



Research article

Conservation tillage and nutrient management practices in summer rice (*Oryza sativa* L.) favoured root growth and phenotypic plasticity of succeeding winter pea (*Pisum sativum* L.) under eastern Himalayas, India



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HIGHLIGHTS

- Residual effect of tillage and nutrient management in summer rice assessed on morpho-physiology of succeeding pea.
- Rice residues, weed biomass (WB) and *Tephrosia* sp. biomass (GLM) used along with 50% nutrient dose.
- Higher root surface area, total root length etc. observed under CT than NT and MT.
- Higher leaf area expansion, thickness and turgidity in pea observed under of NT and MT than CT.
- Higher yield and partitioning efficiency observed under MT/NT and 50% NPK+WB/GLM than others.

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ABSTRACT

Low soil moisture during dry season, poor soil properties and lack of adequate crop varieties are the major constraints for sustainable intensification of eastern Himalayas in changing climate. Suitable varieties, tillage alteration and integrated nutrient management with emphasis on locally available crop residues/plant biomass may help addressing these issues. The role of minimum tillage (MT) and no-till (NT), and organic matter substitution on conferring of favourable root environment, improvement in morpho-physiology and subsequent productivity of the crops are not objectively studied in Himalayan ecosystems. Thus, a six year field study was conducted for examining the residual effect of tillage and nutrient management (NM) practices applied to summer (rainy) rice (*Oryza sativa* L.) on root growth-attributes and impact on morpho-physiology of succeeding winter pea (*Pisum sativum* L.) grown uniformly under NT. Higher root surface area, total root length, root volume, root length ratio (RLR) and root tissue density in pea crop were observed under residual effect of conventional tillage (CT) relative to NT and MT. In addition, significantly higher values of functional root traits viz., root length ratio (RLR), root mass ratio and root fineness in pea were observed under CT and application of 50% NPK and 100% NPK relative to other tillage and NM practices. However, increased root exudation was observed under NT and MT along with organic residue addition. Noticeable changes in stress responsive morpho-physiological traits like enhanced chlorophyll pigmentation and favourable leaf characteristics were observed in pea crop grown under NT with 50% NPK+weed biomass (WB)/green leaf manure (GLM) applications. Higher leaf area expansion and thickness were recorded with optimum turgidity under NT and MT than that under CT. Comparative increase in green pod and stover yield of pea with enhanced partition efficiency and harvest index were recorded under MT/

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NT along with 50% NPK+WB/GLM application than that under CT and other NM practices. Thus, adoption of MT/NT along with 50% NPK+WB/GLM in summer rice is recommended for inducing favourable root environment and optimised pea production in succeeding winter season in study region of the Eastern Himalayas, India and other similar agro-ecosystems.

1. Introduction

Himalayan region endowed with rich biodiversity and natural resources witness relatively fragile and challenging agro-ecologies under changing climate owing to its unprecedented land degradation, soil and nutrient loss across hill slopes (Das et al., 2017). Under this stressful environment, meeting nutrient and water requirements of major crops and cropping systems is nearly formidable challenge. Under this context, the advent of effective conservation tillage and residue management has a strong impact on soil quality, resource use efficiency, and productivity of major cropping systems of Indian Himalayan region. Adoption of no till (NT) and minimum tillage (MT) along with *in-situ* conservation and recycling of crop residues helps in forging better soil environment which stimulates plant growth (Srinivasarao et al., 2014) with increased system resilience (Gupta and Seth, 2007). Incorporation of organic biomass as like farmyard manure (FYM) or mulch cover or use of any form of organic by-product augment available water content (AWC) and water infiltration rate (Reicosky and Forcella, 1998). Recycling of organic residues can increase soil organic carbon (SOC) and soil moisture contents (Das et al., 2017), nutrient mineralization and crop growth (Patel et al., 2010; Das et al., 2008). Further, tillage-induced changes have been reported on soil organic matter (SOM) content, availability of N and C: N ratio (de Moraes Sá et al., 2013), soil moisture and temperature regimes and regulation of microbial activity (Sharma et al., 2013). Adoption of conservation tillage practices can maintain SOM contents and ensure long-term sustainability and crop productivity in hill agro-ecosystems of north eastern region [NER, about 26.27 million hectare (M ha) total geographical area] of India. The NER, popularly called as Eastern Himalayan region (EHR) of India, is in strong and urgent need for improving soil fertility and nutrient balance (Das et al., 2016) for sustainable crop production.

Several studies conducted to assess the potential benefits of adopting conservation agriculture (CA) and residue management during dry (winter) season have documented improved crop performance by alleviation of multiple environmental stresses such as soil water and nutrient deficiencies (Das et al., 2016). In a system perspective, however, the influence of CA and organic residue incorporation are neither assessed nor understood on root architecture, changes in root environment, regulation and alleviation of stress tolerance (low green water during post rainy/winter season, low nutrient availability in soil, soil acidity etc.) especially in stress prone EHR. Further, altered rhizospheric environment and root growth behavior are not widely considered as source for crop resilience under apparent multiple stress conditions (Beebe et al., 2013). Thus, effects of tillage systems on root activity and its environment in the rhizosphere are not adequately studied (Spedding et al., 2004).

Some of the root specific traits in relation to stress tolerance are rooting depth (Mohammadi et al., 2005), root length ratio (RLR), root tissue density (RTD). These traits substantiate the potential of a plant for soil resource acquisition and modification of diverse morpho-physiological traits under stress conditions (Abenavoli et al., 2016). Structural components and associated phenotypic plasticity (Waisel and Eshel, 2002) are characterized by root length ratio (RLR), root mass ratio (RMR, root mass per unit of plants dry mass), root dry mass per unit root volume (RTD), and root fineness (RF, root length per unit root volume). Therefore, crops must be specifically adapted to the edaphic environments of the EHR. As much as 85% of the soils of the EHR are acidic with severe constraints of nutrient supply and elemental toxicity. Therefore, understanding the functional and structural root plastic traits can be advantageous to adaptation of crops and cultivars (Abenavoli et al., 2016). Different stress responsive root traits are root

length density (RLD) and their abundance, and total (Tran et al., 2015) and lateral root length or branching (Kano-Nakata et al., 2013). These traits have been reported to improve shoot biomass, water uptake, photosynthesis and yield stability under drought and low nutrient conditions (Sandhu et al., 2015).

Root phenotype and architecture measurements are important tools in understanding abiotic stress tolerance of crop plants in agro-ecosystems (Abenavoli et al., 2016). In particular, adoption of CA practices can alleviate constraints of drought, low nutrient availability, soil acidity-induced P efficiency and elemental toxicities. Thus, assessing and monitoring root growth behavior changes and whole plant responses are pertinent for the NER.

The response of root environment, in terms of varied root exudation and the attendant plant-microbe interaction (Sun et al., 2012), is critical to an efficient nutrient release and uptake. Root exudates are source of carbon for microbes (Badri and Vivanco, 2009). The extent of root exudation; which varies with season, plant growth potential and soil conditions; has a strong impact on agronomic yield (Peuke, 2000). However, the response of root exudation as influenced by altered soil environment with varied tillage and residue management which may alleviate the extent of damage by intractable stress factors (i.e., nutrient and water limitation, mineral toxicities) need to be validated for acid soils of the EHR, India.

Vast stretches of rice fallows in the EHR (>2 M ha) are not under cultivation during post rainy season because of unfavourable soil moisture regime (low soil moisture in plains and wet conditions in hills/mountain), lack of irrigation facilities, non-availability of stress tolerant short duration varieties and many other reasons. However, these lands can be used for cultivation with the adoption of CA, residue management, and identification of short cycle crop varieties like pulses or oilseeds (Kuotsu et al., 2014). The soil moisture deficit due to low rainfall during the post-rainy and winter season is the major constraint to crop intensification in the NER. In contrast, high soil moisture at the time of the harvest of rainy season rice is the constraint in the hilly region of the NER in lowland rice fallow. Further, pulse crops are sensitive to mid and terminal drought (moisture deficit) and the low nutrient availability in acid soils of the region. Therefore, improvements in water, nutrient and SOC content by CA practices on root growth and physiological plasticity of pulses must be ascertained and objectively studied. Growing of the main crop under CA can have a post-harvest residual soil fertility effect and yield advantage to the succeeding second season crop (Das et al., 2009). Pea (*Pisum sativum* L.) is a pulse crop of choice (seeds are consumed as pulse and green pods as vegetable) as a source of protein and has a relatively higher market demand. Cultivation of peas also improves soil quality and increases farm income. The tillage and nutrient management practices adopted in summer season rice may have a substantial effect on growth and physiology succeeding dry season crop. However, there is hardly any information available in this regards particularly for EHR region. Therefore, the present study was conducted with the objective of understanding the manifestation of root growth behavior and phenotypic plasticity of morpho-physiological traits responsible for improved productivity under residual effect of diverse tillage and NM practices in the preceding summer crop of rice in the NER. The hypotheses tested was that conservation tillage and residue management in preceding rice crop will have favourable impact on physiological traits and root growth of succeeding rainfed pea crop leading to stress tolerance and higher productivity.

2. Material and methods

2.1. Experimental location

A field experiment involving the rice-pea cropping system was conducted during 2009–2016 in lowland Agronomy Farm of Indian Council of Agricultural Research (ICAR) Research Complex. The physiological traits of pea in present study was recorded during 2015–16. The experimental site is located in the North Eastern Hill (NEH) Region, Umiam, Meghalaya (950 m above mean sea level, 25°30'N latitude and 91°51'E longitude), EHR, India. However, the specific observations/measurements pertaining to the present study were obtained in 2014–2015, during the sixth year of the study. The experimental site is characterized by a subtropical climate with mild winter and warm summer. The total amount of rainfall received during the experimental period (June, 2014 to March, 2015) was 2002 mm. Relatively higher average daily rainfall (14–20 mm) and the maximum temperatures (25–32.3 °C) were observed during July and lowest temperatures of 3–14 °C during Jan–Feb. Seasonal trend of total rainfall, mean monthly maximum and

minimum temperature, mean monthly maximum RH (morning RH) and mean monthly minimum RH (evening RH) recorded during cropping season (2014–2015) were depicted in Figure 1a and Figure 1b.

2.2. Treatment details and layout

The experiment with the summer (rainy) season rice (cv. Shahsarang-1) comprised of a two factor experiment: tillage and nutrient management. Three tillage treatments included no-till (NT), minimum tillage (MT) and conventional tillage (CT). Five nutrient along with residue management (NM) practices were: 50% NPK, 100% NPK, 50% NPK + *in-situ* rice residue retention (ISRR), 50% NPK + weed biomass (WB) and 50% NPK + green leaf manure (GLM). The recommended dose of NPK (100% NPK) for rice and pea are 80:60:40 kg and 20:60:40 kg N, P₂O₅ and K₂O ha⁻¹, respectively. The experiment was laid out in a factorial randomized block design (FRBD) with three replications. Under NT, a systemic herbicide (Glyphosate @ 5 mL L⁻¹ of water) was applied 10 days before transplanting without any ploughing or puddling. Power tilling one time under MT and two times under CT with followed by planking

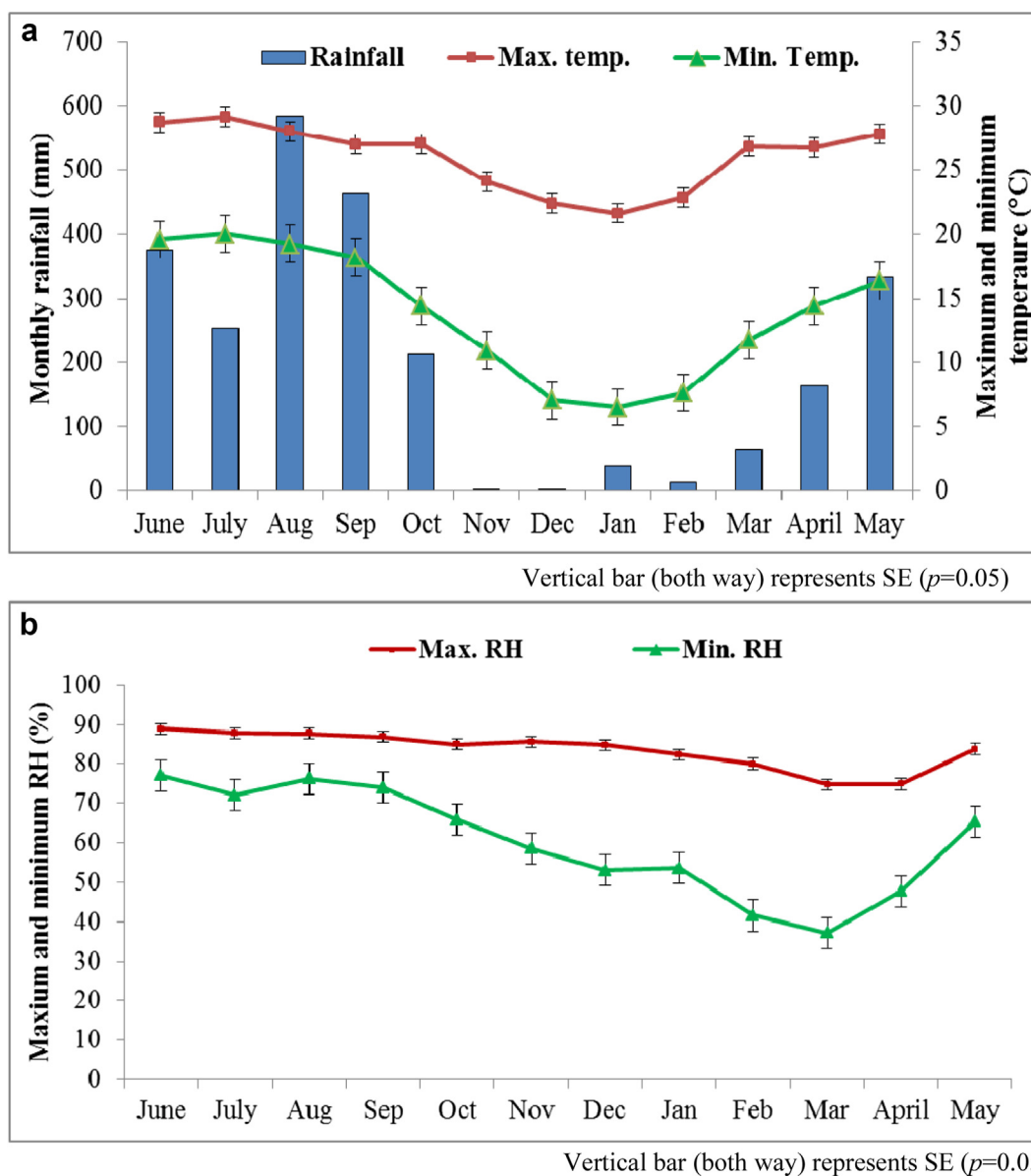


Figure 1. a. Seasonal trend of total rainfall, mean monthly maximum and minimum temperature recorded during cropping season (2014–15); b. Seasonal trend of mean monthly maximum RH (morning RH) and mean monthly minimum RH (evening RH) recorded during cropping season (2014–2015).

were done before transplanting of rice. Two 25-day old rice seedlings were transplanted per hill at 20 × 20 cm spacing using a manual dibbler.

The biomass chopped into 10 cm long pieces was applied at 20 days before transplanting of rice as rice straw at the rate of 5 Mg ha⁻¹ in ISRR, fresh biomass of *Ambrosia artemisiifolia* (locally available weed) at the rate of 10 Mg ha⁻¹ in WB, and as fresh biomass of *Tephrosia purpurea* (leguminous hedge plant grown in the fences and bunds) at 10 Mg ha⁻¹ in GLM. Leaves and tender twigs were used (discarding woody material) in both WB and GLM treatments. The excess water of rice fields were drained off at physiological maturity (one week before harvesting) to create a suitable soil condition for sowing of pea during the next season. After harvest of rice, seeds of two improved pea cultivars [Prakash (field pea) and Arkel (garden pea)] were sown ~80 kg per hectare under NT systems by opening a narrow slit of ~3 cm depth with a manually operated furrow opener in between the two rows of rice, thus, giving a row to row spacing of 20 cm. The plant to plant spacing was maintained at 8 cm for Arkel and 10 cm for Prakash. Recommended dose of nutrients and seeds were applied in the furrow and covered with soil: FYM mixture (2:1 ratio) for better seed and soil contact. Residual effects of tillage and NM practices applied to the preceding summer rice were assessed on succeeding winter season pea cultivars grown uniformly under NT.

The N, P and K for rice and pea were supplied through urea (46% N), single super phosphate (16% P₂O₅) and muriate of potash (60% K₂O), respectively. As basal application, only 50% of recommended N and full dose of P and K were applied, and the remaining part of N was applied in two equal splits at 30 and 60 days after transplanting (DAT) of rice. In case of pea, full dose of N, P and K were applied as basal dose during sowing. The N, P, K content in biomass of *A. artemisiifolia* and *T. Purpurea* were 3.12, 0.11, 0.78% and 2.25, 0.30, 0.77%, respectively. The soil of the experimental site was clay loam in texture. The soil of the experimental field was low in available P (20.2 kg P₂O₅ ha⁻¹), medium in N (250 kg ha⁻¹) and high in K (200 kg K₂O kg ha⁻¹). The pH and organic carbon content of the soil was 4.85 (1:2.5 soil water) and 2.4%, respectively. The initial soil samples had bulk density of 1.12 Mg m⁻³ and the maximum water holding capacity of 63–65%.

2.3. Plant observations

2.3.1. Plant material

Two elite lines of pea (cv. Arkel and Prakash) were selected for study. Prakash is of dwarf type, late maturing (110–115 days) with moderate growth rate, and is cultivated for dry pea seeds. In contrast, Arkel is early maturing (70–80 days), pole type cultivar with vigorous growth, and is preferably cultivated for harvesting as green pods. Response of both cultivars to treatments were assessed in terms of root growth and root activity attributes viz., root architecture, root exudation and several morpho-physiological traits at active growth stage (60 DAS). Yield and yield related attributes were measured at physiological maturity.

2.3.2. Root architecture and functional traits

At the active growth stage, root samples of pea cultivars were manually excavated and uprooted by loosening the soil around the roots using mechanical hand tools. Attempt was made to recover all coarse and fine roots with little or no damage. During excavation, a smooth flush of low water pressure was used to obtain the horizontal surface root volume along with that of the tap roots. The uprooted roots were carefully rinsed with water to remove adhering soil, and were air dried under laboratory conditions. Air dried and fresh roots were separated by shoot system and spread on a fibre-glass plate to ensure a minimum overlapping. The fiber-glass plates were used for root imaging using Epson root scanner (EPSON V700). The scanned images of roots were acquired by using the WinRHIZO professional software (Reagent instruments, Quebec city, Canada; [Abenavoli et al., 2016](#)) for obtaining information on root morphology and two dimensional architectural traits viz., total root length (TRL), root surface area (RSA), root volume (RV), root diameter (RD), average link length (Avg.Linklen), average link surface area (Avg.LinkSA), average link diameter (Avg.LinkD), number of

tips (Ntips), number of forks (N forks), number of cross (Ncross) and number of links (Nlinks). This method provides details of root size and distribution of pea cultivars grown under different tillage and NM practices, and these data are expressed on single plant basis. The scanned roots and separated shoots of the pea cvs. were further dried in hot air oven at 72 °C for 48hr or to a constant weight for obtaining the dry biomass. Total dry matter (TDM) at active growth stage was arrived at by adding shoot and root dry weight of the crop. Root:shoot ratio was obtained by dividing the dry weight of the roots by the dry weight of shoots in gram (g).

TRL was measured by Eq. (1):

$$\text{Length} = \text{number of pixels in the skeleton} \times \text{pixel size} \quad (\text{Eq.1})$$

WinRHIZO was estimated as the average diameter from the total projected root area and length. Average diameter was calculated by Eq. (2):

$$\text{Diam}_{\text{avg}} = \text{Projected area} / \text{Total length} \quad (\text{Eq. 2})$$

The above measurements were used to compute the root length ratio (root length/whole plant dry weight, cm g⁻¹), root mass ratio (root dry weight by whole plant dry weight, g g⁻¹), root fineness (root length by root volume, g cm⁻³), and root tissue density (root dry mass by root volume, g cm⁻³).

2.3.3. Rhizosphere acidification

The assessment of root organic acid exudation of pea cvs. grown under different conservation tillage and NM practices was performed using the standard protocol ([Yan et al., 2002](#)). Briefly, the intact roots of uprooted pea cvs; were thoroughly washed with de-ionized water or double distilled water and air dried under laboratory conditions for 10–15 min. The roots were then spread on empty petri-plates of 20cm diameter containing agar media (pH 6.0) with 0.75% (w/v) agar, 0.006% (w/v) bromocresol purple, 2.5 mM K₂SO₄ and 1mM CaSO₄. The intact roots were carefully pressed into the agar medium without being damaged. The petri dish containing the intact roots were kept under adequate light (~600 μEi cm⁻² S⁻¹) and humidity (~70%) conditions for 36–48 h. The visual change in color of the agar medium surrounding the roots was qualitatively recorded by obtaining the quality photographs.

2.3.4. Estimation of leaf pigments

The contents of chlorophyll, carotenoid and anthocyanin pigments in fresh and matured leaves were estimated by the acetone extraction method. Known weight of leaf tissue (0.5g) was fully homogenized in 15 ml of 80% acetone: 20% water solution using a pre-cooled pestle and mortar at 4 °C. A pinch of CaCO₃ was added to the extraction solution during grinding of the samples to neutralize any plant acids which might be liberated during grinding. After thorough grinding, the extracted solution was filtered through Whatman No.42 filter paper in volumetric flask and the volume of the extract made to 25 ml using 80% acetone: 20% water solution. Each sample was placed in a cuvette and absorbance was recorded at 645, 663 and 480 nm through UV visible spectrophotometer (UV-2100). The absorbance values were substituted in the following formulae to calculate the chl a, chl b, total chlorophyll (Chl a + b) (Eqs. (3), (4), and (5)) and the pigment contents (Eq. 6) were expressed in mg g⁻¹ on fresh weight basis ([Misyura et al., 2012](#))

$$\text{Chl } a \text{ (mg g}^{-1}\text{)} = (12.72 \times A_{663} - 2.58 \times A_{645}) \times (V/W) \times (1/1000) \quad (\text{Eq.3})$$

$$\text{Chl } b \text{ (mg g}^{-1}\text{)} = (22.87 \times A_{645} - 4.67 \times A_{663}) \times (V/W) \times (1/1000) \quad (\text{Eq.4})$$

$$\text{Chl } a+b \text{ (mg g}^{-1}\text{)} = (8.05 \times A_{663} + 20.29 \times A_{645}) \times (V/W) \times (1/1000) \quad (\text{Eq.5})$$

$$\text{Carotenoids} = (A_{480} + 0.114 \times A_{663} - 0.638 \times A_{645}) \times (V/W) \times (1/1000) \quad (\text{Eq.6})$$

Where, V refers to the total volume of the extract, W to weight of the tissue taken for pigment measurements, and A₆₆₃, A₆₄₅ and A₄₈₀ are the optical absorbance values recorded by UV-2100 at 663, 645, and 480nm, respectively.

For measurement of the Anthocyanin, ~0.5 g of fresh and matured leaves was homogenized by grinding in 20 ml of extracting mixture solution containing propanol-HCl-H₂O (18:1:81 on v/v). The extraction vials/flasks were incubated in boiling water for 1.5 min. For full pigment extraction, the tubes were incubated in dark for 24 h in the extraction medium at 25 °C. Thereafter, extracts were centrifuged for 40 min at about 5000G and supernatant was collected for recording the absorbance (A) at 535 nm and 650 nm. The A values at 535 nm were corrected for scattering (S) using the A values at 650 nm (A₆₅₀) using Rayleigh's formula. Thus, corrected A₅₃₅ nm is considered for actual anthocyanin calculation, since there is no or less absorption by anthocyanin at 650 nm (Lange et al., 1971). Total anthocyanin was calculated using Eqs. (7) and (8):

$$\text{Corrected } A_{535} = A_{535\text{nm}} - A_{650\text{nm}} \quad (\text{Eq.7})$$

$$\text{Anthocyanin (mg g}^{-1}\text{)} = (\text{Corrected } A_{535}) * \text{Volume made up} * (1/W) * (1/1000) \quad (\text{Eq.8})$$

Where, W is the weight of fresh leaves taken for extraction, and V is volume of the leaf extract.

The ratio of chlorophyll a/b, carotenoids/total chlorophyll, anthocyanin/total chlorophyll is calculated by division of individual pigment quantities in the leaves.

2.3.5. Measurement of leaf characteristics

The fully expanded matured leaves, the fourth leaf from the top, was used for measurement of leaf thickness (LT), specific leaf area (SLA), leaf dry matter content (LDMC) and specific leaf weight (SLW) measurements. LT was measured using absolute digital vernier caliper (Mitutoyo corp. Japan) at the broadest part of the leaf excluding major veins with accuracy of ±0.01 mm and expressed in µm. This measurement was made by pressing the caliper gently to avoid overestimation and any injury to the leaf. For SLW, the selected leaves from different treatments were assessed for the leaf area using the leaf area meter and respective dry weight of the leaf after drying in an oven at 60 °C to constant weight. The SLW was computed by Eq. (9):

$$\text{SLW (g cm}^{-2}\text{)} = \frac{\text{Leaf weight}}{\text{Leaf area}} \quad (\text{Eq. 9})$$

The SLA is obtained by 1/SLW. Both SLW and LT indicate the robustness of leaf. Percent total water content (TWC) of the leaf was calculated as the difference in leaf fresh weight and dry weight after oven drying and LDMC and by estimating the ratio of leaf dry mass to saturated fresh mass of leaf (Vile et al., 2005).

2.3.6. Determination cell membrane stability (CMS)

The CMS was determined as per cent leakage of cell contents in fresh leaves of pea cultivars (Sullivan and Ross, 1979). Finely cut leaf pieces weighing to 0.5 g were taken from the top third leaf and immersed in 50 ml of deionised water and incubated under laboratory conditions for 3h. At the end of 3h, initial electrical conductivity (C₁) was measured using a conductivity meter (Elico co.). Then the beaker containing deionized water with leaf pieces was boiled over a hot water bath for 30 min and the final electrical conductivity (C₂) was measured. Cell membrane integrity was computed and expressed by Eq. (10):

$$\text{CMS (\%)} = [1 - (C_1/C_2)] \times 100 \quad (\text{Eq.10})$$

2.3.7. Assessment of cultivar performance stress response

To assess overall growth variation and stress as response of pea cultivars to different tillage and NM practices, phenotypic plasticity was assessed. The Response Co-efficient (RC) for various morpho-physiological traits (viz., chlorophyll pigmentation, leaf characteristics, root architectural traits and shoot growth characteristics) were derived and are mentioned in parenthesis of each value in the respective data tables (Valladares et al., 2006). However, differential pattern of root

growth in pea cultivars were assessed as root architecture and root exudation. Phosphorus efficiency, yield and yield related traits are reported in terms of the absolute values.

2.3.8. Phenotypic plasticity indices

The RC as phenotypic plasticity index was calculated for each cultivar by Eq. (11) (Poorter and Nagel 2000).

$$\text{RC} = V_T/V_C \quad (\text{Eq.11})$$

Where, V_T and V_C represent average values under reduced tillage treatment (NT and MT) and NM practices over CT and 100% NPK. Root architectural (TRL, RSA, RV, RD, RDW, RLR, RMR, RF, RTD), leaf pigmentation (Chl a, chl b, total chlorophyll, Carotenoids and anthocyanin) and shoot traits (LT, SLW, SLA, TWC, LDMC, CMS) were determined for calculating the plasticity indices. A higher RC value indicates advantageous nature of the treatments to plants under stress conditions.

2.3.9. Estimation of tissue phosphorus and its efficiency

The contents of P were estimated in shoot (mixed both leaves and stem) and root tissues of pea cultivars after harvest of crop by using the vanadomolybdate phosphoric acid yellow colour method (Jackson, 1973).

2.4. Yield and yield related traits

2.4.1. Partition efficiency (PE)

The PE was calculated as the ratio of green pod yield to total aboveground biomass, and was also expressed in terms of energy content of seed to the energy content of total above ground biomass at full maturity (Koester et al., 2014). The green pod yields of each cultivar from 3-4 pickings were added to obtain yield per plot which was later converted to yield in Mg ha⁻¹. The stover yield was determined after drying the shoot biomass in the oven for 72 h at 62 °C, and the PE was computed by using Eq. (12):

$$\text{PE (\%)} = (\text{Economic yield} * 100) / (\text{Above ground biomass (Stover yield} + \text{economical yield)}) \quad (\text{Eq.12})$$

2.4.2. Harvest index

The yields of green pods, harvested three times after physiological maturity, were used for computing the HI (Eq.13). Economic yield (Eq.14) and stover yield (Eq.15) were estimated after oven drying of selected plant pods and stover obtained from centre of each plot and estimates were adjusted to 13% tissue moisture content. The HI determined by using was expressed as %:

$$\text{HI} = \frac{\text{Economic yield}}{\text{Biological yield}} \times 100 \quad (\text{Eq.13})$$

$$\text{Economic yield} = \text{seed yield} \quad (\text{Eq.14})$$

$$\text{Biological yield} = \text{Total plant biomass (seed yield} + \text{stover yield} + \text{root biomass}) \quad (\text{Eq.15})$$

2.5. Statistical analysis

All traits were analysed for computing the two way Analysis of Variance (ANOVA) with tillage and NM practice as main factors for their significance. Subsequently, all data were tested by comparing the means of all parameter of both the cultivar at tillage and NM level through "F" test. Standard error of means [S.Em (±)] and Least Significant difference (LSD) at 0.05 probabilities (p = 0.05) were worked out for each parameter (Gomez and Gomez, 1984) to compare treatment means. Interactions between tillage and NM Practices were described wherever found significant. Duncan Multiple Range Test (DMRT) have been used in Figures 4, 5, and 6 to compare treatment means for various variables.

Table 1. Root morphological parameters of pea cultivars as influenced by tillage and NM practices under rice fallows.

Treatment	Root surface area (cm ² plant ⁻¹)		TRL (cm plant ⁻¹)		RV (cm ³ plant ⁻¹),		Av. diameter (mm)		RDW (gplant ⁻¹)	
	A	P	A	P	A	P	A	P	A	P
Tillage										
NT	46.14 (0.55)	46.77 (0.77)	81.1 (0.62)	78.7 (0.77)	2.72 (0.50)	1.47 (0.56)	1.49 (0.47)	1.46 (0.72)	0.324 (1.12)	0.323 (1.31)
MT	58.85 (0.70)	49.10 (0.81)	88.7 (0.68)	86.3 (0.84)	3.18 (0.58)	1.61 (0.62)	1.89 (0.60)	1.60 (0.79)	0.316 (1.09)	0.368 (1.50)
CT	83.86 (C)	60.95 (C)	129.9 (C)	102.4 (C)	5.44 (C)	2.61 (C)	3.16 (C)	2.02 (C)	0.290 (C)	0.246 (C)
S.Em (±)	3.03	2.12	2.40	4.23	0.26	0.11	0.05	0.05	0.003	0.010
I.s.d (p = 0.05)	8.78	6.13	6.94	12.2	0.76	0.33	0.13	0.15	0.009	0.030
Nutrient management practices										
50% NPK	38.98 (0.74)	31.50 (0.75)	101.9 (0.96)	88.6 (0.93)	2.73 (0.80)	0.95 (0.59)	2.12 (1.15)	1.26 (0.93)	0.312 (0.84)	0.310 (0.94)
100 % NPK	52.99 (C)	42.06 (C)	106.5 (C)	94.9 (C)	3.40 (C)	1.62 (C)	1.84 (C)	1.35 (C)	0.372 (C)	0.328 (C)
50% NPK+ISRR	56.89 (1.07)	47.53 (1.13)	86.6 (0.81)	84.2 (0.89)	3.98 (1.17)	1.39 (0.85)	1.95 (1.06)	1.44 (1.07)	0.251 (0.68)	0.306 (0.93)
50% NPK+WB	70.51 (1.33)	64.20 (1.53)	94.7 (0.89)	91.7 (0.97)	3.77 (1.11)	2.13 (1.31)	2.25 (1.22)	2.14 (1.58)	0.274 (0.74)	0.320 (0.97)
50% NPK+GLM	95.37 (1.80)	76.06 (1.81)	109.7 (1.03)	86.5 (0.91)	5.03 (1.48)	3.38 (2.08)	2.75 (1.50)	2.29 (1.69)	0.341 (0.92)	0.297 (0.91)
S.Em (±)	3.91	2.73	3.09	5.46	0.34	0.15	0.06	0.07	0.004	0.013
I.s.d (p = 0.05)	11.3	7.91	8.96	NS	0.98	0.42	0.17	0.19	0.011	0.038
CV (%)	18.65	15.67	9.29	7.48	26.92	22.99	8.08	11.79	3.70	12.67

Note: NT- No-till, MT- Minimum tillage, CT- Conventional tillage, ISRR- *In-situ* residue retention; WB- Weed biomass; GLM- Green leaf manure, I.s.d (p = 0.05) least significant difference, CV- Co-efficient of variation, RSA: Root surface area, TRL: Total root length, RV: Root volume, Av. diameter: Average root diameter, RDW: Root dry weight, R:S ratio: Root to shoot ratio, A-Arkel, P- Prakash, C-Control, NS- Non-significant. Figures in parenthesis indicate response co-efficient.

3. Results

3.1. Root phenotyping and its behavior

Root growth and architectural traits assessed by comparing the means of absolute values and by calculating response co-efficient for primary root architectural traits (viz., TRL, RSA, RV and average root diameter) differed significantly among tillage and NM practices (Table.1 and Figure 2). Other functional root architectural traits (viz., RLR, RMR, RF and RTD) of both pea cultivars were also significantly influenced and responded differentially by residual effect of tillage and NM practices (Table 2). Total root length of both pea cultivars was significantly higher under CT and with the application of 100% NPK and 50% NPK alone than with other tillage and NM practices. However, the root surface area was significantly higher under CT and with the application of 50% NPK +

GLM and 50% NPK + WB than that under other tillage and NM practices in both pea cultivars. Root volume and average root diameter were also significantly higher in both the cultivars under CT and 50% NPK+GLM and 50% NPK+WB. Most of the root morphological traits were more for cv. Arkel than those for cv. Prakash. Root dry weight was the maximum under NT along with sole application of 100% NPK and 50% NPK. Both cultivars had relatively higher TRL and RSA under CT whereas, root volume and root diameter were recorded more under NT than those under other tillage practices. The RC for RSA, TRL, RV, RD were significantly increased under MT than those under CT. However, RC calculated for different NM practices in comparison with 100% NPK had higher values for RSA, RV and RD under 50% NPK+GLM. In comparison, RC for TRL was the maximum under 50% NPK alone followed by that under 50% NPK+WB. Further, RC for RDW was higher under NT and 50% NPK+GLM and 50% NPK+WB than that under other treatments.

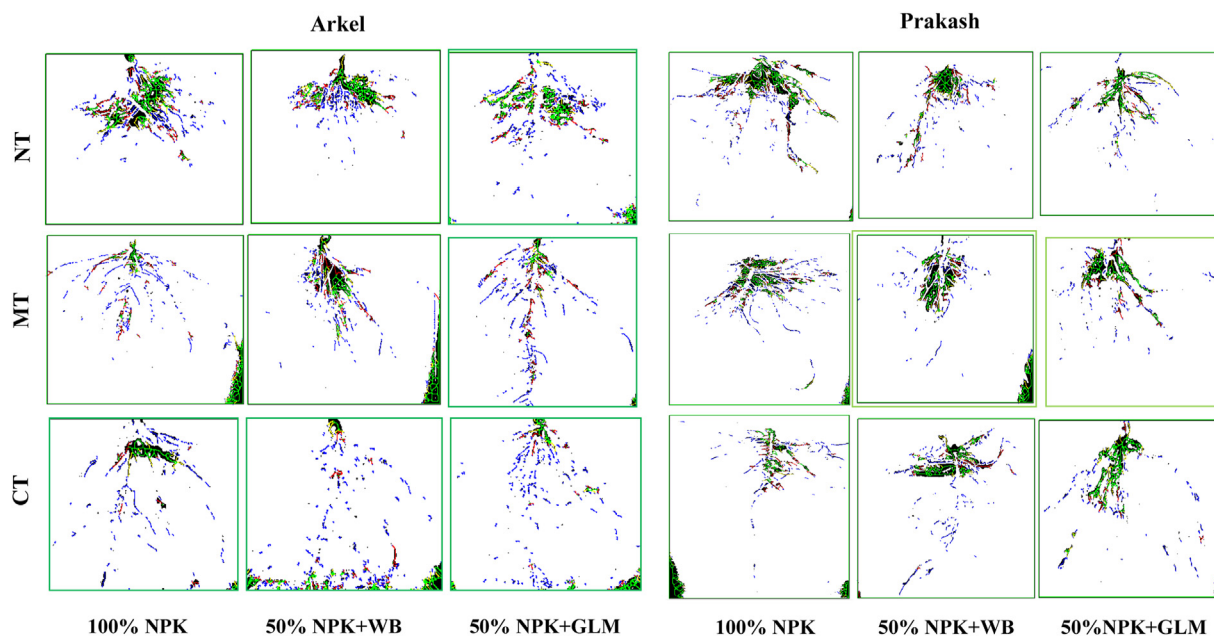


Figure 2. Root architecture of selected pea cultivars under different tillage and nutrient management practices. NT- No-till, MT- Minimum tillage, CT - Conventional tillage, WB - Weed biomass.

Table 2. Functional root parameters of pea cultivars as influenced by residual effect of tillage and NM practices under rice fallows.

Treatment	RLR		RMR		RF		RTD	
	A	P	A	P	A	P	A	P
Tillage								
NT	15.8 (0.58)	16.9 (0.78)	0.065 (1.08)	0.063 (1.21)	34.7 (1.37)	75.1 (1.46)	266.7 (0.55)	269.5 (0.64)
MT	16.3 (0.59)	14.2 (0.65)	0.056 (0.91)	0.062 (1.19)	32.9 (1.30)	76.0 (1.48)	292.4 (0.61)	238.7 (0.57)
CT	27.4 (C)	21.7 (C)	0.061 (C)	0.052 (C)	25.4 (C)	51.3(C)	482.7 (C)	421.2 (C)
S.Em (\pm)	1.10	1.14	0.002	0.004	2.17	6.00	12.73	17.87
L.s.d ($p = 0.05$)	3.20	3.31	0.007	NS	6.28	17.4	36.88	51.75
Nutrient management practices								
50% NPK	24.0 (1.01)	19.9 (1.03)	0.073 (0.92)	0.068 (1.04)	44.1 (1.30)	98.7 (1.63)	334.9 (1.08)	306.9 (0.91)
100 % NPK	23.9 (C)	19.4 (C)	0.080 (C)	0.065 (C)	34.0 (C)	68.1 (C)	309.7 (C)	337.1 (C)
50% NPK+ISRR	18.2 (0.76)	15.5 (0.80)	0.052 (0.66)	0.055 (0.85)	25.5 (0.75)	68.2 (1.12)	343.5 (1.11)	302.4 (0.90)
50% NPK+WB	15.3 (0.64)	15.4 (0.79)	0.042 (0.53)	0.053 (0.82)	27.6 (0.81)	57.9 (0.95)	428.3 (1.38)	293.3 (0.87)
50% NPK+GLM	17.8 (0.75)	15.8 (0.82)	0.056 (0.70)	0.054 (0.84)	23.6 (0.69)	44.4 (0.73)	320.0 (1.03)	309.3 (0.92)
S.Em (\pm)	1.43	1.48	0.003	0.005	2.80	7.75	16.43	23.06
L.s.d ($p = 0.05$)	4.13	NS	0.009	NS	8.11	22.4	47.61	NS
CV (%)	21.56	16.94	15.36	23.35	27.14	31.1	14.20	16.57

Note: NT- No-till, MT- Minimum tillage, CT- Conventional tillage, ISRR- *In-situ* residue retention; WB- Weed biomass; GLM- Green leaf manure, L.s.d ($p = 0.05$) = least significant difference, CV – Co-efficient of variation, A-Arkel, P- Prakash, NS- Non-significant, RLR-Root length ratio, RMR-Root mass ratio, RF-Root fineness, RTD-Root tissue density, C-Control. Figures in parenthesis indicate response co-efficient.

Functional root attributes derived from primary root architectural traits (i.e., RLR, RMR, RF and RTD) differed significantly among cultivars (Table 2). The RLR was higher under CT and 50% NPK and 100% NPK, whereas RMR was higher under NT and with 50% NPK alone in both the cultivars than those in other treatments. RF of *cv. Arkel* was higher under NT and 100% NPK alone whereas, the RF of *cv. Prakash* was higher under MT and 50% NPK alone than under other tillage and NM practices. RTD was significantly higher under CT than that under MT and NT in both the cultivars. The *cv. Arkel* had significantly higher RTD under 50% NPK+WB and 50% NPK+GLM than that under other NM practices. RC values calculated for derived root traits indicated that NT had lower RLR and RTD, higher RMR and RF in *cv. Arkel*. In comparison, *cv. Prakash* had higher RLR, RMR, RTD and lower RF in CT than those under other tillage treatments. However, MT produced higher RLR, RTD and lower RMR and RF in *cv. Arkel* but lower RLR, RMR, RTD and higher RF in *cv. Prakash* than those under CT. Among different NM practices, 50% NPK produced higher RLR, RMR, RF in both cultivars than under other NM practices.

However, RTD was higher under 50%NPK+WB in *cv. Arkel* and 50% NPK+GLM in *Prakash* than those under other NM practices. Relatively higher values of Avg. link length, and Avg. link SA were observed under NT, but more Avg. Link D was observed under MT and NT than those under other tillage practices.

3.2. Rhizosphere acidification

In *cv. Arkel*, rhizosphere acidification was relatively higher under NT and CT than that under MT. However, the degree of increase in acidification, as indicated by more area of yellow colour change around roots, was more under NT than that under CT. In addition, the degree of exudation was more under NT and CT with application of 50% NPK, 100% NPK 50% NPK + WB and 50% NPK+ISRR than those under other NM treatments. However, no significant increase was observed in the treatment with 50% NPK+GLM application (Figure 3). Furthermore, there was no rhizosphere acidification or the

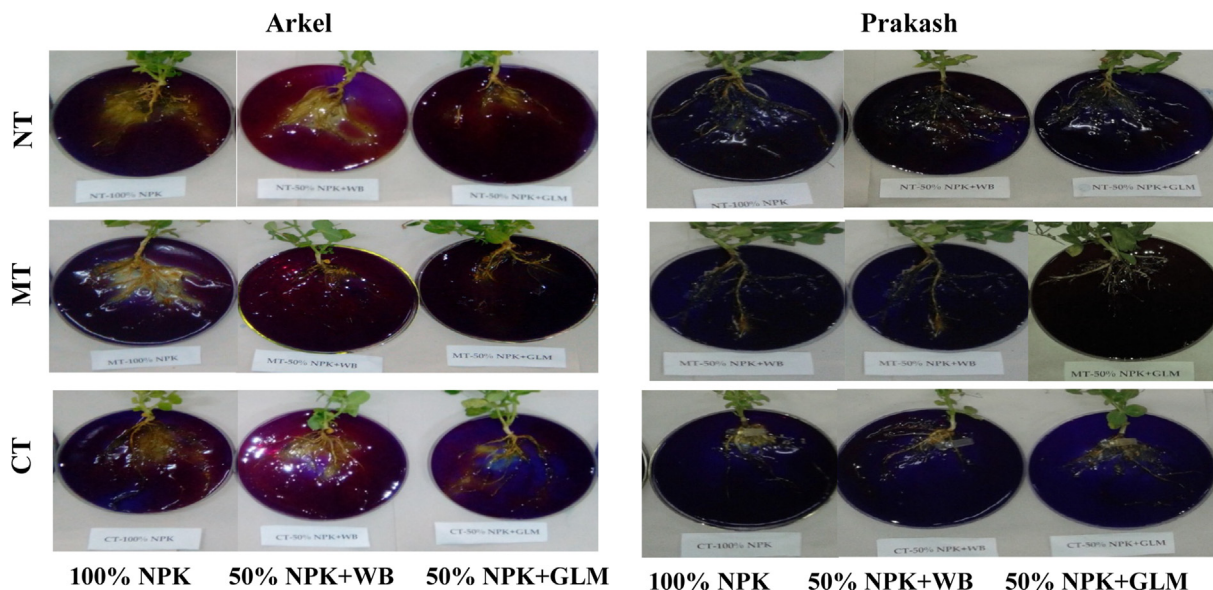


Figure 3. Rhizosphere acidification of selected pea cultivars after incubation for 48 h with different root exudation patterns under different tillage and nutrient management practices (NT-no-till and MT- Minimum tillage CT- Conventional tillage).

Table 3. Leaf pigmentation of pea cultivars as influenced by tillage and NM practices under rice fallows.

Treatment	Chl a (mg g ⁻¹ FW)		Chl b (mg g ⁻¹ FW)		Total chl. (mg g ⁻¹ FW)		Car (µg g ⁻¹ FW)		Anth (µg g ⁻¹ FW)	
	A	P	A	P	A	P	A	P	A	P
Tillage										
NT	0.76	0.82	0.24	0.24	1.19	1.27	39.3	38.2	32.1	29.4
MT	0.74	0.93	0.22	0.28	1.18	1.26	37.6	35.6	27.1	27.2
CT	0.67	0.81	0.20	0.27	1.06	1.14	36.4	32.5	25.4	25.7
S.Em±	0.02	0.04	0.01	0.01	0.04	0.04	1.16	1.01	1.36	1.00
<i>l.s.d</i> (p = 0.05)	0.07	NS	0.02	0.03	0.11	0.11	NS	2.92	3.94	2.89
Nutrient management practices										
50% NPK	0.60	0.71	0.18	0.24	1.10	1.18	34.7	31.4	22.0	23.2
100 % NPK	0.64	0.74	0.19	0.24	1.12	1.20	35.3	32.1	27.0	24.9
50% NPK+ISRR	0.69	0.85	0.21	0.25	1.14	1.22	37.6	34.9	29.5	27.2
50% NPK+WB	0.80	0.96	0.26	0.28	1.17	1.25	39.8	38.6	32.4	31.2
50% NPK+GLM	0.89	1.00	0.26	0.30	1.20	1.28	41.4	40.1	30.2	30.7
S.Em±	0.03	0.05	0.01	0.01	0.05	0.05	1.49	1.30	1.76	1.29
<i>l.s.d</i> (p = 0.05)	0.09	0.14	0.03	0.04	NS	NS	4.33	3.77	5.09	3.72
CV (%)	12.56	17.01	14.37	15.03	11.90	12.30	11.87	11.02	14.62	14.07

Note: A-Arkel, P- Prakash, NT- No-till, MT- Minimum tillage, CT- Conventional tillage, ISRR- *In-situ* residue retention; WB- Weed biomass; GLM- Green leaf manure, *l.s.d* (p = 0.05)- least significant difference, CV – Co-efficient of variation, NS- Non-significant, Chl a – Chlorophyll a, Chl b – Chlorophyll b, Tot. chl- Total chlorophyll, Car- Carotenoids, Antho-Anthocyanin.

observed colour change in *cv.* Prakash irrespective of tillage and NM practices.

3.3. Chlorophyll pigmentation

During the active growth stage, the contents of primary leaf pigments (*viz.*, chl a and chl b) differed significantly among different tillage and NM practices in both cultivars. The contents of chl a were significantly higher under NT in *cv.* Arkel, but not in *cv.* Prakash. The contents of chl. b were significantly higher in *cv.* Arkel under NT and in *cv.* Prakash under MT. Among different NM practices, significantly higher contents of chl. a and b were observed under 50% NPK+GLM in both cultivars,

but lower contents were observed under 50% NPK alone in both cultivars (Table.3). The total contents of chlorophyll pigment (Chl a + b) were higher under NT in both cultivars but did not differ significant among NM practices. The contents of other pigments (*i.e.*, carotenoids and anthocyanin) also differed significantly among tillage and NM practices. Tillage practices significantly influenced carotenoid content only in *cv.* Prakash, with the highest contents being under NT. However, the carotenoid contents were significantly increased in both cultivars with the application of 50% NPK+GLM and 50% NPK+WB. The contents of synthesized anthocyanin were significantly higher under NT and 50% NPK+GLM in both cultivars than those under other tillage and NM practices (Table 3).

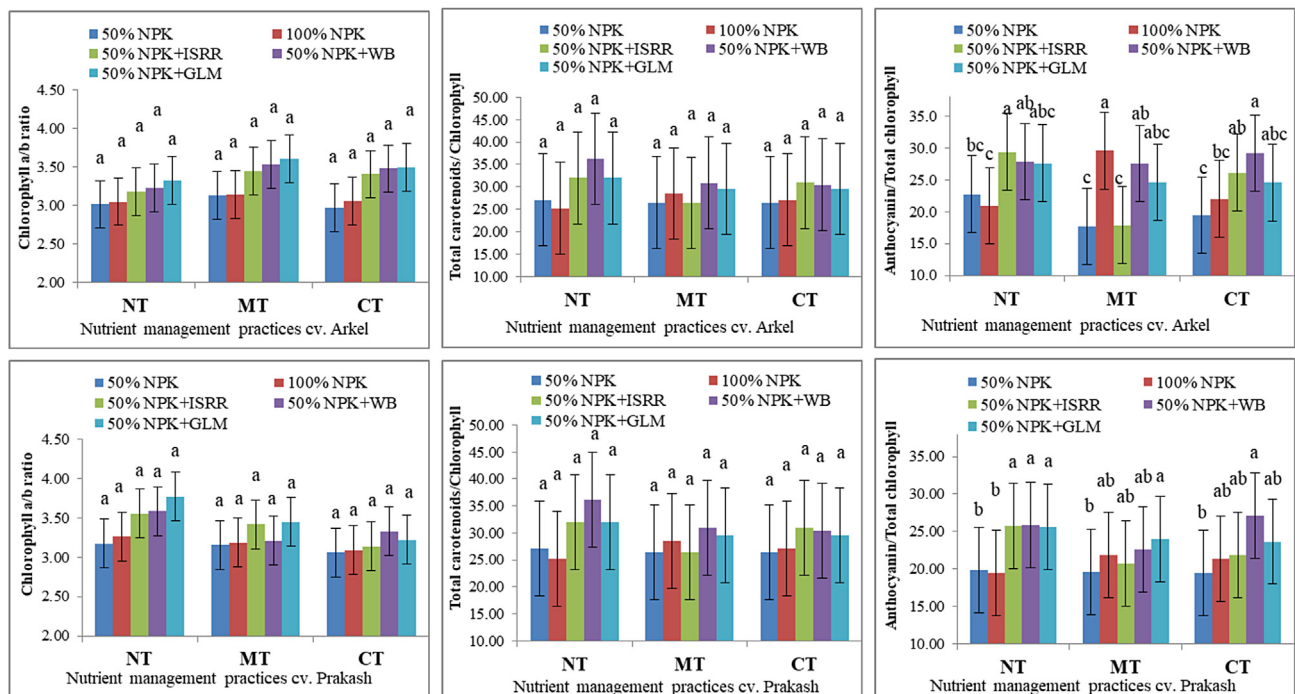


Figure 4. Performance of Pea cultivars in terms of chlorophyll a/b ratio, carotenoids/total chlorophyll and anthocyanin/total chlorophyll content under different residual effect tillage and nutrient management practices NT - No-till, MT - Minimum tillage, CT- Conventional tillage, ISRR- *In-situ* residue retention; WB- Weed biomass; GLM- Green leaf manure. Vertical bars represent standard error. Bars with same letters are not significant and with different letters are significantly different at p = 0.05 after Duncan's multiple range test.

Table 4. Leaf characteristics of pea cultivars influenced by conservation tillage and NM practices under rice fallows.

Treatment	Leaf thickness (μm)		Specific leaf area (cm^2g^{-1})		Specific leaf weight (mg cm^{-2})		LDMC		TWC (%)	
	A	P	A	P	A	P	A	P	A	P
Tillage										
NT	318 (0.98)	355 (0.96)	86.2 (0.97)	154.8 (0.88)	12.1 (1.05)	7.20 (1.13)	0.636 (1.08)	0.636 (1.07)	57.5 (0.82)	57.3 (0.83)
MT	343 (1.05)	383 (1.04)	97.7 (1.10)	121.7 (0.69)	11.4 (0.98)	8.40 (1.31)	0.630 (1.07)	0.617 (1.04)	58.9 (0.84)	62.3 (0.90)
CT	325 (C)	369 (C)	88.6 (C)	175.5 (C)	11.6 (C)	6.39 (C)	0.589 (C)	0.592 (C)	69.9 (C)	68.9 (C)
S.Em (\pm)	6.73	6.53	6.36	3.61	0.75	0.21	0.005	0.003	1.15	0.88
L.S.D ($p = 0.05$)	19.5	18.9	NS	10.5	2.18	0.60	0.013	0.010	3.32	2.54
Nutrient management practices										
50% NPK	330 (1.01)	368 (1.03)	99.3 (0.96)	121.9 (0.77)	10.8 (1.00)	8.53 (1.31)	0.605 (0.99)	0.605 (1.00)	65.6 (1.03)	65.7 (1.01)
100 % NPK	327 (C)	357 (C)	103.0 (C)	157.8 (C)	10.9 (C)	6.52 (C)	0.612 (C)	0.607 (C)	63.7 (C)	64.9 (C)
50% NPK+ISRR	320 (0.98)	370 (1.04)	83.7 (0.81)	149.4 (0.95)	12.2 (1.13)	7.22 (1.11)	0.617 (1.01)	0.616 (1.01)	62.4 (0.98)	62.4 (0.96)
50% NPK+WB	321 (0.98)	366 (1.02)	85.4 (0.83)	164.5 (1.04)	12.0 (1.11)	6.36 (0.97)	0.623 (1.02)	0.628 (1.03)	60.7 (0.95)	59.3 (0.91)
50% NPK+GLM	346 (1.06)	386 (1.08)	83.5 (0.81)	159.8 (1.01)	12.6 (1.16)	8.02 (1.23)	0.634 (1.04)	0.619 (C)	58.2 (0.91)	61.8 (0.95)
S.Em (\pm)	8.69	8.43	8.21	4.66	0.97	0.27	0.006	0.004	1.48	1.13
l.s.d ($p = 0.05$)	NS	NS	NS	13.5	NS	0.77	0.017	0.013	4.29	3.28
CV (%)	7.93	6.85	27.09	9.27	24.98	10.86	2.90	2.14	7.15	5.41

Note: A-Arkel, P- Prakash, NT- No-till, MT- Minimum tillage, CT- Conventional tillage, ISRR- *In-situ* residue retention; WB- Weed biomass; GLM- Green leaf manure, l.s.d ($p = 0.05$)- least significant difference, CV – Co-efficient of variation, LDMC-Leaf dry matter content, TWC-Total water content, NS- Non-significant. C - Control. Figures in parenthesis indicate response co-efficient.

The ratio of chl a/b, carotenoids to total chl and anthocyanin to total chl was also influenced by residual effect of tillage and NM practices. The residual effect of tillage treatment MT and nutrient application with 50% NPK+GLM (which was at par with 50% NPK+WB and 50% NPK+ISRR) significantly increased the chl a/b ratio. However, a higher chl a/b ratio was observed in Prakash than those under cv. Arkel (Figure 4). Reverse was observed for anthocyanin/total chl content. In general, anthocyanin/total chl content ratio was higher under 50% NPK+ISRR/WB/GLM than 50% NPK or 100% NPK alone, with the exception that 100% NPK had similar ratio with 50% NPK+ISRR/WB/GLM in case of Arkel. However, there was no significant effect of tillage on anthocyanin/total chl content. But, the ratios of total carotenoids/total chl were not significantly influenced by residual tillage and NM practices. The RC values were calculated for the pigment content by taking CT and 100%NPK as control in tillage and NM practices, respectively. In cv. Arkel, RC indicated that NT had higher chl a, chl b, total chl, carotenoid and anthocyanin contents than those under other tillage treatments. Incv. Prakash, however, MT had higher chl a, chl b and total chl than those under other treatments. In both cultivars, values of RC for chl a, chl b, total chl and carotenoids were higher under 50% NPK+GLM compared with those under 100% NPK alone (Table 3 and Figure 4).

3.4. Changes in leaf characteristics

Leaf traits (viz., LT, SLA, LDMC, SLW) measured during the active stage of crop growth differed significantly among tillage and NM practices. Leaf thickness was significantly higher under MT with 50%

NPK+GLM in both cultivars than that under other treatments. The SLA and SLW were significantly higher under MT along with the application of 50% NPK+WB than those under other tillage and NM practices in both cultivars (Table 4). However, LDMC was higher under NT in both cultivars than that under other tillage treatments. Among NM practices, LDMC was higher under 50% NPK+GLM in cv. Arkel and under 50% NPK+GLM incv. Prakash than those under other NM practices. The CMS, computed for fresh matured leaves was significantly higher under NT and 50% NPK+WB in both the cultivars than that under other treatments. The CMS under different tillage practices were in order of NT>MT>CT (Figure 5). The leaf growth of both cultivars differed significantly among tillage and NM practices. The leaf expansion was more under MT along with 50% NPK+WB and 50% NPK+GLM application than that under other treatment combinations. The LWC was also significantly influenced by tillage and NM practices. In cv. Arkel, the calculated value of RC indicated that NT had lower LT and TWC but higher SLW, LDMC, CMS than those under other tillage treatments. In cv. Prakash, LT, SLW and LDMC were higher under NT than those under CT. However, MT had higher LT, TWC in both cultivars and lower SLW only in Arkel and LDMC in both the cultivars than that under CT. Among NM practices, 50% NPK + GLM had the maximum LT, SLW and LDMC and CMS (Table 4 and Figure 5).

3.5. Shoot characteristics

The shoot growth traits (i.e., vertical shoot length, number of branches and shoot dry weight) differed significantly among residual

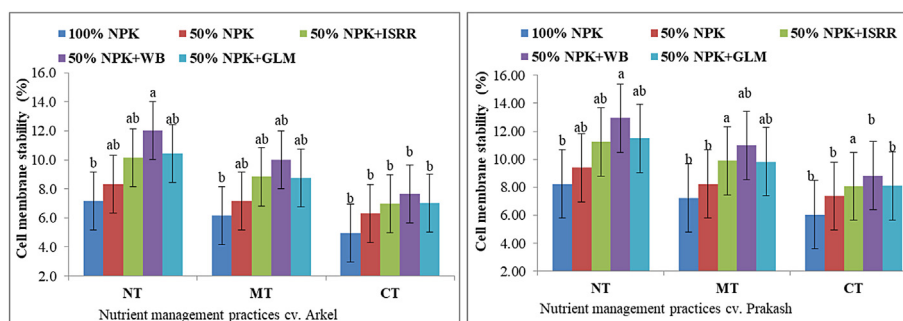


Figure 5. Performance of Pea cultivars as reflected by varied cell membrane stability under different residual effect of tillage and nutrient management practices. NT- No-till, MT- Minimum tillage, CT- Conventional tillage, ISRR- *In-situ* residue retention; WB- Weed biomass; GLM- Green leaf manure. Vertical bars represent standard error. Bars with same letters are not significant and with different letters are significantly different at $p = 0.05$ after Duncan's multiple range test.

Table 5. Shoot characteristics of pea cultivars as affected by different tillage and NM practices.

Treatment	Shoot dry weight (g plant ⁻¹)		Shoot length (cm)		No. of primary branches		R:S ratio		TDM (g plant ⁻¹)		PE (%)	
	A	P	A	P	A	P	A	P	A	P	A	P
Tillage												
NT	4.77 (1.37)	4.65 (0.89)	77.9 (1.03)	72.9 (1.03)	1.80 (1.23)	1.67 (1.02)	0.242 (1.01)	0.134 (1.17)	5.18 (1.03)	5.25 (1.10)	56.5 (1.10)	55.6 (1.02)
MT	4.50 (1.29)	6.25 (1.19)	82.4 (1.09)	75.4 (1.06)	2.00 (1.36)	1.68 (1.03)	0.220 (0.92)	0.109 (0.94)	5.89 (1.18)	6.28 (1.31)	56.1 (1.10)	54.4 (1.00)
CT	3.48 (C)	5.24 (C)	75.7 (C)	71.1 (C)	1.47 (C)	1.63 (C)	0.239 (C)	0.115 (C)	5.01 (C)	4.78 (C)	51.1 (C)	54.4 (C)
S.Em±	0.15	0.27	1.46	0.87	0.16	0.21	0.012	0.006	0.21	0.21	0.75	0.61
L.s.d (p = 0.05)	0.45	0.78	4.24	2.53	NS	NS	NS	0.017	0.60	0.62	2.18	1.76
Nutrient management practices												
50% NPK	2.91 (0.69)	4.89 (1.08)	68.2 (0.89)	65.5 (0.94)	1.33 (0.92)	1.33 (0.91)	0.166 (0.92)	0.108 (0.97)	4.35 (0.91)	4.62 (0.91)	52.1 (0.98)	53.5 (0.98)
100 % NPK	4.22 (C)	4.55 (C)	76.9 (C)	69.4 (C)	1.44 (C)	1.47 (C)	0.180 (C)	0.111 (C)	4.77 (C)	5.06 (C)	53.4 (C)	52.5 (C)
50% NPK+ISRR	4.50 (1.07)	5.27 (1.16)	81.0 (1.05)	75.4 (1.09)	1.89 (1.31)	1.56 (1.06)	0.295 (1.65)	0.120 (1.08)	4.96 (1.04)	5.59 (1.10)	55.1 (1.03)	55.0 (1.03)
50% NPK+WB	4.32 (1.02)	6.09 (1.34)	84.9 (1.10)	78.3 (1.13)	2.11 (1.46)	1.82 (1.24)	0.226 (1.26)	0.118 (1.06)	6.42 (1.35)	6.10 (1.21)	56.5 (1.06)	57.1 (1.07)
50% NPK+GLM	5.30 (1.26)	6.10 (1.34)	82.5 (1.07)	77.0 (1.11)	2.00 (1.38)	2.11 (1.44)	0.301 (1.69)	0.138 (1.25)	6.29 (1.32)	5.80 (1.15)	55.9 (1.05)	55.8 (1.04)
S.Em±	0.20	0.35	1.89	1.13	0.20	0.28	0.015	0.007	0.27	0.28	0.97	0.78
L.s.d (p = 0.05)	0.58	1.01	5.48	3.27	0.59	NS	0.044	NS	0.77	0.80	2.84	NS
CV (%)	14.12	19.41	7.41	4.62	34.86	49.78	19.58	18.60	14.91	15.27	5.33	4.29

Note: NT- No-till, MT- Minimum tillage, CT- Conventional tillage, ISRR- *In-situ* residue retention; WB- Weed biomass; GLM- Green leaf manure, L.s.d (p = 0.05) = least significant difference, CV – Co-efficient of variation, R:S ratio-Root to Shoot ratio, TDM: Total dry matter, PE-Partitioning Efficiency, NS- Non-significant, A-Arkel, P-Prakash.

tillage and NM practices (Table 5). In both cultivars, vertical shoot length, number of branches and shoot dry weight were higher under MT and NT along with the application of either 50% NPK + WB or 50% NPK+GLM than those under CT. However, extent of shoot growth increase was more incv. Prakash compared to that under cv. Arkel. Ratio of root to shoot dry weight (R: S) was significantly more in cv. Arkel than that under cv. Prakash under MT and NT along with the application of 50% NPK+ISRR, 50% NPK+GLM and 50% NPK+WB as compared to that under CT and 100% NPK. Higher TDM was observed under MT along 50% NPK+WB in both cultivars than that under other tillage and NM practices (Table 5). RC values derived for most of shoot traits were significantly higher under NT/MT along with NM practices of 50% NPK+WB/GLM than those under CT.

3.6. Yield and yield related traits

The PE was significantly affected by the residual effect of tillage and NM practices in both cultivars. For example, residual interaction effect revealed that PE was higher under MT and NT along with either 50% NPK + WB or 50% NPK+GLM than that under CT and other NM practices (Figure 6). In cv. Prakash, the significantly highest PE was observed under NT (55.6) along with 50% NPK+WB (57.1). Among tillage treatments, increase in PE was significant only in cv. Prakash. Among NM practices, significantly higher values of PE were observed under 50% NPK+WB (56.5) and 50% NPK + GLM (55.9) than those under other NM treatments only in cv. Arkel. The HI of both cultivars also differed significantly among tillage and NM practices. Significantly higher HI was observed in both cultivars under MT and NT than that under CT, but with no significant differences among NM practices (Figure 6). However, the productivity (green pod yield) of both cultivars was significantly higher under MT compared to those under NT and CT treatments. Significantly higher pod yield was obtained with 50% NPK+WB (7.97 Mg ha⁻¹) and 50% NPK+GLM (8.13 Mg ha⁻¹) compared with those under 50% NPK (6.60 Mg ha⁻¹) and 100% NPK (7.10 Mg ha⁻¹) treatments. However, interaction studies (Figure 6) revealed that MT along with different NM practices (except those of 50% and 100% NPK alone) produced similarly higher green pod yield in both cultivars than those under NT and CT but with a significantly higher green pod yield obtained for cv. Prakash than that for Arkel.

3.7. Tissue P content, its uptake and utilization efficiency

Tissue P content of both cultivars, along with its uptake and utilization efficiency, differed significantly with residual effect of tillage and NM practices (Table 6). Higher root P content in cv. Arkel was observed under MT, however, in cv. Prakash root P content was more under NT, but a higher shoot P content was observed under NT in cv. Arkel and under CT in cv. Prakash than that under other tillage practices. Application of 50% NPK + WB resulted in a higher root P content of both cultivars whereas, higher shoot P content was observed for 50% NPK+ISRR than that for other treatments. Further, a higher shoot P to root P ratio was observed with application of 50% NPK+ISRR followed by that for 50% NPK+WB. Increased shoot:root P ratio was noticed under NT than that for other tillage practices. The P uptake efficiency was higher with application of 50% NPK+ISRR under both CT and NT. Further, P utilization efficiency was also higher under MT along with application of 50% NPK+GLM which was followed by that under MT along with 50% NPK+WB (Table 6). RC for root P and utilization efficiency of P were higher under MT in both cultivars whereas, shoot to root P ratio was higher under NT than that under other tillage treatments in both cultivars. Higher RC for P uptake efficiency under CT was observed in cv. Arkel but under NT in cv. Prakash. Application of 50% NPK+WB had higher root P in both cultivars, whereas higher shoot P, shoot:root P ratio and P uptake efficiency were observed under 50% NPK+ISRR than those for other NM practices in both the cultivars. Higher RC for P utilization efficiency was observed with 50% NPK+GLM which was followed by that under 50% NPK+WB.

4. Discussion

CA based agronomic practices potentially improved crop growth and productivity of winter crop pea in marginal and degraded soils of NER with increased resource use efficiency, improved root architecture, morpho-physiology and enhanced system resilience. The present study was aimed to unravel the effect of altered soil conditions (as manifested by long term adoption of effective conservation agricultural practices) on root architecture and its plasticity and to find the possible link for corresponding changes in morpho-physiological traits which primarily modulate the overall improved crop growth and productivity. Selected

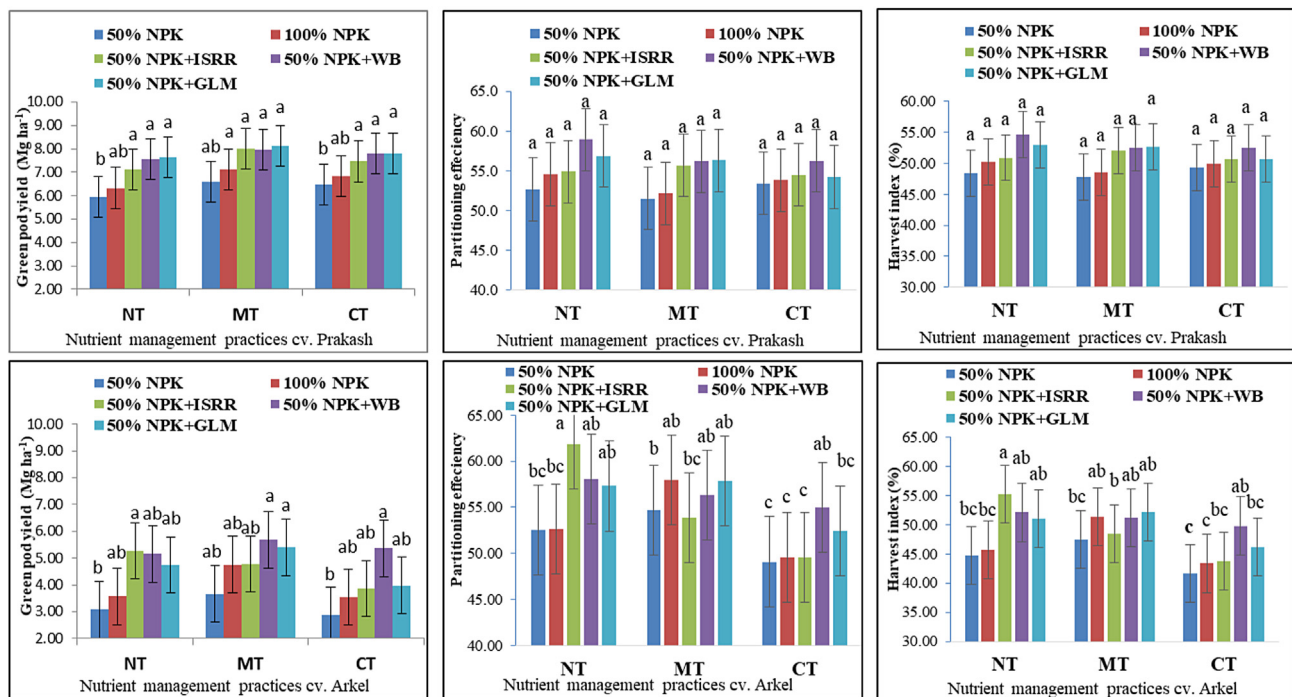


Figure 6. Performance of Pea cultivars in terms of yield components under different residual effect tillage and NM practices. NT- No-till, MT- Minimum tillage, CT- Conventional tillage, ISRR- *In-situ* residue retention; WB- Weed biomass; GLM- Green leaf manure. Vertical bars represent standard error. Bars with same letters are not significant and with different letters are significantly different at $p = 0.05$ after Duncan's multiple range test.

Table 6. Tissue phosphorus content and its efficiency in pea cultivars as influenced by different of tillage and NM practices under rice fallows.

Treatment	Tissue P (mg g ⁻¹)				Shoot P: Root P ratio		PUPE (mg of shoot P g ⁻¹ of root weight)		PUE (g of shoot mg ⁻¹ of shoot P)	
	Arkel		Prakash		Arkel	Prakash	Arkel	Prakash	Arkel	Prakash
Tillage	Root	Shoot	Root	Shoot						
NT	2.71	3.87	2.32	2.84	1.43	1.45	13.5	9.03	0.81	1.08
MT	2.87	3.04	3.25	2.68	1.05	0.89	10.0	7.35	1.06	1.11
CT	2.72	3.72	2.52	3.74	1.39	1.48	14.1	15.8	0.79	0.82
S.Em (±)	0.05	0.05	0.13	0.02	0.04	0.07	0.33	0.48	0.04	0.05
L.S.D (p = 0.05)	NS	0.15	0.38	0.07	0.10	0.20	0.95	1.40	0.10	0.15
Nutrient management practices										
50% NPK	2.78	3.69	2.84	2.93	1.38	1.09	12.2	10.2	0.69	0.81
100% NPK	2.49	2.99	2.57	3.52	1.19	1.41	8.07	12.2	0.92	0.88
50% NPK+ISRR	2.80	4.18	2.24	3.58	1.50	1.64	17.4	13.0	0.77	1.05
50% NPK+WB	2.93	4.00	3.48	2.31	1.37	0.73	16.6	7.31	0.92	1.13
50% NPK+GLM	2.83	2.85	2.34	3.11	1.01	1.52	8.34	10.9	1.12	1.14
S.Em (±)	0.07	0.07	0.17	0.03	0.05	0.09	0.42	0.62	0.05	0.07
L.s.d (p = 0.05)	0.20	0.20	0.48	0.09	0.13	0.26	1.22	1.81	0.14	0.19
CV (%)	7.30	5.81	18.63	2.85	10.50	20.80	10.10	17.45	15.82	19.48

Note: NT- No-till, MT- Minimum tillage, CT- Conventional tillage, ISRR- *In-situ* residue retention; WB- Weed biomass; GLM- Green leaf manure, l.s.d (p = 0.05) = least significant difference, CV – Co-efficient of variation, NS- Non-significant, PUPE-Phosphorus uptake efficiency, PUE-Phosphorus utilization efficiency.

pea cultivars differentially responded to modified root architecture changes thereby resulting in variegated abiotic stress tolerance for optimized productivity. Both root phenotypes and architectural trait plasticity assessed in the current study were in accord with the calculated RCs (Abenavoli et al., 2016).

4.1. Modifications of root architecture of pea cultivars

In the present study, measured primary root architectural traits like TRL, RSA and RV had higher values for both the cultivars under CT than those under MT and NT (Table 1). In addition, functional root traits (i.e.,

RLR, RTD) and root fractal traits (root branching and link length) were also considerably higher under CT than those under other tillage treatments in both cultivars (Table 2). This trend of increased root growth of both cultivars under CT over NT/MT may be attributed to meagre availability of water and nutrients that are exhausted or drained because of repeated soil disturbances (Das et al., 2017). Increased root extension and proliferation under CT is essential for extensive exploration of nutrients and water which acts as one of the typical adaptive response of pea cultivars to prevailing stress condition due to unprecedented soil evaporation during post rainy seasons (So and Ringrose-Voase 1996). Moreover propensity of increased root traits under CT may also be due to less

penetration resistance by repeated tilling. In contrast, under reduced tillage (MT and NT) there was marked increase in root biomass, RMR, RF compared with that under CT (Table 2). Even though CT increased some primary and functional root traits, it did not affect overall root biomass and R:S ratio. However, root biomass and R:S ratios significantly increased under MT relative to CT which might have benefited both the cultivars by improving nutrients and water uptake during the stress period. However, higher RMR, R:S and RF observed under MT and NT were advantageous to both cultivars compared with that under CT (Table 2). The degree of increase in root architecture traits was more in *cv.* Arkel than that under Prakash which differentially benefitted the shoot growth. Under CT, the root branching was noticed more in Arkel than that under Prakash whereas, under NT root branching of Prakash was more than that of Arkel. This trend indicates differential response of cultivars to different tillage practices. Grzesiak et al. (1997) also observed that drought tolerant bean genotypes exhibited higher root dry weight and length than the drought susceptible cultivars. Further, in the present study, the practice of retention and incorporation of plant biomass especially GLM, WB and ISRR have significantly modified root architecture for achieving needed stress tolerance. Many of the measured root architectural traits viz., RSA, TRL, RV, RD, RDW and RTD were higher under organic residue (GLM/WB/ISRR) substitution along with 50% NPK over 50% NPK and 100% NPK alone (Table 1). However, few functional root traits (viz., RLR, RMR, RF) were observed higher under sole application of 50% NPK and 100% NPK than that under other NM treatments (Table 2). Organic residue retention and incorporation in the degraded soil of NER might have improved SOC along with positive increase in water infiltration rate, water retention capacity (Saikia et al., 2015) and soil hydraulic conductivity (Kuotsu et al., 2014). Inputs of organics may improve the bulk density of the soil, encourage favorable plant-microbiota interaction, affect nutrient mineralization and release in the rhizosphere. The alteration in bulk density and C:N ratio under diverse tillage and organic matter incorporation treatments might have also influenced root growth proliferation in pea (Kuotsu et al., 2014).

The variation in functional root architecture traits under either 100% NPK or 50% NPK were adversely impacted by the lack of inputs of organic matter and low nutrient supply on root system alteration. The RC, calculated by taking CT and 100% NPK as control, showed a relative advantage of reduced tillage (MT/NT) and organic residues retention on different root functional attributes. Moreover, the increased root branching of cultivars under CT, 50% NPK and 50% NPK + ISRR indicated poor nutrient supply in the rhizosphere. But fractal root traits (i.e., the link lengths) under MT and 50%NPK and 50% NPK+ISRR (Supplementary Table 1 and 2) indicated the scope of increased root proliferation for possible exploration of deficit nutrients. Further, water deficit is a lesser important limiting factor than mechanical stress for root growth under dry conditions (Bengough et al., 2011). Finally root tips region/whorls with higher water and nutrient uptake due to the presence of root hair and non-lignified tissues (Paula and Pausas, 2011), while higher root whorl number determined an improvement of soil exploration (Lynch and Brown, 2012) for water and nutrient.

Lynch and Brown (2012) observed that several root traits are useful to improve soil resource acquisition. Similarly, the present study of root morphology and architecture of pea cultivars indicated multiple stress tolerance ability under reduced tillage (MT/NT) and organic residue application through plasticity indexes. Higher RLR trait contribute to the increased biomass allocation (RMR) and structural traits (Fineness and tissue density) whose response patterns changed with root length (Romano et al., 2013). Hence, the plants could improve root length by increasing the biomass allocation or efficiently utilizing this biomass to increase root fineness and reducing the tissue density. RF may be an adaptive trait for pea cultivar as induced by reduced tillage which increased root-soil contact and thus, water and nutrients uptake (Rewald et al., 2011), increased radial conductivity (Huang and Eissenstat, 2000) and a greater hydraulic conductance per unit root/leaf surface area (Peman et al., 2006) or per stem section area (Hernandez et al., 2010).

The dimorphic root strategy with increasing basal and lateral roots and maintaining higher length of tap root owing to P and drought stress have been reported (Sandhu et al., 2015). In the present study, MT/NT improved tissue P content, shoot P: root P, and the P utilization efficiency. Inputs of organic residues through GLM/WB/ISRR also increased tissue P status, shoot P: root P ratio, P utilization and uptake efficiency.

Complete recycling of organic plant residues and their eventual mineralization would supply approximately 30% of the N, between 20-30% of the P, and more than 100% of the K applied in inorganic fertilizers. As incorporation of crop residue affects the biological and chemical processes in the soil that govern the conversion of C, N, and P availability in the soil during succeeding crop season (Bird et al., 2003), causing positive physiological traits that significantly influence the productivity of both the pea cultivars under rice fallow conditions. Improved root architecture under CT and 50% NPK with either GLM or WB which acts as stress protective mechanisms, can enable the plant to explore increased quantities of water along with essential nutrients from sub-soil because of the large surface area of the root system. Therefore, reduced tillage along with residue retention not only saves additional photosynthate diverted to root by the plant, it also induces favorable root architectural traits for better growth and physiological condition of the plant. Relative advantage of reduced root allocation and enhanced availability of resources (water and nutrients) under reduced tillage and plant biomass supplementation in soil moisture and nutrients to the crop during dry periods (*rabi* season) (Ghosh et al., 2010) might have contributed to enhanced productivity of *rabi* crop (pea).

4.2. Variegated root exudation with altered soil condition and pea cultivar

In addition to root architecture changes, qualitative examination of root exudation indicated the differential capability of pea cultivars in synthesis and excretion of increased organic acids in response to residual effect of varied tillage practices and nutrient regimes (Figure 3). The study implied that roots of *cv.* Arkel have special capacity of root exudation which encourages not only the favorable microbiota but also increase nutrient uptake especially the limited and fixed forms of P in acid soils of the NER (Krishnappa and AftabHussain, 2014). Exuded organic acids may chelate toxic elements (Al, Fe) in acidic soils. Since root exudation was below the level of detection in *cv.* Prakash, microbial community and P uptake is relatively low. Improved root exudation in *cv.* Arkel especially under NT and 50% NPK + GLM/WB application could significantly improve soil health in the rhizosphere and favour plant soil and nutrient interactions. The P content and efficiency data recorded among the cultivars with varied tillage and nutrient management practices were reflection of mineralization processes and recruitment of organic acid exudation by pea cultivar. This further substantiates the impact of residue retention or incorporation of organic residue to soil in conserving soil moisture, soil fertility and enhances plant nutrition there by enhances productivity of pea cultivar.

4.3. Alteration in the chlorophyll pigmentation

Differentially increased root architectural traits in pea cultivars under CA have significantly influenced the morpho-physiological condition of shoot in terms of varied chlorophyll pigmentation and optimized leaf characteristics. Significant increase in leaf pigmentation under reduced tillage (NT and MT) and under 50% NPK+GLM in both the cultivars may be due to enough availability of nutrients and water achieved by positive root growth behavior for chlorophyll biosynthesis (Table 5, Figure 4). In contrast under CT and sole application of 100% NPK and 50% NPK, the chlorophyll content was lower than NT/MT and input of organics because these practices reduce environmental stresses such as imminent moisture deficits, low nutrient availability, and leaching of nutrients with repeated physical soil disturbances (Krishnappa et al., 2015). This decrease in chlorophyll pigments is caused either due to reduced synthesis or enhanced degradation of chlorophyll pigments under stress

condition (Ashraf and Harris, 2013). Parallel increase in the contents of accessory pigments like carotenoids and anthocyanin under CT followed by MT and under 50% NPK followed by 50% NPK+ISRR is an indication of prevailing stress effects (Figure 4). Moreover, the ratio of carotenoids to total chlorophyll was also higher under CT than that under other tillage methods indicating the prevalence of stress conditions. But the anthocyanin to total chlorophyll ratio was higher under NT and 50% NPK due to reduced nutrient supply in particular P. Higher carotenoids under CT and 50% NPK+WB/GLM than that under other treatments are key factors of triggered plant antioxidant defense system to protect and sustain photochemical processes under stress conditions (Havaux, 1998).

However, the favourable changes in other leaf characteristics like LT and increased SLA, SLW under reduced tillage (NT and MT) and organic matter incorporation/retention implies that plants have an optimal growth with reduced periods of water deficits and optimum nutrient availability. SLA, SLW and LDMC, as surrogates of LT under altered soil condition, increased leaf capability in terms of providing multiple layers of mesophyll cells and there by enhanced photosynthesis and biomass accumulation by the plant (Vile et al., 2005). In addition, higher water content and leaf dry biomass under reduced tillage may be attributed to increased water retention with optimum nutrient supply (Saikia et al., 2015). Increased water absorption by pea cultivars with improved hydraulic conductivity enables the plant to retain more water in leaf and green pod with optimum turgidity with reduced water loss from the soil (Kuotsu et al., 2014). Optimal leaf status for cellular structure and function for improved metabolic activity were maintained under MT/NT and with inputs of organics. Apart from this, cell membrane stability assessed as a reflection of cellular disturbances in leaf tissue and to bring out the after effects of improved soil quality which had positive trends under NT and 50% NPK+GLM/WB. Cell membrane is the first living structure of any cell exposed to the external environment. Membrane stability is important to appropriate metabolism and leaf function during different growth stages of the plant. The interaction data presented herein indicated a higher CMS under NT and 50% NPK+GLM/WB as the cell membrane was stable and there was an optimum supply of nutrients under conservation tillage (Figure 5). These reduced CMS may be due to changes in abiotic stresses affecting the structure and configuration of the membrane or inducing biochemical change in protein and lipid composition (Gajewska et al., 2012).

4.4. Shoot growth, biomass and harvest index

The data presented show an increased incremental shoot length, shoot dry weight and TDM under reduced tillage and with inputs of organics through increased water and nutrient supply with improved soil moisture status and congenial physical root environment. Allocation of more biomass towards root growth by cv. Arkel under reduced tillage than that under cv. Prakash may lead to stress resilient growth under marginal lands of NER. The PE in cv. Prakash was significantly influenced by residual effect of tillage than that under cv. Arkel. However, the input of organic residues changed the PE significantly in cv. Arkel than that in cv. Prakash. The higher HI under MT and NT and 50% NPK+GLM/WB (Figure 6) may be an indication of a resilient cultivar to mobilize and enhance accumulated biomass towards economic components even in degraded soils with the intervention of tillage and nutrient practices which increased optimal crop growth and modulate the yield.

5. Conclusions

The results presented here in supported that functional root traits and activity are important to understand the plant resilience and stress tolerance as modulated by NM and tillage practices. The results highlighted the differential response of pea cultivars with regard to improved root architectural plasticity and rhizosphere acidification, morphophysiological responses with moderate increase in pod yield under MT along with 50% NPK+WB/GLM in the preceding rice. Further, it is

suggested that adoption of MT along with 50% NPK+WB/GLM is a recommendable option for pea cultivation in rice fallows for better productivity. However, further research is needed to understand the direct effect of tillage and crop residue application on source-sink relationships, lucidsoil-plant-microbe interactions and quality of green pods of pea cultivars under acidic soils.

Declarations

Author contribution statement

Anup Das; Krishnappa Rangappa; Jayanta Layek; Ramkrushna Gandhiji Idapuganti: Conceived and designed the experiments; Savita Basavaraj: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Utpal Dey: Performed the experiments; Analyzed and interpreted the data.

Meghna Haloi: Performed the experiments; Analyzed and interpreted the data.

Rattan Lal; Shishomvano Ngachan: Wrote the paper.

Nishant A Deshmukh; Gulab Singh Yadav; Subhash Babu: Contributed reagents, materials, analysis tools or data.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

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