The rice-wheat production system is one of the principal agricultural production systems of the world and covers 10 million hectares (M ha) area in the Indo-Gangetic Plains of north-western India. In rice cultivation puddling is done to make soil soft for transplanting that also diminishes water percolation losses, increases water use efficiency and reduces weed growth leading to an environment favourable for growing a successful rice crop. However, continuation of this monoculture may give rise to the soil physical conditions which are unfavorable for the cultivation of following wheat crop. Repeated puddling and submergence of the soil every year before transplanting rice deteriorates soil physical condition by increasing bulk density and decreasing hydraulic conductivity in the surface soil layer owing to the breakdown of the soil aggregates and subsurface compaction. Unlike rice, wheat cultivation needs a well-drained soil with good aeration for producing better yield. Soil compaction resulted due to rice cultivation creates poor soil aeration that restricts root proliferation which results in poor crop growth and grain yield particularly in medium to fine textured soils. It is reported that the root zone of wheat crop sown after rice suffered from oxygen stress immediately after first irrigation. It also restricted water movement that resulted in poor root development leading to reduction in crop yield. Tractorized multi-pass tillage practices destroys soil structure such as aggregates and cause compaction within the plough layer which further deteriorates soil conditions. An increase in bulk density from such practices could explain the adverse effect of land ploughing and harrowing on crop performance. The present investigation was undertaken to study the long-term effects of integrated nutrient management on root growth of wheat and physical properties of soil after twenty one years of continuous cropping.

**MATERIAL AND METHODS**

A long-term field experiment with rice followed by wheat was initiated during kharif season (May-October) 1991 in a silty clay loam soil (Typic Hapludalf) at the experimental farm of Chaudhary Sarwan Kumar Himachal Pradesh Agricultural University, Palampur, India (32°6’ N, 76°3’ E, 1290 m above mean sea level). Agro-climatically, the site lies in the Palam
valley at foothills of Dhauladhar ranges and represents the mid-hill wet-temperate zone of the North-West Himalayas, which is characterized by mild summers, severe winters and experiences occasional snowfall during winters. At the beginning of the experiment in 1991, following properties of surface soils (0-0.15 m) were recorded: acidic soil with a pH of 5.5 (1:2.5 soil: water); medium in organic carbon (6 g kg⁻¹), phosphorus (22 kg ha⁻¹) and potassium (221 kg ha⁻¹) and high in available nitrogen (675 kg ha⁻¹). The field experiment was established with rice and wheat as test crops with ten treatments replicated 4 times in randomized block design. A part of nitrogen (25% and 50% of the recommended 100%...
Table 4. Root weight density (g m⁻³) variation under continuous fertilization and cropping after harvest of wheat (2011-12)

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Soil depth (m)</th>
<th>0-0.15</th>
<th>0.15-0.30</th>
<th>0.30-0.45</th>
<th>0.45-0.60</th>
<th>0.60-0.75</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1: No manure or chemical fertilizer (Control)</td>
<td>1.09</td>
<td>0.31</td>
<td>0.16</td>
<td>0.06</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>T2: 50% NPK to both rice and wheat</td>
<td>1.25</td>
<td>0.33</td>
<td>0.18</td>
<td>0.08</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>T3: 75% NPK to both rice and wheat</td>
<td>1.45</td>
<td>0.43</td>
<td>0.20</td>
<td>0.09</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>T4: 100% NPK to both rice and wheat</td>
<td>1.80</td>
<td>0.51</td>
<td>0.27</td>
<td>0.11</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>T5: 50% NPK + 50% N through FYM to rice followed by 100% NPK to wheat</td>
<td>2.10</td>
<td>0.72</td>
<td>0.34</td>
<td>0.16</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>T6: 75% NPK + 25% N through FYM to rice followed by 75% NPK to wheat</td>
<td>1.83</td>
<td>0.58</td>
<td>0.30</td>
<td>0.13</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>T7: 50% NPK + 50% N through wheat straw to rice followed by 100% NPK to wheat</td>
<td>2.11</td>
<td>0.68</td>
<td>0.32</td>
<td>0.12</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>T8: 75% NPK + 25% N through wheat straw to rice followed by 75% NPK to wheat</td>
<td>1.72</td>
<td>0.55</td>
<td>0.27</td>
<td>0.10</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>T9: 50% NPK + 50% N through green manure to rice followed by 100% NPK to wheat</td>
<td>2.04</td>
<td>0.85</td>
<td>0.31</td>
<td>0.13</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>T10: 75% NPK + 25% N through green manure to rice followed by 75% NPK to wheat</td>
<td>1.68</td>
<td>0.53</td>
<td>0.29</td>
<td>0.11</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>LSD (p=0.05)</td>
<td>0.248</td>
<td>0.109</td>
<td>0.057</td>
<td>0.024</td>
<td>NS</td>
<td></td>
</tr>
</tbody>
</table>

*Followed by a dose of nitrogen was supplemented through different organic sources viz., FYM (farmyard manure), wheat cut straw and green manure in the treatments T5 to T10.

The same set of treatments was repeated in the permanent laid out plots over the years with following treatment details: T1 - Control, T2 - 50% NPK to both the crops, T3 - 75% NPK to both the crops, T4 - 100% NPK to both the crops, T5 - 50% NPK + 50% N through FYM to rice followed by 100% NPK to wheat, T6 - 75% NPK + 25% N through FYM to rice followed by 75% NPK to wheat, T7 - 50% NPK + 50% N through wheat straw to rice followed by 100% NPK to wheat, T8 - 75% NPK + 25% N through wheat straw to rice followed by 75% NPK to wheat, T9 - 50% NPK + 50% N through green manure to rice followed by 100% NPK to wheat and T10 - 75% NPK + 25% N through green manure to rice followed by 75% NPK to wheat.

Rice cultivar Arize 6129 and wheat cultivar HPW-155 was grown in sequence and the 100% recommended doses of N, P and K used were 90, 17, and 33 kg ha⁻¹ for rice and 120, 26, and 25 kg ha⁻¹ for wheat, respectively. Sesbania aculeata (Dhaincha) was grown as an ex-situ green manure crop during kharif (May to July) for a period of 60-65 days and was chopped into small pieces of 4-6 cm and incorporated into the soil by a power operated rotavator at the time of puddling before transplanting of rice every year. The depth wise (0-0.15, 0.15-0.30, 0.30-0.45, 0.45-0.60 and 0.60-0.75 m) soil and root samples were taken after the harvest of wheat (June, 2012) using soil column cylinder auger to study bulk density, moisture content and root parameters viz., root volume and root weight density. For bulk density core sampler method was used while soil moisture content was estimated by gravimetric method. Root volume was determined by displacement method. For this 100 ml of distilled water was poured into a 200 ml measuring cylinder and roots belonging to the given treatment were transferred to it and change in water volume reading was recorded. Root weight density was obtained as a ratio between the weight of dry roots and the volume of soil (i.e. volume of sampling core) from which these were sampled.

RESULTS AND DISCUSSION

Bulk density: The bulk density was significantly affected by different treatments over the years up to 0.60 m depth and below that differences were found to be non-significant (Table 1). Integrated application of chemical fertilizers and organics (T5 to T10) significantly reduced values of bulk density over their respective inorganically treated plots in all the soil depths. In surface layer (0-0.15 m) it varied from 1.30 Mg m⁻³ in T5, where 50% NPK + 50% N through FYM was applied to rice followed by 100% NPK to wheat, to 1.00 Mg m⁻³ in T1 (control). In subsurface layers, bulk density reduced from 1.35 Mg m⁻³ in T1 to 1.36 Mg m⁻³ at 0.15 to 0.30 m depth; 1.50 (T1) to 1.41 (T5) Mg m⁻³ at 0.30 to 0.45 m depth; 1.58 (T2) to 1.49 (T5) Mg m⁻³ at 0.45 to 0.60 m depth and from 1.62 (T2) to 1.55 (T5) Mg m⁻³ at 0.60 to 0.75 m depth. The bulk density under different treatments in subsurface layers followed similar trend as observed under surface layer. Application of fertilizers alone (T2 to T4) or in combination with organics (T5 to T10) significantly decreased soil bulk density over control and the extent of...
decrease was more when organic manures were applied along with chemical fertilizers. Among graded doses of chemical fertilizers 100% NPK (T4) was better over 50% NPK (T2).

Substitution of 50% N through any of the organics resulted in decreased soil bulk density as compared to its 25% substitution in all the soil depths, however, the differences were found significant only in case of surface layer (0-0.15 m). Marginal reduction in bulk density in NPK treated plots over control in top two layers could be ascribed to the increased root biomass production in fertilized plots over non-fertilized plots that might have increased organic matter content of the soil. An increase in bulk density with the use of inorganic fertilizers was observed because of deterioration of soil structure by the application of nitrogenous fertilizers leading to the compaction of the soil. Continuous application of chemical fertilizers along with organics (T5 to T10) for twenty one cropping cycles caused the highest decrease in the bulk density of soil may be due to the addition of higher organic matter in these treatments that might have resulted in more pore space and good soil aggregation.

**Moisture content:** Moisture content was significantly affected by different treatments over the years in all the soil depths (Table-2). The results showed that moisture content at different soil depths increased with increase in depth, but the pronounced effect was observed under 0.15-0.30 m soil layer. In surface layer (0-0.15 m) it varied from 9.9% in T2 where 50% NPK was applied to both the crops to 16.8% in T5 where 50% NPK + 50% N through FYM was applied during kharif followed by 100% NPK during rabi. Application of chemical fertilizers alone (T2 to T4) registered relatively less moisture retention capacity over control, whereas, integrated application of organics and chemical fertilizers (T5 to T10) increased moisture retention capacity compared to control as well as plots receiving chemical fertilizers alone. Amongst integrated treatments (T5 to T10), T5 recorded the highest moisture percentage (16.8%) which was at par with moisture content recorded in T7 (16.5%) and T9 (16.0%). In subsurface layers, per cent moisture content varied from 11.7 (T2) to 20.6 (T5) at 0.15 to 0.30 m depth; 13.0 (T2) to 21.3 (T5) at 0.30 to 0.45 m depth; 14.2 (T2) to 21.7 (T5) at 0.45 to 0.60 m depth and 15.1 (T2) to 22.4 (T5) at 0.60 to 0.75 m depth. The moisture content in different treatments under subsurface layers followed similar trend as observed under surface layer. Less moisture retention capacity in NPK treated plots over control in all the layers could be ascribed to the deterioration of soil structure by use of inorganic fertilizers leading to compaction of soil resulting in less infiltration of water in soil. Continuous application of chemical fertilizers along with organics for twenty one cropping cycles caused significantly higher moisture retention capacity over chemical fertilized plots and control may be due to the addition of higher organic matter that resulted in more pore space and good soil aggregation. Organic manure application improved organic matter status and total porosity in soil that might have favourably affected soil water holding capacity and modify rainfall infiltration resulting in higher moisture content under integrated treatments.

**Root volume:** Data in Table-3 revealed that root volume was affected by different treatments, however, significant differences were found up to 0.60 m depth only. The root volume in different treatments decreased with increase in depth. In surface layer (0-0.15 m) it varied from 9.1 ml in T1 (control) to 10.8 ml in T5 where 50% NPK + 50% N through FYM was applied to rice followed by 100% NPK to wheat every year. Application of chemical fertilizers alone (T2 to T4) or in combination with organics (T5 to T10) increased root volume over control. However, integrated use of chemical fertilizers and organics had more pronounced effect on root volume in comparison to the use of chemical fertilizers alone. Application of graded doses of chemical fertilizers (T2 to T4) did not differ significantly in increasing root volume (Table-3). Amongst integrated treatments (T5 to T10), T5 recorded highest root volume which was at par with T7 and T9. The root volume in different treatments under subsurface layers followed almost similar trend as observed under surface layer. In subsurface layers, root volume varied from 5.93 (T1) to 7.05 (T5) ml at 0.15 to 0.30 m depth; 3.25 (T1) to 4.50 (T5) ml at 0.30 to 0.45 m depth; 1.25 (T1) to 2.00 (T5) ml at 0.45 to 0.60 m depth and 0.25 (T1) to 0.63 (T5) ml at 0.60 to 0.75 m depth. Substitution of 50% N through any of the organics was found to be superior over their 25% N substitution in all the depths studied. Increase in root volume with the application of chemical fertilizers alone or in combination with organics over control may be due to better fertilization which results in better root growth. Increased root volume where integration of chemical fertilizers and organics was done may be ascribed to the better physico-chemical environment of soil that would have created ambient thermo-hydral regime suitable for optimum plant growth.
Similar results were also reported earlier\textsuperscript{13}. Root growth of wheat is significantly affected by the bulk density of soil in the root zone and increased with the decrease in soil bulk density. Decrease in bulk density is associated with decrease in soil penetration resistance and increase in porosity of the soil. These changes probably were responsible for higher root growth of wheat\textsuperscript{14}. It is reported earlier that application of green manure has favorable effect on the root growth of rice and following wheat\textsuperscript{15}. Residual effect of organic sources and increasing levels of fertilizer enhanced the root length density of wheat.

**Root weight density**: Root weight density (Table-4) data revealed that it was affected significantly by different treatments over the years. The root weight density of the different treatments decreased with increase in depth. In surface layer (0-0.15 m) it varied from 1.09 g m\(^{-3}\) in T1 (control) to 2.16 g m\(^{-3}\) in T5 where 50% NPK + 50% N through FYM was applied during kharif followed by 100% NPK during rabi. In subsurface layers, root weight density followed similar trend as in the surface layer and it varied from 0.31 (T1) to 0.72 (T5) g m\(^{-3}\) at 0.15 to 0.30 m depth; 0.16 (T1) to 0.34 (T5) g m\(^{-3}\) at 0.30 to 0.45 m depth; 0.06 (T1) to 0.15 (T5) g m\(^{-3}\) at 0.45 to 0.60 m depth and 0.02 (T1) to 0.06 (T5 and T9) g m\(^{-3}\) at 0.60 to 0.75 m depth. Application of chemical fertilizers alone (T2 to T4) or in combination with organics (T5 to T10) increased root weight density over control and the extent of increase was more when organic manures were applied along with chemical fertilizers. Among graded doses of chemical fertilizers 100% NPK (T4) recorded the highest root weight density as compared to 75% NPK (T3) and 50% NPK (T2) treated plots (Table-4). Amongst integrated treatments (T5 to T10), T5 recorded the highest root weight density which was statistically at par with root weight density recorded in T7 and T9, showing equal effect of all the three organic sources at its 50% substitution rate. The root weight density in different treatments under subsurface layers followed almost similar trend as observed under surface layer. Substitution of 50% N through any of the organics was found to be superior over their 25% N substitution in all the depths studied. Root weight density increased with the application of chemical fertilizers alone or in combination with organics over control. However, the increase was more in treatments where integration of chemical fertilizers and organics was done. This may be attributed to the better root growth in these treatments due to improvement in physico-chemical environment of soil by use of organics along with chemicals. Similar results were reported earlier\textsuperscript{14,16}. Irrespective of nutrient management treatments, nearly 65% of the total root weight density was recorded in the plough layer (0-0.15 m) and it decreased with soil depth. This indicates that beyond 0.15 m depth; concentration of finer adventitious/seminal roots increased which contributed more to length than mass and volume. Similar results were reported earlier\textsuperscript{17}.

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