winter) crop cultivation can be a successful approach to have minimum adverse effect of poplar tree canopy on crop yield till the rotation age of poplar windbreak. The western aspect yield was better than eastern aspect due to more availability of solar radiation resulting in better photosynthetic activity and vigorous plant growth and higher productivity in terms of grain yield. The leaf shedding during winter in the sheltered area also resulted in poor performance of wheat crop. Leaf-fall before sowing gets incorporated in to the soil but after the sowing interfere in the emergence and/or seedling growth of wheat crop. The proportion of leaf fall is inversely related to the wheat crop yield. The addition of large quantity of leaf litter through leaf fall on western aspect may be another factor for enhanced yield. The physical environment gets improved, thus resulting in more efficient nutrient utilization. Plant nutrient uptake increases adjacent to the poplar tree rows due to leaf biomass addition, thus increase the nutrient use efficiency. Addition of leaf litter, increasing the nutrient status through poplar leaf and reduction in wheat yield (grain and straw) in field plot with poplar boundary have also been estimated by number of other workers[28].

Reduction in number of grain per m^2 in poplar windbreak based AFS at a distance of 3–10 m from the tree base compared to distance of 30 m from the tree base[29]. Further they reported decrease in average wheat yield at a distance

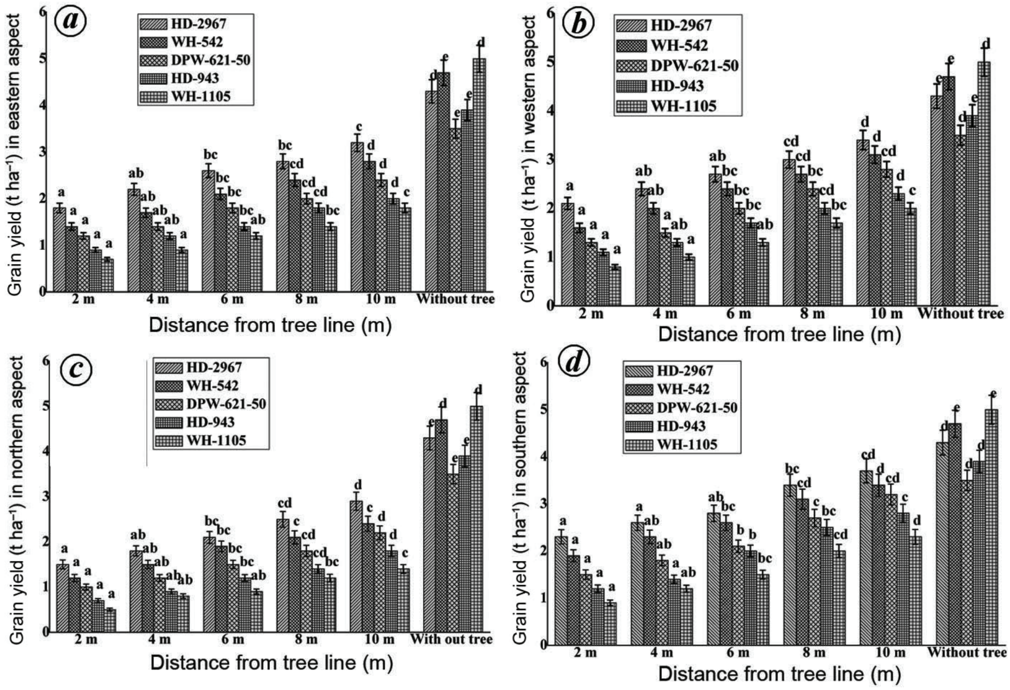

Figure 5. ***a–d***, Grain yield (tonne ha^{-1}) of winter wheat varieties (WH-1105, WH-542, HD-2967, HD-943 and DPW-621-50) during 2013–14 delimited by a row of deciduous poplar trees (7-year-old) in east–west and north–south directions. (The E–W tree line divides the farmlands into two aspects, i.e. northern and southern and whereas the N–S tree line divides them into eastern and western aspect.) Error bars are ± SE, values with the same letter are not significantly different from one another at significance level $P < 0.05$ according to Duncan multiple range test (DMRT).

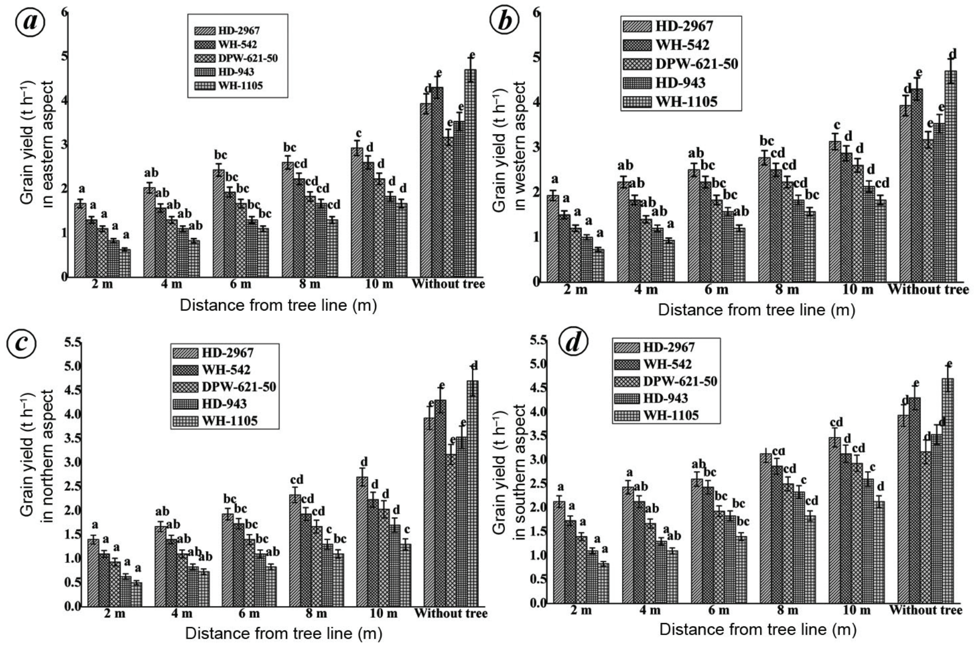

Figure 6. ***a–d***, Grain yield (tonne ha^{-1}) of winter wheat varieties (WH-1105, WH-542, HD-2967, HD-943 and DPW-621-50) during the 2014–15 delimited by a row of deciduous poplar trees (8-year-old) in the east–west and north–south directions.

near the tree base in comparison to open field (sole crop). The shading effect of the hybrid walnut during high temperature, reduce the desiccant effect of wind velocity and thereby it increased the yield of winter agricultural crops[30].

The progressive grain reduction with in age was attributed to the increased canopy and root competition for moisture and nutrients. The poor crop performance near the poplar tree lines has also been reported by other

Table 1. Mean effects of years for tree height (TH; m) and diameter at breast height (DBH; cm) of poplar trees evaluated under two directions (east–west and north–south) during 2013–14 and 2014–15

	2013–14		2014–15	
Direction	TH	DBH	TH	DBH
East–west	19.7 ± 1.02	28.4 ± 1.47	20.2 ± 1.05	30.6 ± 1.59
North–south	20.9 ± 1.08	29.3 ± 1.52	21.3 ± 1.10	31.6 ± 1.64

workers and increase in yield with increase in distance from tree line can be attributed to the reduced root competition and shade affect. In present study, straw yield reduction rate was comparatively lower than grain yield in both the aspects of north–south row direction of poplar windbreak AFS. However, all the wheat varieties performed better as monocrops when it compared to poplar windbreak AFS near the tree line (distance 2–6 m). The reason of lower yield of wheat crop in poplar windbreak AFS up to an extent of 6 m from tree line due to the competition for resources such as solar radiation, water and soil nutrients between trees and wheat crop[31]. These results are similar to as reported in the previous studies where winter wheat was intercropped with walnut[30].

Poplar tree growth: Significantly higher values for the tree height (TH) were recorded in north to south direction compared to east to west direction plantation. TH and DBH for poplar planted in north to south direction (21.3 m and 31.6 cm respectively) was more than TH and DBH of poplar planted in east to west direction. In poplar tree growth, overall, about two centimetre current annual increment (CAI) was recorded in DBH of poplar, when averaged across the years (Table 1). The average poplar tree DBH ranged between 28.4–29.3 cm and 30.6–31.6 cm (2013–14 and 2014–15 respectively) under both the poplar boundary plantation (east–west and north–south). When averaged across years, an increment of about half metre was observed in TH in 2013–14 compared to 2014–15. The study showed that there was significant effect of tree on available light intensity during both the years. The tree height of poplar varies significantly on different directions, whereas plantation direction has no significant effect on dbh value[25]. The results showed that maximum light intensity (1195.9 and 1187.8 Lux) was recorded in southern aspect which was statistically at par with eastern aspect (1136.1 and 1128.3 Lux) but significantly higher than western aspect (1022.4 and 1014.2 Lux) at 1.00 pm at a distance of 10 m compared to other distances from poplar tree line in the month of March. The southern aspect allows maximum sunlight on the field throughout the day[25]. The light intensity received by the sole crop was significantly higher than the light intensity received by the crop under different row directions of poplar.

Conclusion

In the present study on poplar windbreak based AFS, it has been observed that the growth and yield of wheat varieties varied spatially (both at direction and distances) when grown as intercropped with poplar. In general, all the wheat varieties in eastern aspect of north–south poplar windbreak had a reduced grain and straw yield. Moreover, at the same direction, grain yield of shading region (eastern aspect) was lower than slightly non-shading (western aspect) region. However, among all the wheat varieties, wheat cultivar HD-2967 recorded the highest yield when intercropped along with deciduous poplar trees row in East to West and North to South directions. Wheat crop yield in regard to varietal performance within poplar-wheat system in semi-arid region of Hisar, India showed notably positive relation with moisture content and soil fertility status which ultimately enhanced the yield of wheat varieties up to some extent. It is quite evident from the results that under shelter conditions, grain yield of wheat crop was considerably more impacted near the tree line (treatments T_1 and T_2) by the presence of mature fast growing poplar windbreak AFS compared to increasing distances from tree line as well as control plot. At the same time the findings indicate that poplar windbreak AFS had favourable effect on microclimatic conditions from 1 m to 6 m distance from tree line (T_1–T_3). The extent of competition differs with geographic locality, type of agriculture crop, silvicultural characters of tree windbreak and nutrient status of soil or environmental conditions. Furthermore, in changing climates, windbreaks can play a significant role in adaptation strategies as agricultural producers. The study concludes for optimizing the production potential of poplar based windbreak AFS, the orientation of windbreak and spacing of trees can improve microclimate and ecosystem services of the system and ultimately achieve higher productivity and economic returns.

Conflict of interest: The authors declare that they have no conflicts of interest.

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