Available online at www.ijpab.com

DOI: http://dx.doi.org/10.18782/2320-7051.2162

ISSN: 2320 – 7051

Int. J. Pure App. Biosci. **4 (1):** 133-165 (2016)

International Journal of Pure & Applied Bioscience

Review Article

OPEN ACCESS

Soil Conservation Practices for Sustainability of Rice-Wheat Systemin Subtropical Climatic Conditions: A Review

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Received: 30.11.2015 | Revised: 11.01.2016 | Accepted: 20.01.2016

ABSTRACT

Rice-wheat cropping system is the predominant and most profitable cropping system and emerge as the major cropping system in the Indo-gangetic plains leading to the Green Revolution; Punjab, Haryana, Western Uttar Pradesh (UP) crescent has been the heartland of the Green Revolution (GR).It occupies an area about 65 mha in these states, out of this rice is grown on 40 mha and wheat on 25 mha and this system contribute more than 70 % of total cereal production in India. In Asia,the rice-wheat system is grown on an estimated at 23.5 million ha, including China with about 10 million ha,and South Asia with about 13.5 million ha. The area of rice-wheat system in India, Pakistan, Bangladesh and Nepal is 10.0, 2.2, 0.8, and 0.5 million ha, respectively. Rice-wheat systems represent 32 per cent of the total rice area and 42 per cent of the wheat area in these countries. Several problems associated to this system in the Indo-gangetic plains, however, the major problems are reduction in organic matter of soil, depletion of water resources, lowering water quality and groundwater pollution, burning of residue, reduction in productivity, higher cost of production and environmental pollution. Due to these reasons the sustainability of rice-wheat system under great threat. Conservation agriculture offer a new paradigm for agricultural research and development different from earlier one, which mainly aimed at achieving specific food grains production targets. A shift in paradigm has become a necessity in view of widespread problems of resource degradation, which accompanied past strategies to enhance production with little concern for resource integrity. Integrating concerns of productivity, resource conservation, food quality and environment is now fundamental to sustained productivity growth. Conservation Agriculture (CA) offers an opportunity for arresting and reversing downward spiral of resource degradation, decreasing cultivation costs and making agriculture more resource-use-efficient, competitive and sustainable. 'Conserving resources-enhancing productivity' (CREP) has to be new mission.

Keywords: *Conservation agriculture; Resource conservation interventions; Soil properties; RW system. Water productivity*

Cite this article: Naresh, R.K., Singh, S.P., Dwivedi, A., Kumar, P., Kumar, L., Singh, V., Kumar, V. and Gupta, R.K., Soil Conservation Practices for Sustainability of Rice-Wheat Systemin Subtropical Climatic Conditions: A Review, *Int. J. Pure App. Biosci.* **4(1):** 133-165 (2016). doi: http://dx.doi.org/10.18782/2320-7051.2162

INTRODUCTION

The rice–wheat cropping system being the oldest and most prevalent agricultural practices in India is also practiced in many other regions of the world and wetland culture is the predominant soil management system adopted. Rice occupies 153 m ha land throughout the world. In India, out of the 43 m ha area under rice cultivation, puddled rice culture occupies 24 m ha; about 56% of the area[5].This involves ploughing the soil when wet, puddling it and keeping the area flooded for the duration of the rice crop. Wetland rice culture thus destroys soil structure and creates a poor physical condition for the following wheat crop. This soil condition can reduce wheat yield[20]presumably by limiting root growth and distribution[128]. For regeneration and maintenance of soil structure within this cropping system, plant residue is very important[189], but for various reasons, the amount of residue being returned to the soil is not adequate. Rice grown with conservation tillage can produce yields similar to that under conventional puddling with minimized expenses on field preparations[161]. Besides declining soil fertility, low wheat yields in rice wheat cropping system are also obtained due to a short turnover period between rice harvest and delayed wheat sowing due to a number of factors, including delayed rice transplanting resulting in delayed rice harvest, high soil moisture content after the rice harvest, delay in removal of rice straw (a large part of it is being burned *in situ*, which besides the loss of precious organic C creates environmental and health problems), etc.

Sustainability is generally related to soil quality, which is defined as, ‘‘the capacity of a specific kind of soil to function, within natural or managed boundaries, to sustain plant and animal productivity, maintain or enhance air and water quality and support human health and habitation[82]’’.The soil’s ability to function as a component of an ecosystem may be degraded, aggraded or sustained as use-dependent properties change in response to land use and management. Therefore,to achieve sustainable higher productivity, efforts must be focused on reversing the trend in natural resource degradation by adopting efficient resource conservation technologies. One of these RCT’s is Conservation tillage. Conservation tillage practices generally result in higher amounts of soil organic matter (OM), reduced erosion, increased infiltration, increased water stable aggregates and greater microbial biomass carbon when compared to conventional tillage systems[146].

Laser Land Leveling

Laser land leveling is another water-saving technology, usually appropriate for regions with uneven fields where a considerable amount of irrigation water is lost due to extensive application of flooding method of irrigation. Unevenness of fields reduces input-use efficiency and creates larger biotic and abiotic pressures on crop growth, which ultimately reduce yield potential and add to the cost of production. Laser land leveling (LLL) was first introduced in India in 2001 in western Uttar Pradesh. Several field studies conducted in the Indo-Gangetic Plains, where flooding is a common method of irrigation, have brought out that laser leveling technology could save irrigation water by 10-30 per cent, improve fertilizer-use efficiency by 6-7 per cent and enhance crop yield by 3-19 per cent, besides expanding cropped area by 3-6 per cent[75,81,121,164]. A series of studies on LLL in rice-wheat systems of the IGP have found 10-30% irrigation water savings,3-6% effective increase in farming area, 6-7% increase in fertilizer use efficiency, and 3-19% increase in yield[73]. A reduction of 75 % in labour requirement for weeding was reported due to LLL. There is a strong correlation between the levelness of the land and crop yield. Considerable increase in yield of crops is also possible due to LLL[152]. It was concluded that the laser land leveling saves farm inputs like water and fertilizers, improves crop stand and encourages uniform germination[37].

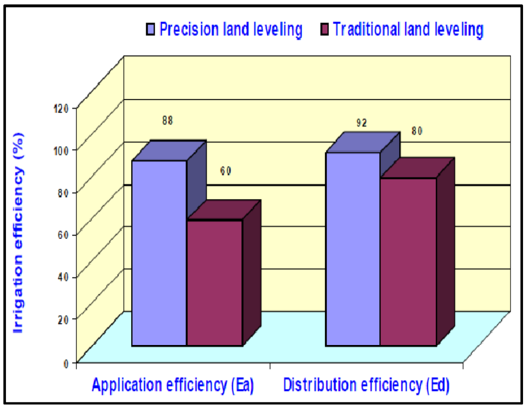


Fig.1: Effect of land leveling on irrigation efficiency in wheat[140]

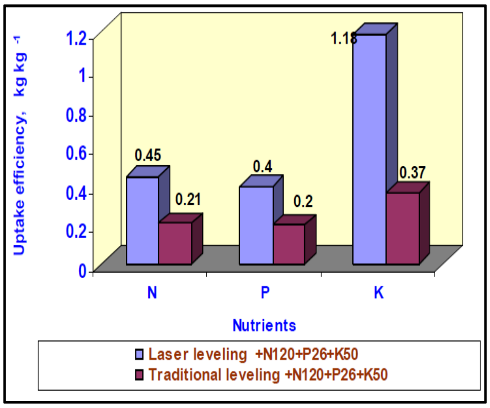
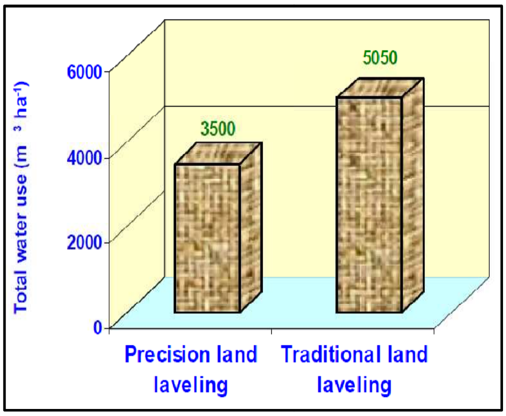
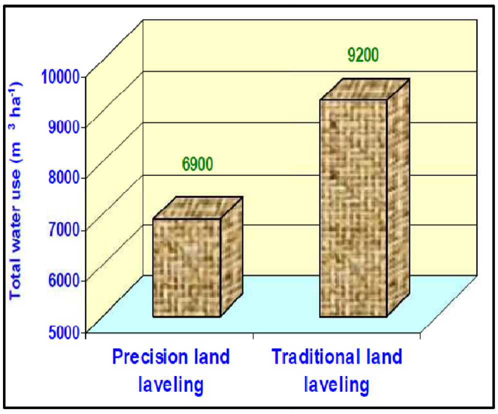


Fig.2: Effect of precision land leveling on uptake efficiency of N,P and K in rice[129]



Wheat

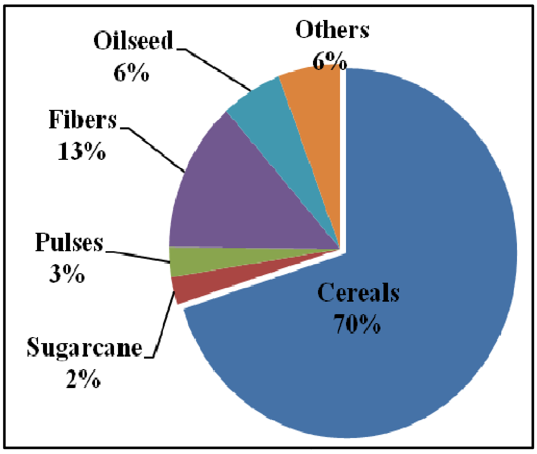


Rice

Fig.3: Total Water Use (m^3 ha^{-1}) in Wheat and Rice

Zero or Reduced Tillage

Zero tillage, also known as zero till, no till, direct seeding and direct drilling, has been reported as one of the most successful resource conservation technologies in the Indo-Gangetic Plains[39]. In 2003-04, a total of 820 thousand hectares of wheat area was tilled using this technology. Most of it, however, was confined to Haryana (46 per cent), Punjab (26 per cent) and western Uttar Pradesh (21 per cent).Adoption of zero/reduced tillage has started picking up in eastern Uttar Pradesh and Bihar. Zero tillage generates substantial environmental and economic benefits around 80 per cent saving in tractor-time, 60-80 per cent in fuel consumption and 20-35 per cent in irrigation water[38].Other benefits of zero tillage include improvements in soil organic carbon content and reduction in weed pressure. In regions where sowing of wheat is delayed due to late planting of rice, its yield is affected due to terminal drought. Zero tillage enables timely sowing of wheat on residual moisture after rice harvest and helps wheat crop escape terminal drought. Yield or income gains due to zero tillage are quite reasonable. It improves wheat yield by 15.4 per cent (9.4 per cent due to timeliness in sowing and 6.0 per cent due to improved input-use efficiency)[118]. Lack of access to information about technology, high initial capital investment on machinery and equipment and dominance of smallholdings are important constraints to the adoption of zero tillage.



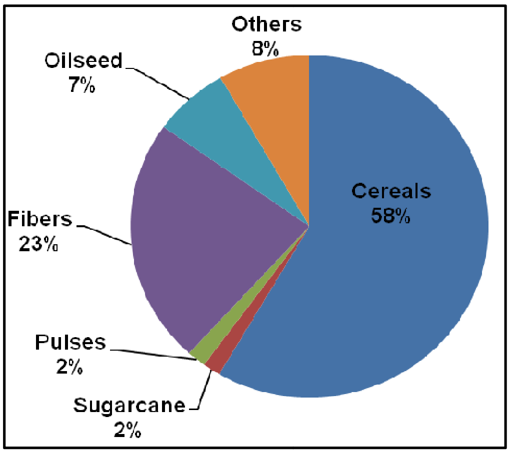


Fig.4: Contribution of various crops in residue generation **Fig.5:** Surplus of various crop residues in India in India

(Calculated from MNRE report 2009).

Experimental data have shown that water saving with zero tillage (ZT) in wheat could be 36 percent, on an average. Reduction of water use in first irrigation varied from 30-50 percent while for subsequent irrigations it ranged between 15-20 percent. Water use could be further reduced if ZT is used in combination with other technologies like raised bed planting and laser land leveling[63,122]. The results of adoption of resource conservation interventions (RCIs) for rice-wheat system (RWS) showed that there is significant reduction in the cost of production of wheat[38,188].

Trapping of CO_2: Reduction of CO_2 concentration in atmosphere

Biomass can be efficiently utilized as a source of energy and is of interest worldwide because of its environmental advantages. During recent years, there has been an increase in the usage of crop residue for energy production and as substitute for fossil fuels. It also offers an immediate solution for the reduction of CO_2 content in the atmosphere. Mitigation of CO_2 emission from agriculture can be achieved by increasing carbon sequestration in soil through manipulation of soil moisture and temperature, setting aside surplus agricultural land, and restoration of soil carbon on degraded lands. Soil management practices such as reduced tillage, manuring, residue incorporation, improving soil biodiversity, micro aggregation, and mulching can play important roles in sequestering carbon in soil. Some technologies such as intermittent drying,site-specific N management, etc. can be easily adopted by the farmers without additional investment, whereas other technologies need economic incentives and policy support[195].

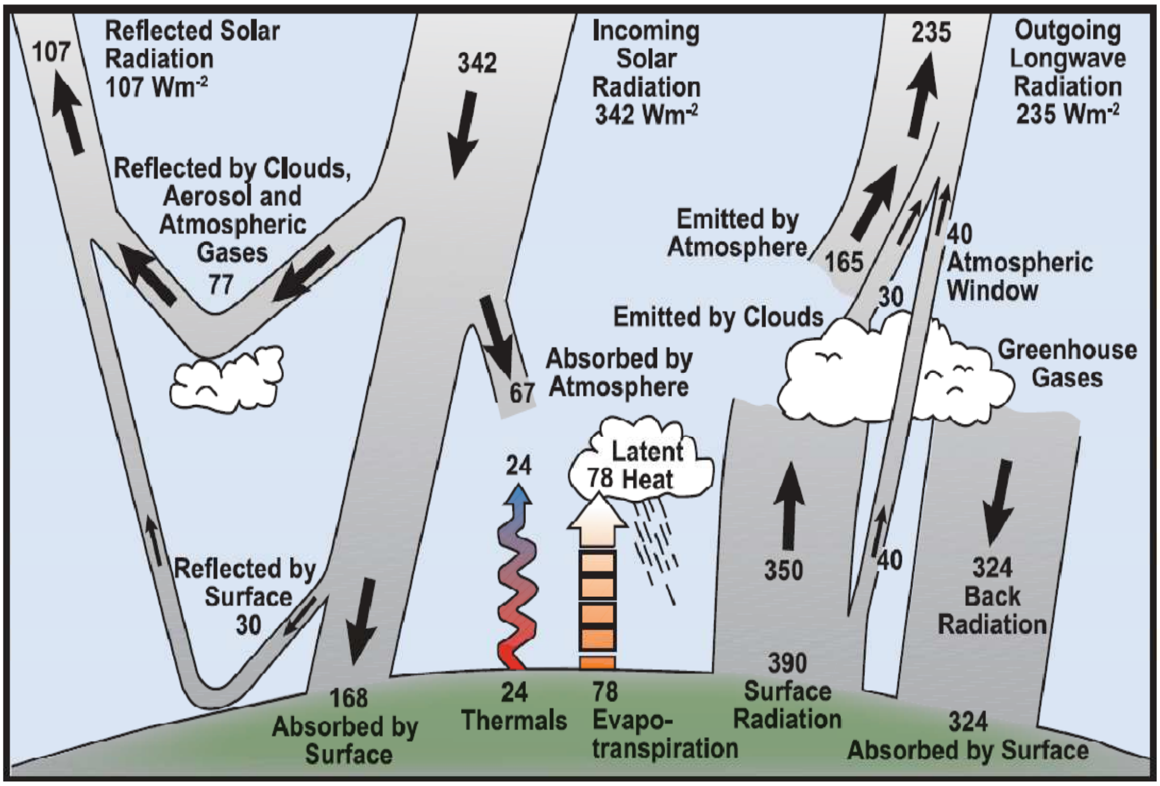


Fig. 6: Estimate of the Earth's annual and global mean energy balance.

Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing long wave radiation. About half of the incoming solar radiation is absorbed by the Earth's surface. This energy is transferred to the atmosphere by warming the air in contact with the surface (thermals), by evapo-transpiration and by long wave radiation that is absorbed by clouds and greenhouse gases. The atmosphere in turn radiates long wave energy back to Earth as well as out to space.

The retention of crop residues on the soil surface normally associated with conservation agriculture-based no-till system has an important influence on soil water storage[25,106]. Four-year average net economic returns for wheat grown in the zero tillage system increased about 30% as compared with the traditional tillage system. It also resulted in higher yields and lower production costs. Experimentation is underway to further enhance incorporation of paddy residue through use of improved ZT drill with disk furrow opener. In this method entire paddy straw can be left on surface and wheat can be sown under ZT. This has several added advantages. Firstly, the covered land surface reduces evaporation losses and therefore maintains soil moisture and temperature which are conducive for plant growth. Secondly, mulching effect suppresses weed growth (about 40 percent less weed growth) and increases plant population. Also there is saving of weedicide, resulting in additional economic and environmental benefits. Finally, farmers may not burn paddy straw for sowing of wheat, as done under conventional technique (CT) and therefore significant environmental benefits are added[63].

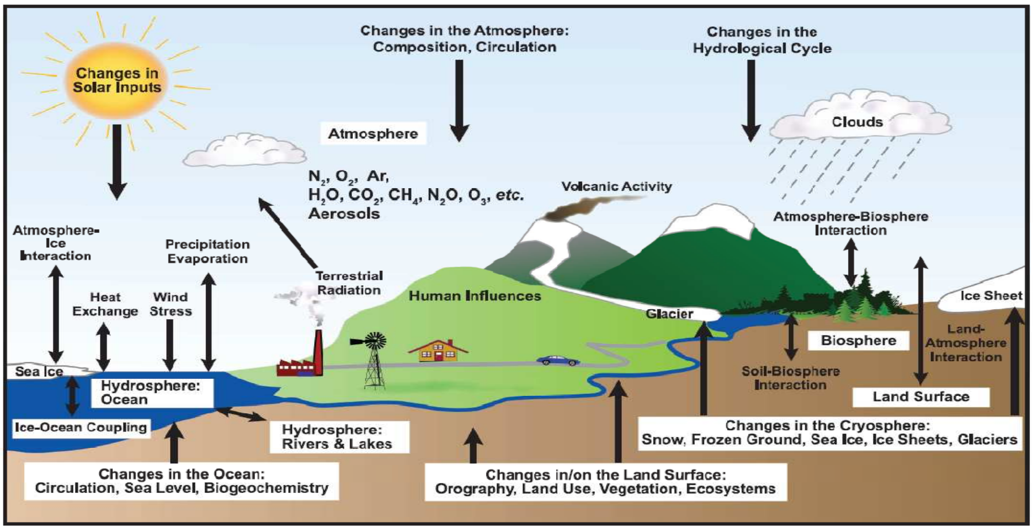


Fig.7: Schematic view of the components of the climate system, their processes and interactions.

Soil and crop management can greatly improve the residence time and new C storage in soil, which is worthy of consideration under the Kyoto Protocol[24]. Different land uses and agronomic practices were evaluated with respect to their effect on carbon sequestration or release[7].A distinction is made between practices causing a decrease of carbon loss, an increase in carbon input into the soil, or a combination of both. Naresh *et al*[123]., reported that incorporation of crop residues in soil or retention on surface has several positive influences on physical, chemical and biological properties of soil. It increases hydraulic conductivity and reduce bulk density of soil by modifying soil structure and aggregate stability. Mulching with plant residues raises the minimum soil temperature in winter due to reduction in upward heat flux from soil and decreases soil temperature during summer due to shading effect. Retention of crop residues on soil surface slows runoff by acting as tiny dams, reduces surface crust formation and enhances infiltration. The channels (macropores) created by earthworms and old plant roots, when left intact with no-till, improve infiltration to help reduce or eliminate runoff. Combined with reduced water evaporation from the top few inches of soil and with improved soil characteristics, higher level of soil moisture can contribute to higher crop yield in many cropping and climatic situations. Rasmussen and Collins[143] found that retaining crop residues on the soil surface, rather than burning them or incorporating them by tillage, increases organic carbon and total soil nitrogen in the top 5-15 cm of soil. This higher level of carbon and nitrogen in the surface layers was attributed to slower residue decomposition, slower oxidation of soil carbon, and less erosion. Many farmers dispose of residues by burning, especially in fields that are combining harvested. Burning can result in up to 80% loss of tissue nitrogen by volatilization[139] and can also be a significant source of air pollution.

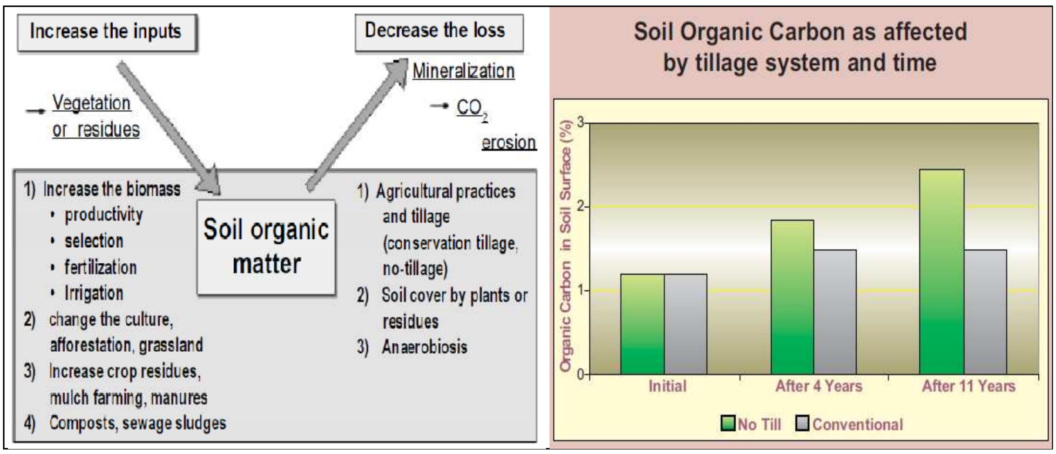


Fig.8: Management of soil organic matter in agriculture **Source:** Bessam, F and R.Mrabet[12]

Crop residue left on soil surface led to an increase in soil organic carbon (SOC) from 5.62 to 7.21 t/ha in 0-25 mm under no-tillage after 4 and 11 years (experimental field, at Sidi El Aidi, Morocco). At the same horizen, SOC did not change under conventional tillage after the same periods. The results revealed that no-tillage soil had sequestered 3.5 and 3.4 t/ha of SOC more than the conventional tillage after 4 and 11 years. The figure 8 illustrates that over 11 years the horizon gained 13.6% and 3.3% of its original SOC under no-till and conventional tillage respectively.

In reduced- or zero-tillage systems, soil fauna resume their bioturbating activities gradually. These loosen the soil and mix the soil components (also known as biotillage). The additional benefit of the increased soil organic matter and burrowing is the creation of a stable and porous soil structure without expensive, time-consuming and potentially degrading cultivations[135]. Ferreira *et al*[47]., reported that zero-tillage systems, the action of soil macro-fauna gradually incorporate cover crop and weed residues from the soil surface down into the soil. The activity of micro-organisms is also regulated by the activity of the macro-fauna, which provide them with food and air through their burrows. In this way, nutrients are released slowly and can provide the following crop with nutrients. Hungria *et al*[71]., 1997 indicates a 200–300-percent increase in population size of root nodule bacteria in a zero-tillage system compared with conventional tillage.

Aerobic rice system to improve water productivity

Aerobic rice is a new way of production system in which specially developed, input-response rice varieties with aerobic adaptation are grown in well-drained, non-puddled, and non-saturated soils without ponded water[104]. It entails growing rice in aerobic soil, with the use of external inputs such as supplementary irrigation and fertilizers, and aiming at high yields[18]. Main driving force behind aerobic rice is the economic water use. A fundamental approach to reduce water inputs in rice is growing like an irrigated upland crop, such as wheat or maize. Instead of trying to reduce water input in lowland paddy fields, the concept of having the field flooded or saturated is abandoned altogether[18]. Case studies showed yields to vary from 4.5 to 6.5 t ha^{-1}, which is about double than that of traditional upland varieties and about 20–30% lower than that of lowland varieties grown under flooded conditions. However, the water use was about 60% less than that of lowland rice, total water productivity 1.6–1.9 times higher, and net returns to water use was twofold higher. Aerobic rice requires lesser labor than lowland rice and can be highly mechanized[62]. Input water savings of 35–57% have been reported for dry seeded rice (DSR) sown into non puddled soil with the soil kept near saturation or field capacity compared with continuously flooded (5cm) transplanted rice[19].However,yields were reduced by similar amounts due to iron or zinc deficiency and increased incidence of nematodes. Contrary to the results of small plot replicated experiments, participatory trials in farmers‘ fields in India and Pakistan suggest a small increase or 10% decline in yield of DSR on the flat compared with puddled transplanted rice, and around 20% reduction in irrigation time or water use[200].

Aerobic rice maximizes water use in terms of yield and is a suitable crop for water-limiting conditions[200]. In a study, rice yields under aerobic conditions were 2.4–4.4 t ha^{-1}, which were 14–40% lower than under flooded conditions[28]. However, water use decreased relatively more than yield, and water productivity under aerobic cultivation increased by 20–40%. The aerobic rice technology eliminates puddling and flooding, and presents an alternative system in reducing water use and increase water productivity. Aerobic rice saved 73% of irrigation water for land preparation and 56% during the crop growth period[28]. In a two year field experiment at Indo-Gangetic plains to evaluate various tillage and crop establishment systems for their efficiency in labor, water and energy use, and economic profitability, the yields of rice in the conventional puddled transplanting and direct-seeding on puddled or non-puddled (no-tillage) flatbed systems were equal[15,123]. Nevertheless, decline in yield was observed when aerobic rice was continuously grown and the decline was greater in the dry than in the wet season[134].

Fig.9: Cultivation shift from puddled to aerobic rice production system

Furrow irrigated raised beds (FIRB)

The latest performance appraisal studies in term of water application have recognized that laser land leveling, zero tillage and bed-furrow interventions can be prosperous in ameliorating field level efficiency and irrigation water saving[61,69,123]. The RCTs interventions lead to augmentation of wheat yield and reducing its production cost[79].The water productivity of wheat is highest under bed furrow intervention whereas flat basin irrigation technique has the lowest yield and maximum water consumption. The water saved by bed-furrow intervention, can be used to enhance the cropping intensity and leaching salts. Based on the water productivity, the bed-furrow intervention is the best effective surface water use intervention[123]. Bed-furrow planting of wheat has special role in North Western India. In the low-lying areas having poor drainage, the bed-furrow planting intervention is more favorable than the zero tillage[122]. In the recent years, planting of wheat on raised bed is being advocated in South Asia for improving resource use efficiencies i.e., water use efficiency (WUE). Significant increase in WUE on laser level fields has been reported by several researchers under different soil and climatic conditions[62,74,121]. A raised bed-planting technology for wheat-based cropping systems was developed in Mexico. In raised bed-planting the wheat rows are planted on the top of beds with furrow irrigation between the beds. It overcomes some of the disadvantages of flood irrigation such as low potential irrigation water use efficiency, inefficient use of fertilizer and crusting of the soil surface[193]. The cumulative effects of the various advantages resulted in improved wheat quality and increase wheat yield by more than 10%[192].

Wheat on Raised Beds

There are many anecdotal reports of large irrigation water savings for wheat on beds in comparison with conventional tillage in farmers' fields. The few published data show reduced irrigation time of around 50% and slightly higher yields (mean 5%) on the beds[141]. It is likely that most of these reports from farmers' fields are for fresh beds. Replicated experiments in small plots also generally show reduced irrigation amounts (but smaller than those suggested in the farmer fields above) and similar or higher yields of wheat on permanent beds compared with conventional tillage[15,102,123,177]. However, Kukal *et al*[89]., found similar irrigation amounts on permanent beds and conventionally tilled wheat irrigated using the same irrigation scheduling rules based on cumulative pan evaporation. Yields on the permanent beds and in conventionally tilled wheat were similar on the loam, but tended to be lower on the beds on the sandy loam, possibly due to water deficit stress. On a marginally sodic silt loam at Modipuram, Sharma *et al*[162]., also found lower yields on the permanent beds which were associated with increased accumulation of salts on the beds. The decline in yield was greater than the decline in irrigation amount, leading to significantly lower WPI. The lower yields (and WPET) of Choudhury *et al*[30]., on permanent beds were possibly due to inability of the crop on beds to compensate for the wide row spacing as a result of late planting.

There have been few studies to quantify the causes of the irrigation water savings for wheat on beds. In the comparison of zero till wheat on permanent beds with conventionally tilled wheat on sandy loam and loam soils at Delhi, irrigation water use was lower on the beds due to lower ET which was probably due to poorer crop growth, and also due to less deep drainage in one of the 2 years of this experiment[30]. It is likely that soil evaporation from beds is higher than from flats during the first part of the season, from the time the soil is bare until the crop has developed significant amount of leaf area. This is because the formation of beds increases the soil surface area – by about 50% in the case of the narrow beds (30 cm bed top, 37.5 cm furrow width, and 15 cm furrow depth) commonly used in NW India. Humphreys *et al*[70]., showed that the beds (at 10 and 20 cm) dried more rapidly that than the flat plots after sowing on sandy loam and loam soils, more so on the sandy loam.

Conservation Agriculture and Soil Characteristics

Conservation Agriculture reduces or eliminates soil tillage, maintaining soil covered by vegetation or crop residues. This protects the soil from impact of raindrops and increases infiltration, naturally improves the soil structure and fertility, reduces pollution of surface water, promotes carbon sequestration in the soil, and decreases the emission of carbon dioxide. Particularly, Conservation Agriculture greatly reduces soil erosion - over 90% with no-tillage and over 60% with minimum tillage. This ensures good quality ground and surface water bodies due to reduced sediment load, surface runoff, and the consequent reduced off-site transport of pesticides and nutrients. Soil quality can be seen as a conceptual translation of the sustainability concept towards soil. Karlen *et al*[82]., defined soil quality 'the capacity of a specific kind of soil to function, within natural managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation'. Conservation agriculture is claimed to reduce negative impacts of climate change by optimising crop yields and profits while maintaining a balance between agricultural, economic and environmental benefits[53]. Pasricha[133] revealed that improved soil and crop management practices that reduce tillage intensity and increase amount of plant residue to return to the soil are needed to increase soil organic matter (SOM) and sustainability of a cropping system. The turning of crop residue C and N into mineral forms ($CO_2$and NH4+/NO_3-) or stabilization into humic substances is determined in part by tillage practices. Conventional tillage (CT) disturbs the soil and may result in the oxidation of crop residue C and N into mineral forms while no-till (NT) practice helps in stabilization of these C and N contents into humic substances. Reduced tillage can alter soil moisture and temperature, that both in turn regulate soil respiration. A common observation is that N supplying potential of soil increases after NT practices have been adopted for a few growing seasons, as does the closely related content of active N. It is especially important to understand how tillage management, that can greatly influence soil NO_3 levels, affects soil N mineralization (N source) and N use by crop (N-sink).

Table 1: Example of an interpretation framework for soil health indicators under agricultural land uses

Indicator	Ranking		
	Low	Medium	High
Total organic matter content (organic C %×1.7)	poor pore structure, hard workability (<1.7%)	friable, but poor workability (1.7-2.6%)	extremely friable and easy workability (> 2.6%)
Light fraction organic matter	noticeable fine root fragments and weed seeds	mixtures of root and leaf litter fragments	dominated by large leaf litter fragments.
Organomineral fraction organic matter	deep red red with discolored brown flakes of clay particles	deep red with consistent brown colored clay particles	near pitch-dark organic with mixtures of consistent red mineral flakes
Soil pH	high acid < 5.5	medium acid to neutral 5.5 to 7.0	neutral to basic 7.0 to 8.0
Soil cation exchange capacity	< 10 $mmol_c$ kg^{-1}	10 to 20 $mmol_c$ kg^{-1}	> 20 $mmol_c$ kg^{-1}
Soil aggregate stability	water stable aggregation of 50-60% indicates weak structure highly erodible	water stable aggregation of 60-80% indicates stable structure but still susceptible to erosion	water stable aggregation of >80% indicates highly stable structure and little susceptibility to erosion

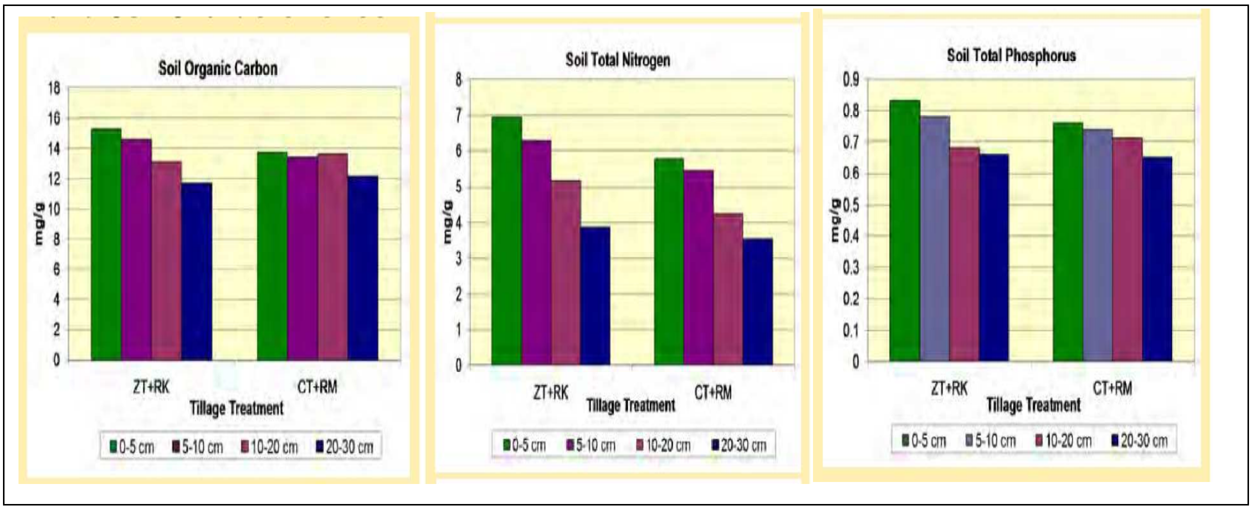


Fig.10: Effect of zero tillage with crop residue conventional tillage with crop residue removed on soil organic carbon, Soil total Nitrogen and Soil total Phosphorus.

Source: Wen Qing *et al*[197].

Wen Qing *et al.*, 2008 compared conventional tillage (with crop residue removed; CT+RM) and zero tillage (with crop residue maintained on the soil surface; ZT+RK), Figure 10. Results showed that over a period of 4 years ZT+RK resulted in increasing soil organic carbon (SOC) content by around 10% in the 0-5 and 5-10 cm layers. Similarly, Soil total Nitrogen (STN) increased by about 18.9% in the 0-5 cm layer and 7.4% in 5-10 cm. While Soil total Phosphorus (STP) was 8.6% higher than under CT in the 0–5 cm layer. ZT+RK thus resulted in improved soil characteristics.

Table 2: Effect of planting method on soil properties, grain yield, water use and water use efficiency (WUE) of wheat on a sandy loam at Delhi.

Planting method	Bulk density (0–10 cm (mg m^{-3})	Infiltration rate (cm h^{-1})	Weed density at 90 DAS (no. m^{-2})	Grain yield (t ha^{-1})	Water applied (cm)	WUE (kg grain $ha^{-1}cm^{-1}$)
Raised bed–3 rows/ bed	1.35	0.83	65	5.31	21.4	186
Conventional sowing	1.42	0.62	793	5.09	24.9	157
LSD (0.05)	0.05	NS	270	0.37	-	27

Source: Aggarwal & Goswami[2]

I. Soil moisture content

Zero tillage achieved a 28% increase in plant available soil water at sowing as compared to conventional tillage and an associated increase of 1.2 t/ha/year wheat grain[116]. More plant residues were left on or near the soil surface no tillage which led to lower evapotranspiration and higher content of soil water in the upper (0-10cm) soil layer[144]. The plant available water content was significantly higher with zero than conventional tillage in rice-wheat cropping system[13,14]. Surface residues maintained under zero tillage system moderate moisture fluctuations and thus reduce both evaporation and runoff[16]. However, different types and extent of tillage did not have any major influence on the moisture content at harvest, although it was high at the time of initial tillage and reduced with subsequent tillage operations[172]. It has been well established that increasing amounts of crop residues on the soil surface reduce the evaporation rate[52,137]. Residue mulch or partial incorporation in soil by conservation tillage has also been shown to increase the infiltration by reducing surface sealing and decreasing runoff velocity[21].

Reduced or minimum tillage is highly effective practice in soil and water conservation when compared with conventional tillage systems. Improved infiltration and reduced evaporation caused more water conservation[184]. Radford *et al*[138]., reported 28% more plant available water at sowing under zero tillage (ZT) system. Conservation tillage practices lead to beneficial changes in soil physical properties *e.g.* soil water content[119] and aggregate stability and soil aggregation[117]. Norwood[126] related tillage system with water availability especially in years receiving low rainfall. This increased soil water availability may be attributed to the crop residues on the surface soil that reduced evaporation losses[120]. Lopez *et al.*, concluded no-tillage is an ineffective practice to improve soil water content. This is due to the fact that soil response to tillage is highly likely on long term basis. It is, therefore necessary to conduct tillage studies under different soil, cropping and climatic conditions. Pore-size distribution and soil organic matter (SOM) content in untilled than tilled soils may cause improved plant available soil water content and higher yields[11].

Sharma *et al.*,[163] showed that the no tillage retained the highest moisture followed by minimum tillage, raised bed and conventional tillage in inceptisols under semi-arid regions of India. Tillage treatments influenced the water intake and infiltration rate (IR) increased in the order of NT > MT > RB > CT and in mulching treatment the order was PM >STM > SM > NM. The maximum mean value of IR (182.4 mm/day) was obtained in case of no tillage and polythene mulch combination and minimum (122.4 mm/day) was recorded in CT and no mulch combination. Several researchers also show the importance of tillage on soil moisture[125]. Tillage enhances soil water storage by increasing soil surface roughness and controlling weeds during a fallow. This stored water may improve subsequent crop production by supplementing growing season precipitation[186].

II. Soil bulk density

The soil bulk density is the dry soil mass per unit bulk volume. Bulk density varies with soil structural conditions, especially related to soil packing. Soil compaction is well known to increase soil bulk density[29]. An ideal soil should contain about 50% solid particles and 50% pore space[136] with bulk density of 1.3 Mg m^{-3}. A bulk density greater than 1.2 Mg m^{-3} (clayey soil), 1.6 Mg m^{-3} (loam soil) and 1.8 Mg m^{-3} (sandy loam soil) may adversely affect the paddy root growth[80]. Grossman and Berdainer[59] proposed root limiting bulk densities of 1.47 Mg m^{-3} for clayey and 1.85 Mg m^{-3} for sandy soils to most of the feed and fiber crops of temperate regions. Stranak[174] concluded that optimal soil density for winter wheat is 1.46–1.54 Mg m^{-3}.The soil bulk density is a decisive factor in cereal production, mainly from germination to tillering. Un-plowed soils may provide more favorable environment conditions for plant growth confirmed for winter wheat. He also suggested that solving the problems of weeds etc. under minimum soil disturbance may yield more grains. Tillage increases the total soil porosity by increasing the pore size distribution and pores[105]. But, reduced tillage operations with elimination of plowing may decrease soil bulk density due to less soil compaction[111].The effect of tillage and residue management on soil bulk density is mainly confined to the topsoil (plough layer). In deeper soil layers, soil bulk density is generally similar in zero and conventional tillage[31,179]. A plough pan may be formed by tillage immediately underneath the tilled soil, causing higher bulk density in this horizon in tilled situations[35].

The two of the most commonly measured soil physical properties affecting hydraulic conductivity are the soil bulk density and effective porosity as these two properties are also fundamental to soil compaction and related agricultural management issues[176]. The studies comparing no-tillage with conventional tillage systems have given different results for soil bulk density. Several studies showed that soil bulk density was greater in no-till in the 5 to 10 cm soil depth. No differences in bulk density were found between tillage systems[107]. However Tripathi *et al.,*[181] found increase in bulk density with conventional tillage in a silty loam soil. Moreover, there are few studies that have examined changes in soil physical properties in response to long term tillage and frequency management (> 20 yr) in the northern Great Plains. The bulk density did varied significantly due to planting techniques and it was significantly reduced under raised bed planting compared to flat sowing. This was attributed mainly due to more pore spaces created in the beds through modified land configuration by accumulations the topsoil. Bed planting provides natural opportunity to reduce compaction by confining traffic to the furrow bottoms[54]. Gál *et al.,*[48] observed higher bulk density in the 0-30 cm layer under zero than under conventional tillage on a silty clay loam in Indiana after 28 years, but no difference in the 30-100 cm layer. In a side-by-side. Rashidi and Keshavarzpour[142] observed that the highest soil bulk density of 1.52 g cm^{-3} was obtained for the NT treatment and lowest (1.41 g cm^{-3}) for the CT treatment. The highest soil penetration resistance of 1250 kPa was obtained for the NT treatment and lowest (560 kPa) for the CT treatment. Jat *et al.,*[74] reported that tillage and crop establishment methods (TCE) methods had a significant effect on bulk density of soil at all the profile depths after two rice-wheat crop cycles. ZTDSR-ZTW had significantly higher bulk density in the 0–5 and 5–10-cm soil profile than with other tillage systems, whereas it was higher under conventional-tillage (PTR-CTW and CTDSR-CTW) in the 10–15 and 15–20-cm soil layers compared with ZTDSR-ZTW and BDSR-PBW treatments. Naresh *et al.,*[123] reported that tillage significantly affected the soil significant variations after three crop cycles the soil physical properties in Bulk density, Water Stable aggregates, Aggregate porosity, Clod breaking Strength and organic carbon were recorded due to different treatments. The bulk density did not varied significantly due to land leveling however, planting techniques had significant influence and it was significantly reduced under raised bed planting compared to flat sowing irrespective of the land leveling practice. This was attributed mainly due to more pore spaces created in the beds through modified land configuration by accumulations the topsoil.

III. Soil porosity

Soil porosity characteristics are closely related to soil physical behavior, root penetration and water movement[130,156] and differ among tillage systems[9]. Lal *et al.,*[92] revealed that straw returning could increase the total porosity of soil while minimal and no tillage would decrease the soil porosity for aeration, but increase the capillary porosity; as a result, it enhances the water capacity of soil along with poor aeration of soil[51,190]. However, Borresen[22] found that the effects of tillage and straw treatments on the total porosity and porosity size distribution were not significant. Allen *et al.,*[3] indicated that minimal tillage could increase the quantity of big porosity. Tangyuan, *et al.,*[178] showed that the soil total porosity of 0–10 soil layer was mostly affected; conventional tillage can increase the capillary porosity of soil and the porosities were C > H > S but the non-capillary porosity of (S) was the highest. Returning of straw can increase the porosity of soil. The increase in plant available water capacity of the soil under different tillage treatments was found to decrease with an increase in the level of compaction. Because compaction results in the breaking down of larger soil particle aggregates to smaller ones, it is difficult for water to drain out of the soils because of the greater force of adhesion between the micropores and soil water. For the same tillage treatment, the effect of increasing the axle load upon a soil is to decrease the total porosity and to increase the percentage of smaller pores as some of the originally larger pores have been squeezed into smaller ones by compaction[65]. Tillage is often referred to as a physical modification of soil properties. It either loosens or compacts the soil, thus changing particle-to-particle contact and porosity of soil. One property that is always changed by tillage is the bulk density. A decrease in bulk density affects an increase in total porosity and large pores. Compaction has a reverse effect. A change in porosity and particle-to-particle contact affects all the (physical) state variables of soil that in turn modify the edaphic parameters[49].

IV. Penetration Resistance

Soil compaction is assessed through penetrability measurements. Bradford[23]defined soil penetrability as measure of the ease with which an object may be driven or pushed into the soil. This soil property may help in measuring root growth inhibition due to soil compaction. The greater the soil bulk density, the lower will be the soil porosity for air, water and biological activity. Soil compaction is a major concern for agricultural systems nowadays and the compaction caused by different implements or trafficking (cattle, tractor tires, harvesting and tillage equipments) is a great challenge[95]. The traffic from different farm implements or animal trampling may cause destruction of soil pores and increasing the soil resistance to penetration[45]. The greater the compaction, the more adverse effects are observed on seedling establishment, root development and crop yield. It also affects certain soil properties such as aggregate stability, erosion and water infiltration[95]. Soil properties like particle size distribution, organic matter (OM) content and moisture content affect soil compaction and strength. Soils with more clay than sand tend to show more cohesion and strength[95]. Soil compaction may be managed by minimizing traffic effect. Traffic control is the most feasible and economic viable. The traffic may be restricted to certain field areas or when field is dry[45]. The compaction effects can be alleviated by sub-soiling, deep plowing and chiseling, but these methods are temporary because the soil settles back into place[72].

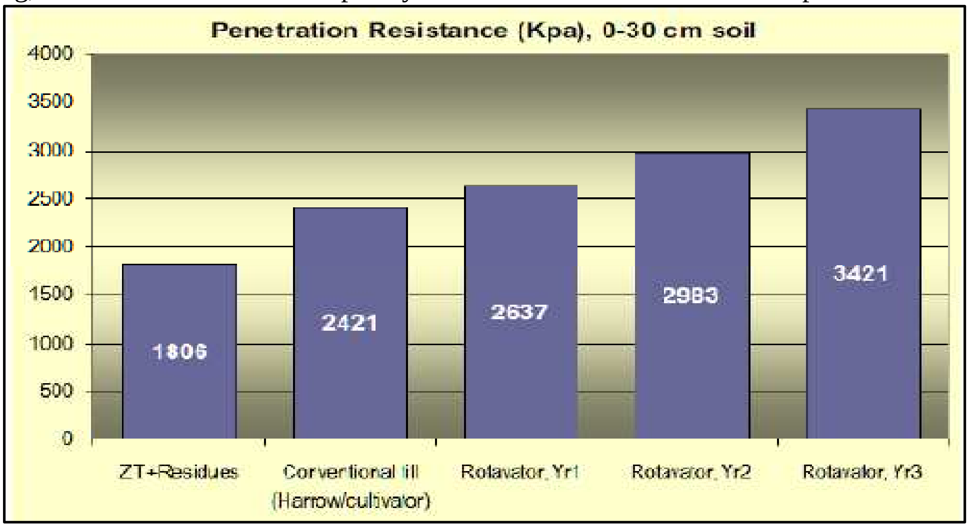


Fig.11: Effect of tillage practices in penetration resistance

Source: Gupta *et al*[64].,

Governments in South Asia are promoting rotavator as a multi-operation easy tool. The Rotavator requires clean fields for tillage and hence promotes burning of residue of the previous crop and seeding by broadcasting. It has been observed that rotavator compacts the soils below 15-cm which causes temporary water logging after an irrigation or rainfall event. Soil compaction impedes root penetration to subsurface soil that results in crop lodging (Figure 11). Thus, farmers who use rotavator generally skip last irrigation that ultimately leads to lower productivity in situations of terminal heat stress.

The comparison of soil bulk density and penetration resistance between NT, RT and CT revealed that soil bulk density increased with increasing depth for all tillage systems and soil penetration resistance was greater under RT and NT than CT[67]. The soil strength was greater in conservation methods but no hindrance to root growth was observed. Moreno *et al*[119].,reported higher penetration resistance in conservation tillage than conventional tillage systems. Wilkens *et al*[198]., reported similar results for NT and CT on a silt loam soil. It was also noted that the conversion from a tilled to NT cropping system caused an increase in soil strength significantly. Naresh *et al*[123]., reported in the higher penetration resistance under intensive conventional-tillage is associated with increased bulk density and shallow hard pans in subsurface layers that reduce the root growth of crop. With each centimeter reduction in rooting depth, recorded a 0.4% reduction in crop yield. The steady-state infiltration rate was also influenced by various crop establishment methods. The infiltration rate was greater under direct seeded rice on permanent wide raised beds (WBed-DSR) than with CT-TPR, which was similar to that with ZT-DSR and CT-DSR. Permanent beds (WBed-DSR) and (ZT-DSR) had significantly higher soil aggregates (>0.25mm) than conventional- tillage (CT-TPR). Further, under conventional-tillage, soil aggregation was static across the seasons, whereas it improved over time under no-till and permanent beds. Puddling destroys soil aggregates, breaks capillary pores, reduces permeability in sub-surface layers and forms hard pans that have a negative effect on the succeeding crops.

V. Soil Temperature

Tillage creates soil temperature optimum for seed germination and seedling establishment. Tillage loosens the soil surface, resulting in decrease of thermal conductivity and heat capacity. Changes in surface roughness and plant residue cover affected by tillage influence the thermal regime of soil. Change in bulk density alters the specific heat capacity of the soil, primarily by changing the relative amounts of mineral matter and water per unit volume of soil. Reduced particle-to-particle contact and volume water content of soil accompanying decreased bulk density lowers the thermal conductivity of the soil. Also, tillage systems that leave most of the residue on the soil surface result in lower soil temperatures Naresh *et al.,*[121]. Green and Lafond[58] reported the heat advantage of tillage and residue management and highlighted that surface residues with no-till system helped in regulating the soil temperature and they noticed that the soil temperature (5cm soil depth) with residue removal and conventional till was 0.29^0C lower during the winter than that of no-till and surface retained residues whereas the soil temperature during summer was 0.89^0C higher under conventional till than no-till surface retained residue situation. Soil temperatures in surface layers can be significantly lower (often between 2 and 8°C) during daytime (in summer) in zero tilled soils with residue retention compared to conventional tillage[127]. In these same studies, during night the insulation effect of the residues led to higher temperatures so there was lower amplitude of soil temperature variation with zero tillage. Dahiya *et al.*,[32] compared the thermal regime of a loess soil during two weeks after wheat harvest between a treatment with wheat straw mulching, one with rotary hoeing and a control with no mulching and no rotary hoeing. Compared to the control, mulching reduced average soil temperatures by 0.74, 0.66, 0.58°C at 5, 15, and 30 cm depth respectively, during the study period. The rotary hoeing tillage slightly increased the average soil temperature by 0.21°C at 5 cm depth compared to the control. The tillage effect did not transmit to deeper depths. Gupta *et al.*[60], also found that the difference between zero tillage with and without residue cover was larger than the difference between conventional tillage (mouldboard ploughing) and zero tillage with residue retention. Both mouldboard ploughing and zero tillage without residue cover had a higher soil temperature than zero tillage with residue cover, but the difference between mouldboard ploughing and zero tillage with residue cover was approximately one-third the difference between zero tillage with and without residue.

In tropical hot soils, mulch cover reduces soil peak temperatures that are too high for optimum growth and development to an appropriate level, favouring biological activity, initial crop growth and root development during the growing season[127]. The soil surface heat flux and soil temperature in the zero tillage practice with a 30 cm residue-free strip were not different from a conventional tillage system and significantly higher than in zero tillage without residue-free strip. The 30 cm residue-free strip did not have a negative impact on soil water content of the top 5 cm layer (depth), where the plant seeds are located. These results indicated that a residue-free strip over the row centre could be important in temperate areas. Licht and Al-Kaisi[103] found that soil temperature increased in the top 5 cm under strip tillage (1.2-1.4°C) compared to zero tillage and that it remained close to soil temperature with chisel ploughing on Mollisols in Iowa, but this change in soil temperature was not reflected in improvement of plant emergence rate index. Gathala *et al.*,[50] reported the soil thermal regime in three contrasting treatments T_1 (CT-TPR/CT-DSW), T_3 (Bed-DSR/Bed-DSW) and T_5 (ZT-DSR/ZTDSW) and found that at minimum soil (5-cm depth) temperature at 0700 and maximum at 1500 h varied between 6 and 16°C and 11to 26°C, respectively. The differences in minimum and maximum temperatures in different treatments ranged between 0.6 and 7.2°C. At 0700 h, soil temperature was generally higher in T_5 than T_1 in the first 16 wk, and thereafter soil temperature remained unchanged; whereas at 1500 h, the trend was reversed between the two treatments. On the other hand, T_3 closely followed T_1 for both minimum (at 0700 h) and maximum temperatures (at 1500 h). The data indicate that diurnal temperature fluctuation at the soil surface was consistently lower in the ZT flatbed system (T_5) than in the CT flatbed (T_1) and raised bed planting system (T_3). Naresh *et al*.,[124] found that soil temperature at transplanting zone depth (5 cm) during rice crop establishment were lowered in treatments ZT–TPR (T_1) and RT-TPR (T_2) by 3.6 and 2.7°C compared to the treatment NBed-TPR (T_3),respectively. Zero tillage reduced the impact of solar radiation by acting as a physical barrier resulting in lower soil temperature than the plough soil. The increasing trend in soil temperature for narrow raised beds. This was probably due to exposure of more surface area to the incident solar radiation in narrow raised beds than in flat conventional treatments. T_3 and WBed–TPR (T_4) recorded higher soil temperature (mean of 38.4 V/S37.7°C) compared to the flat treatments T_1, T_2 and CT-TPR (T_5) at 15 DAT. Soil temperature remained similar when compared separately among flat layout and raised bed treatments.

VI. Water Infiltration

Infiltration of rain water and irrigation water is very important for water conservation, especially in semi-arid environmental conditions. Because of the low annual rainfall in semi-arid areas, it is necessary to increase the interception of water (rain and irrigation) so it is not lost through evaporation or runoff. Infiltration also controls leaching, runoff and increases crop water availability[43]. The amount of water that enters the soil matrix depends on the infiltration rate. Under conditions of low rainfall and low irrigation, incoming water will mostly infiltrate into the soil[95]. When the pores become saturated, the excess water will run off or pond on the soil surface. Water infiltration depends on various factors, such as soil structure and texture, the initial soil water content, pore size distribution and continuity of pore, matric potential and vegetation cover[95]. A coarser and well aggregated soil will have a higher infiltration rate than a fine texture soil that is not well aggregated[183]. A wet soil will have less initial infiltration capacity to dry soil. Pore size distribution and its continuity are important regarding soil hydraulic conductivity. Decaying roots, macropores and earthworm channels increase the soil water infiltration[45].

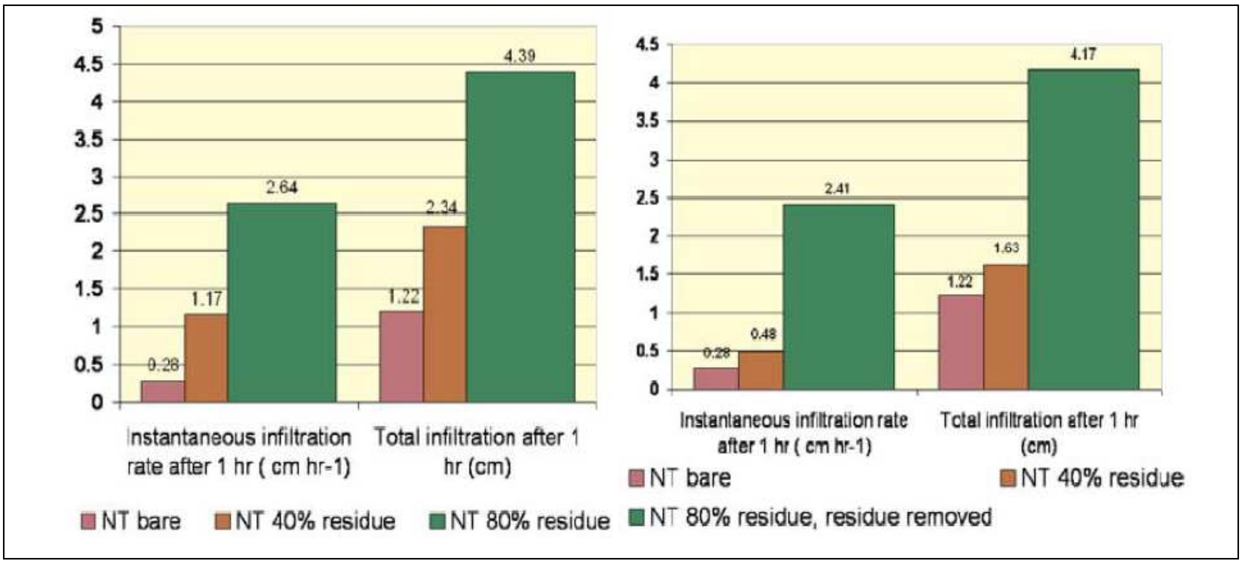


Fig.12: Better Infiltration Results with Residue Retained as Compared to No-Till (NT) Bare

Triplett *et al.*,[182] determined the infiltration rate on a non-cracking soil with a sprinkling infiltrometer on different No-Till (NT) treatments at Ohio, USA, after three years of corn production. The treatments included NT bare, NT with normal surface residue (40%) and NT with double application of surface residue (80%) for the study period (Fig.12). The infiltration rates were calculated both for NT with residue present and with residue removed. It was observed that infiltration increased when residue was retained and was also significantly greater with double-mulch treatment than under NT bare. It is interesting to note that the infiltration was greater than NT bare even when the residue was removed as the soil surface was stabilized and macropores formed under the residue were maintained and functional. Infiltration rates in NT soils will be greater than in CT soils because of retention of more soil organic matter (SOM), increased earthworm activity and more macropores[99]. However, decreased infiltration rates may observe in NT versus CT systems due to higher soil bulk density in NT and large initial soil pores in tilled soils. Conventional tillage systems had significantly higher infiltration than conservation tillage systems on sandy clay loam soil[119]. Hydraulic conductivity of CT, NT and natural prairie was measured and it was noted that the hydraulic conductivity of natural prairie was the largest of all three methods. The CT had significantly lower unsaturated conductivity than NT system. The CT (conventional tillage) system initially increases infiltration and the soil re-consolidates afterwards shortly, reducing less infiltration rate[45]. This might be due to formation of crust short after tillage[160]. Crop residues in case of conservation tillage or NT system will intercept rainfall and prevent soil crusting or sealing. Baumhardt and Lascano[8] noted a higher infiltration and lower runoff on a sandy loam soil in a wheat-cotton rotation than the cotton alone, while in case of clay loam texture, the infiltration was more when organic residues were left on the soil surface than with bare soil. Kumar *et al.*,[90] noted a steady-state infiltration rate in conventionally-tilled plots (32.6 $mm \cdot h^{-1}$) was more than 4 times higher than that of zero tilled plots (7.2 $mm \cdot h^{-1}$). The cumulative infiltration was also higher in CT (665 mm) than in ZT plots (278 mm). Naresh *et al.*,[123] observed that the steady state infiltration rate at wheat harvest was consistently highest with an overall average of 0.37 cm h^{-1} in (raised bed), lowest at 0.18 cm h^{-1} in zero till, and intermediate (0.27–

0.30 cm h^{-1}) in conventional till treatment. The time trend showed a decline (0.02–0.03 cm h^{-1} yr^{-1}) in infiltration rate in T_1 and T_2, and an increase (0.01–0.03 cm h^{-1} yr^{-1}) in T_3 and T_4.

VII. Soil organic matter (SOM) content

SOM storage is determined by intrinsic soil properties, environmental factors and also by management strategies. Conventional tillage practices have resulted in lower carbon contents of agricultural soils due to increased decomposition rates and carbon redistribution[27]. The soil cultivation reduces organic matter and alters distribution and stability of soil aggregates[165]. Cultivation also stimulates soil carbon losses due to accelerated oxidation of soil carbon by microbial action. In conventionally tilled soils, the organic matter is fairly distributed throughout the plow layer due to the incorporation of crop residues evenly in the plowed layer. MT brought about changes in SOM distribution in the A-horizon than conventional tillage (CT). Intensive tillage operations result in more or less even distribution of SOM in the topsoil, but in MT the concentration of organic matter is in the surface (0-5 cm) soil[173]. Paustian *et al.*,[131] reported increased amount of organic matter with the application of conservation tillage. The reduction in soil carbon may be mitigated by the adoption of reduced tillage, increased residue incorporation and perennial vegetation[131]. Decline in OM content was observed when no till soil was tilled to a depth of 10 cm[175]. The merits of conservation tillage system include increase in SOC pool and enhancement of soil quality[16]. However this depends on the capacity of soils to retain organic C. The enhancement of SOM and all associated beneficial effects was the most important change observed by Salinas-Garcia *et al.*,[155] who reported that NT resulted in double SOC in surface soil than moldboard tillage.

The tillage impacts on SOM have been well reported but the results vary due to many contributing factors such as soil type, cropping system, residue management and climatic conditions[110]. Conventional tillage systems generally increase crop productivity by improving soil-air-water relationships necessary for plant growth. This management system increases the chances of soil organic matter loss due to mixing of soil and crop residues, disturbance of soil aggregates and increased porosity. This loss of SOC and destruction of aggregation promote physical, chemical and biological deterioration over long term. These deleterious effects often results in increased soil erosion and water loss through reduced water infiltration and storage[17], decreased soil fertility and hence diminished sustainability of agriculture system[109]. The alteration of soil conditions by tillage implements may significantly affect the productivity and sustainability through influence on the distribution of SOM in soil profile, nutrient dynamics and microbial activity[109]. Tillage systems (no tillage or minimum tillage) that reduce soil disturbance and residue incorporation have generally been observed to increase SOM content[114]. The SOC under no tillage was 9% greater in continuous wheat, 22% greater in rotated wheat-sorghum and 30% greater in continuous wheat-soybean than under conventional tillage. The accumulation of SOC under reduced tillage than conventional system increased with increasing cropping intensity[43]. The residues are usually left on the soil surface under no tillage systems and increased accumulation of residues results in reduced exchange of gas and energy between soil surface and the atmosphere[57]. Tillage practices have effects on soil water, temperature and aeration regimes[103]. Lower soil temperature was observed under no tillage than conventionally tilled plots while, bulk density was greater under no tilled plots[57]. The study by Gosai *et al.*,[56] revealed higher concentration of soil organic matter in the no-till and shallow-tilled plots compared to other conventionally tilled plots that confirms to the findings of Doran[36],Robbins and Voss[153] and Angers *et al.*,[4]. He and Liu[66] reported that addition of organic materials (green manure, crop residues and FYM) resulted in a mean increase (average of six experiments) of 0.053% organic C compared to loss of 0.04% under inorganic fertilizer treatment. They calculated that supply of 3.2 to 4.6 t ha^{-1} (mean of 3.8 t ha^{-1}) of crop residues ha^{-1} $year^{-1}$ would be needed to maintain the soil health and to improve productivity. Kladivko[86], revealed that recycling of crop residues influences soil structure, crusting, bulk density, moisture retention, and water infiltration rate and may help reduce adverse effects of hard pan formation in rice-based cropping systems, which may play an important role in the upland crop (such as wheat or maize) after rice than the rice crop. Increase in soil organic matter under no-tillage may have been a result of reduced contact of crop residues with soil. Surface residues tend to decompose more slowly than soil-incorporated residues, because of greater fluctuations in surface temperature and moisture and reduced availability of nutrients to microbes colonizing the surface residue[159].

Tillage-based systems can be productive but they are not sustainable ecologically and economically in the long-run because the rate of soil degradation (from erosion and other forms of loss of soil quality) is generally higher than that of the natural soil formation and self-recuperation capacity[113]. The degradation of the soil follows from the loss of soil organic matter and the associated soil life and structure due to excessive rates of oxidation resulting from tillage[151]. The relevance of CA for local agricultural development is that, unlike tillage-based systems, it is capable of simultaneously improving crop productivity as well as other ecosystem services such as soil health, carbon sequestration, nutrient, carbon and water cycling[83]. These concerns and situations are creating opportunities for transforming tillage-based agriculture that is increasingly being recognized to be ecologically and economically unsustainable into CA system[44].

Carbon sequestration

Bernoux *et al.*,[10] defined carbon sequestration "soil carbon sequestration for a specific ecosystem in comparison with a reference one, should be considered as the result (for a given period of time and portion of space) of the net balance of all greenhouse gases, expressed in C-CO_2 equivalent or CO_2 equivalent, computing all emission sources at the soil-plant-atmosphere interface, and also all the indirect fluxes, gasoline, enteric emissions etc". Alternatively it may be defined as the storage of soil carbon in a stable form. The conservation of sufficient SOM levels is crucial for the biological, chemical and physical soil functioning in both temperate and tropical ecosystems. Appropriate levels of SOM ensure soil fertility and minimize agricultural impact on the environment through sequestration of carbon (C), reducing erosion and preserving soil biodiversity[169]. Soil carbon sequestration can be accomplished by management systems that add high amounts of biomass to the soil, cause minimal soil disturbance, conserve soil and water, improve soil structure, and enhance soil fauna activity. The impact of No-tillage practices on carbon sequestration has been of great interest in recent years. The literature is replete with studies that show an increase in SOC stock with conversion to NT, at least in the surface soil[33,115]. NT impacts SOC stock in two ways: (i) by reducing disturbance which favors the formation of soil aggregates and protects SOC encapsulated inside these stable aggregates from rapid oxidation[167]; and (ii) by modifying the local edaphic environment: bulk density, pore size distribution, temperature, water and air regime that might also restrict SOC bio-degradation[84]. Paustian *et al.*,[132] and Lal *et al.*,[93] summarized the rate of accumulation of soil organic carbon (SOC) stock under NT at 300-800 kg SOC/ha/year.

Carbon sequestration in agricultural soils counteracts desertification process through the role of increased soil organic matter in structural stability and water retention and the essential role of soil surface cover by plant, plant debris or mulch in preventing erosion and increasing water conservation. Furthermore, soil aggregate stability has been recognized as a relevant factor in the control of water erosion of soils[42] because erodibility of soils is directly related to aggregate stability. The continued existence of large pores in the soil that favor high infiltration rates and aeration depends on the stability of larger aggregates. No-Tillage effects on soils are closely related to the management of crop residues in and on the surface of the soil. Unger and Jones[185] reported that the amount of water stored and the fallow storage efficiency changed from 152 to 217 mm and from 15.2 to 35.2% when shifting from disking to no-tillage in Bushland (USA). These results were confirmed in Morocco by Bouzza. During 5 years of conversion from continuous corn and conventional tillage to 2 or 6 year rotations under no-tillage, the soil density was not affected by the change in management. The soil density depended more on the time of the sampling than on management practices[108]. According to the research conducted by Azooz and Arshad[6], total volume of soil pores with radii <14μm (micropores) were significantly greater in NT than in conventional tillage (CT).Differences in volume of soil pores with radii >14μm (macropores) between CT and NT were not significant. For the initial soil moisture conditions ranging from dry to field capacity, the infiltration rate values were greater by 0.24 to 3.01 cm h^{-1} in NT than in CT for the silt loam and by 3.30 to 4.13 cm $h^{-1}$for the sandy loam. Saturated hydraulic conductivity values were significantly greater in NT (rangefrom 0.36 to 3.0 cm h^{-1}) than in CT (range from 0.26 to 1.06 cm h^{-1}). However, Jarecki and Lal[76] found no differences between tillage treatments in several soil properties including texture, available water capacity, and hydraulic conductivity; however, the NT decreased soil bulk density and p^H in the 0 to 15 cm layer in a silt loam soil. With time, No-tillage can improve soil structure and stability thereby facilitating better drainage and water holding capacity that reduces the extremes of water logging and drought. These improvements to soil structure and carbon sequestration also reduce the risk of runoff and pollution of surface waters with sediment, pesticides and nutrients.

Carbon sequestration and tillage systems

Houghton[68] is of the view that increasing atmospheric greenhouse gas concentration has led serious concerns to work out the possible role of soil as a carbon sinking. The largest surface carbon pool is mainly constituted by soils of the world which is approximately 1500 Gt[158]. This amount is about three times the quantity stored in terrestrial system[168].Any modification of land management, even in agricultural systems, may induce changes in soil carbon stock. Farming/ tillage methods are contributing towards soil carbon losses by the use of mechanical tillage as secondary tillage tools for preparation of seed bed or disking aimed at weed control. The mechanisms may include (1) stimulation of short term microbial activity through aeration and more release of CO_2 and other gases by their activity[87]; (2) mixing of residues into soil where favorable decomposition conditions are available than surface[158] and soil aggregate disruption where mostly SOM is protected from decomposition[166].Soils may become prone to erosion by the use of conventional tillage practices which results in the loss of soil carbon[96]. Soil's ability to provide nutrients and water that fulfills the crop requirement determines the crop growth/yield and crop quality. According to Dick and Durkalski[34]mould board plough and oxen have become synonymous to agriculture. The tillage being used in western Uttar Pradesh include minimum tillage, no-tillage, conventional tillage and deep tillage with a number of primary and secondary tillage tools. According to the research conducted by Naresh *et al.*,[124] higher proportion of macro-aggregates. In the 0–5cm layer, plots raised beds transplanted rice (WBed-TPR) combined with zero tillage on raised beds in wheat (with residue) (WBedZT-DSW+100%SR) had the greatest proportion of large stable macro-aggregates (12.9%) and highest mean weighted diameter (MWD) (1.80mm). 50% surface residue retention caused a significant increment of 15.65% in total aggregates in surface soil (0–5cm) and 7.53% in sub-surface soil (5–10cm). In surface soil, the maximum (13.5%) and minimum (4.3%) proportion of total aggregated carbon was retained with >2 - <0.053 mm size fractions, respectively. WBed-TPR; WBed ZT-DSW+ 100% SR treatment (T_9) had the highest capability to hold the organic carbon in surface (10.73g kg^{-1} soil aggregates).

Carbon storage under different tillage systems

Conservation or reduced tillage systems can store 0.1-0.3 t C ha^{-1} $year^{-1}$; this conservation tillage practice may be adopted on 60 % of the arable land. Intensive tillage operations or the use of mould board ploughing can offset any gains made in carbon sequestration. Organic matter increased under conservation tillage system from 0 – 1.15 t C ha^{-1} in temperate conditions[148] while, carbon accumulation rate was computed 0.1 – 0.5 t C ha^{-1} $year^{-1}$ by Lal *et al*[98].

Soil carbon storage or in other words increased C-sequestration, land use should be reshaped especially on marginal lands. To achieve the goal of sustainable agricultural production, a holistic and systemic approach is needed. The approach should include steps to early warnings of possible soil degradation processes followed by implementation of preventive measures. The increasing crop productivity from existing agricultural lands will also have environmental consequences as suggested by Tilman *et al*[180]. The negative environmental consequences are usually less and may be positive, depending upon land use. The use of conservation tillage has promising results in yield increase on existing soil resources through erosion control, soil moisture conservation and increasing SOM[94]. The atmospheric concentration of CO_2 (8.6 Pg C yr^{-1}) from emissions of processing industry, land use changes, soil tillage and more recently the energy industry is very vital issue faced by the 21st century[97]. The soils fertility status is poor due to intensive cropping and limited addition of organic matter. These conditions have resulted in lower average yield of major crops at farm level[41].

The wheat-rice cropping pattern is mostly observed in India. In India, very little work has been done on how tillage affects soil properties. The new trends in carbon sequestration have not been investigated in Indian soil and climatic conditions. The ultimate aim is to investigate the problem in this specific cropping pattern and how crop growth and yield is affected and how soil properties changed and how much carbon may be sequestered in this system. Different tillage systems may be adopted depending upon the soil and climatic conditions. The efficiency of tillage system depends upon various factors mainly soil, water and climatic conditions. The experimentation with different tillage systems under a set of soil and climatic conditions will generate very critical information of different tillage system used. Each tillage system has its own importance under specific set of conditions. Deep tillage results in loosening of the soil and helps in root penetration[187] whereas, MT is supposed to contribute in stratification and SOM accumulation as compared to CT[26].

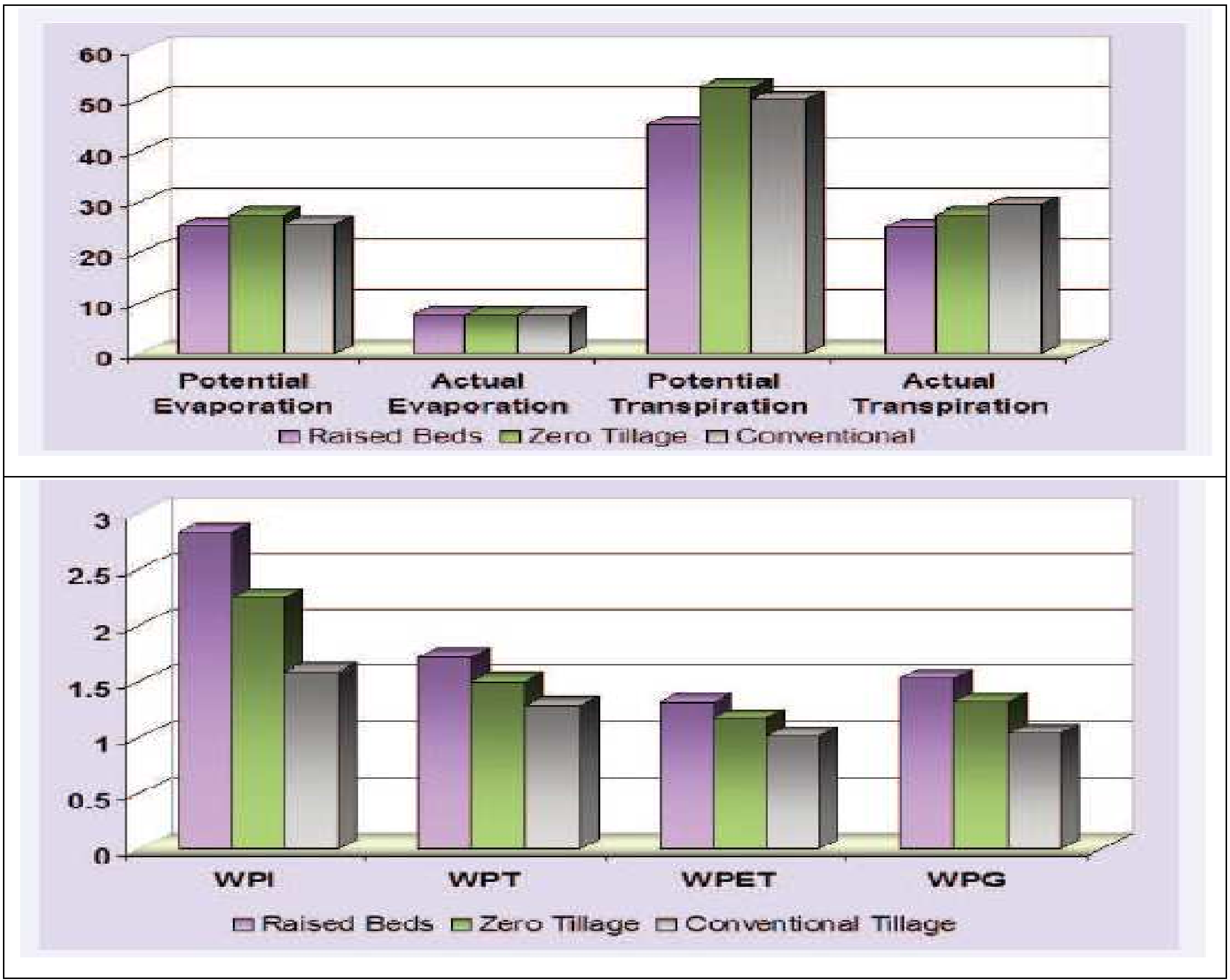


Fig.13: Water Balance Components and Water Productivity under Various Tillage Systems

Source: Ravish *et al*[145].

Note: WPI: Water Productivity (kg/cum of Irrigation Water); ***WPT:*** Water Productivity (kg/cum of Transpiration); ***WPET:*** Water Productivity (kg/cum of Evapo-Transpiration); ***WPG:*** *Water Productivity (kg/cum of Rain and Irrigation Water)*

The water balance components and water productivity in a farmer's field under different tillage systems viz., raised beds, zero tillage and conventional tillage. The water balance components as obtained with SWAP model (given in the upper figure) is generally used to select viable water management options.
Results presented indicate that actual transpiration is much less than potential transpiration indicating that farmers are under-irrigating their wheat crop. As a consequence, actual wheat yields are less than the potential yields. It is observed that water productivity in raised bed planting was higher than zero till system by 25 per cent and by 79 per cent compared to conventional tillage. On the other hand, values of water productivity under zero tillage are higher by 42 per cent from that observed under conventional tillage (given in the lower figure). The study concludes that with appropriate agronomic practices for weed management, yield losses in raised bed planted rice can be altogether avoided besides significant savings in irrigation water.

Crop Yield

Soil management, soil fertility, application of fertilizers, quality of seeds, timely sowing of crops and adoption of better cultural practices all affect yield of wheat crop. There is a close relationship between all these inputs and high crop yields. All the agriculture inputs play an important role in enhancing the crop yield. Yield increase of 16, 21 and 7 percent was recorded for ZT, LLL and Bed-furrow interventions respectively, Latif *et al.*,[101]. The effects of soil quality on agricultural productivity are greater in low-input rain fed production systems than in highly productive systems[55,157]. Govaerts *et al.*, determined the soil quality of plots after more than 10 years of different tillage and residue management treatments. There was a direct and significant relation between the soil quality status of the soil and the crop yield and zero tillage with crop residue retention showed the highest crop yields as well as the highest soil quality status.

In contrast, the soil under zero tillage with crop residue removal showed the poorest soil quality (i.e. low contents of organic C and total N, low aggregate stability, compaction, lack of moisture and acidity) and produced the lowest yields, especially with a maize monoculture[46,55]. In high-input systems, the decreased soil quality status of management practices is reflected in reduced efficiency of inputs (fertilizer, water, labour) resulting in higher production costs to maintain the same yield levels, rather than in lower yields as such[123].

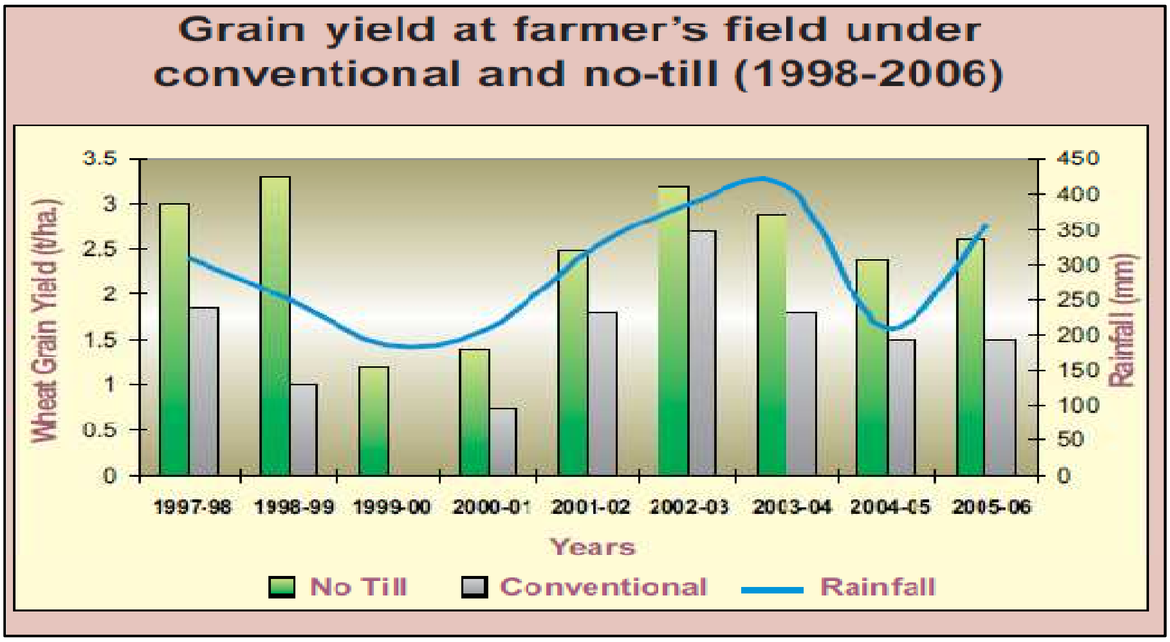


Fig.14: Grain yield at farmer's field under conventional and no-till (1998-2006)

Source: No-till system applied to North Africa Rainfed Agriculture: Case of Morocco

Grain yield reported from no-tillage pioneer farmers field showed increased yield obtained in dry as well wet years. In very dry years with less than 200 mm rainfall, farmers were able to produce 1.1 and 1.5 tonnes of wheat in two different locations where no-tillage fields were the only ones harvested in the entire region **(Fig.14).**In wet years, change in farmer's perception was observed towards crop residue left in the field which was seen as an investment in their soil rather than wasted biomass.

Conservation Agriculture for offsetting Green House Gases

Rice-wheat systems produce greenhouse gases through both biological processes and burning of fuel by farm machinery. Tillage operations contribute CO_2 through the rapid organic matter decomposition due to exposure of larger surface area to increased oxygen supply. Experiments have shown that tillage almost doubles the rate of decline in soil organic carbon levels in the top 20 cm of soil. Every liter of diesel fuel used by tillage machinery and irrigation pumps also contributes 2.6 Kg CO_2 to the atmosphere. Thus nearly 400 Kg CO_2 would be generated per hectare assuming an annual use of 150 litres diesel in the conventional rice-wheat system[123].For the 12 million ha, this would amount to 4.8 Mt CO_2 per annum or 1.3 MMTCE. This is one third the value (4 MMTCE) of CH_4 from rice fields. Diesel use remains greatly an under estimated source of GHG. The presence of nitrogen (N) enhances microbial decomposition and release of CO_2.An important off-site source of CO_2 is the production of N fertilizers. For every kilogram of N fixed in fertilizer 1.8 Kg CO_2 is the by-product. It is presumed that CO_2 generated by burning crop residues.

a) Emission of Greenhouse Gases

According to the Intergovernmental Panel on Climate Change (IPCC), agriculture, deforestation, and land-use change together account for about 31% of total global anthropogenic GHG emissions[170].Just as agriculture and land use change has significant potential to exacerbate GHG emissions and

Climate change, it also holds major potential to mitigate these impacts. Worldwide, the "technical" mitigation potential from agriculture (i.e., the biophysical capacity to mitigate GHG emissions) is estimated to be 5,500-6,000 million tons of CO_2-equivalent per year (Mt CO_2-eq/yr) by 2030[170].The economically feasible mitigation potentials are estimated to be 1,500-1,600, 2,500- 2,700,and 4,000-4,300 Mt CO_2-eq/yr at carbon prices of \$20,\$50 and \$100/tCO_2-eq,respectively.About 70% of this mitigation potential lies in developing countries.

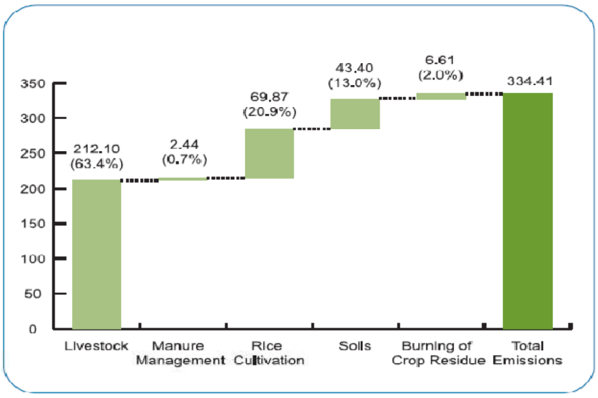


Fig.15: GHG emissions from Agriculture Sector (million tons of CO_2 eq).

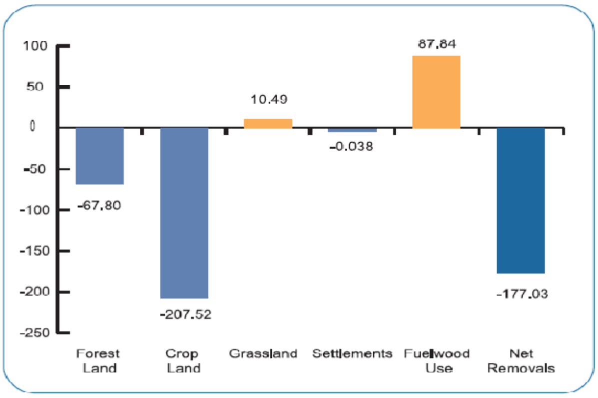
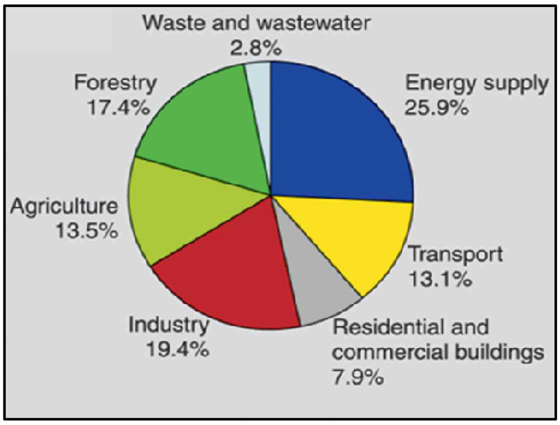


Fig.16: GHG emissions and removals from LULUCF sector (million tons of CO_2 eq).



Greenhouse Gas emissions in world) IPCC2007

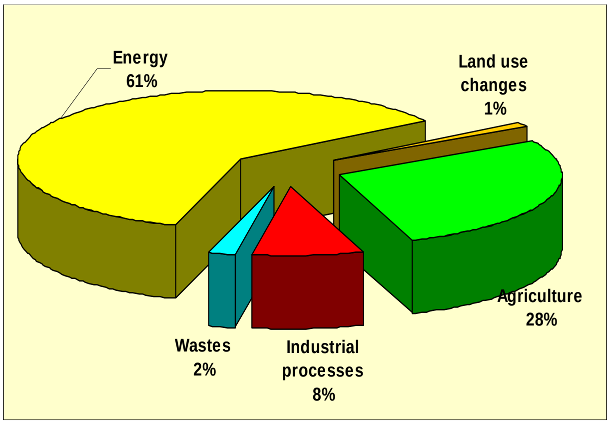


Fig.17: Contribution of major sectors to emission of greenhouse gases in India

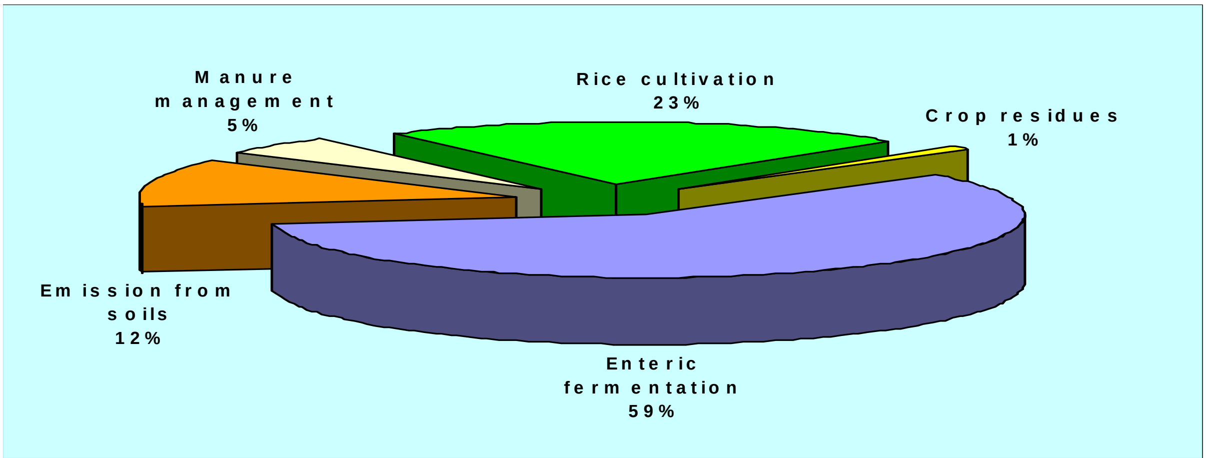


Fig.18: Relative contribution of sub-sectors of agriculture to greenhouse emissions in India.

The net Greenhouse Gas (GHG) emissions from India, that is emissions with LULUCF, in 2007 were 1727.71 million tons of CO_2 equivalent (eq) of which CO_2 emissions were 1221.76 million tons; CH_4 emissions were 20.56 million tons; and N_2Oemissions were 0.24 million tons.GHG emissions from Energy, Industry, Agriculture, and Waste sectors constituted 58%, 22%, 17% and 3% of the net CO_2 eq emissions respectively. The agriculture sector emitted 334.41 million tons of CO_2 eq in 2007 Fig15.Estimates of GHG emissions from the agriculture sector arise from enteric fermentation in livestock, manure management, rice paddy cultivation, agricultural soils and on field burning of crop residue Fig.18.Enteric fermentation in livestock released 212.10 million tons of CO_2 eq (10.1 million tons of CH_4).This constituted 63.4% of the total GHG emissions (CO_2 eq) from agriculture sector in India. The estimates cover all livestock, namely, cattle, buffalo, sheep, goats, poultry, donkeys, camels, horses and others. Manure management emitted 2.44 million tons of CO_2 eq.

Rice cultivation emitted 69.87 million tons of CO_2 eq or 3.27 million tons of CH_4.The emissions cover all forms of water management practiced in the country for rice cultivation, namely, irrigated, rainfed, deep water and upland rice. The upland rice are zero emitters and irrigated continuously flooded fields and deep water rice emit maximum methane per unit area Fig.19.Agricultural soils are a source of N_2O,mainly due to application of nitrogenous fertilizers in the soils. Burning of crop residue leads to the emission of a number of gases and pollutants. Amongst them, CO2 is considered to be C neutral, and therefore not included in the estimations. Only CH_4 and N_2O are considered for this report. The total CO_2 eq emitted from these two sources were 50.00 million tons.

The waste sector emissions were 57.73 million tons of CO_2 eq from municipal solid waste management, domestic waste water and industrial waste water management. Systematic disposal of solid waste is carried out only in the cities in India resulting in CH_4 emissions due to aerobic conditions generated due to accumulation of waste over the years. It is estimated that the MSW generation and disposal resulted in the emissions of 12.69 million tons of CO_2 eq in 2007.The waste water generation emissions are the sum total of emissions from domestic waste water and waste water disposal in industries. Waste water management in both these categories together emitted 45.03 million tons of CO_2.

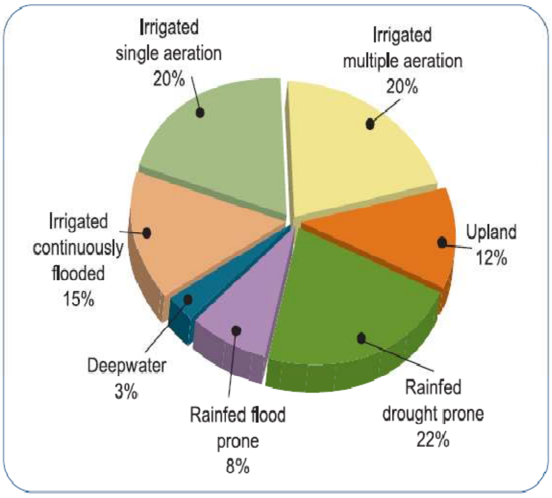


Fig.19: Distribution of rice area under various water management practices in India in 2007.

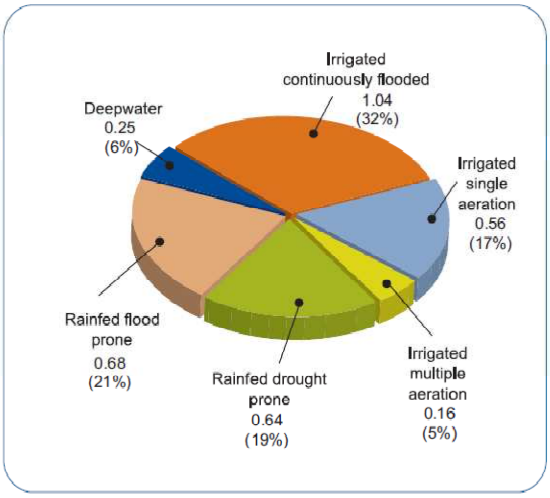
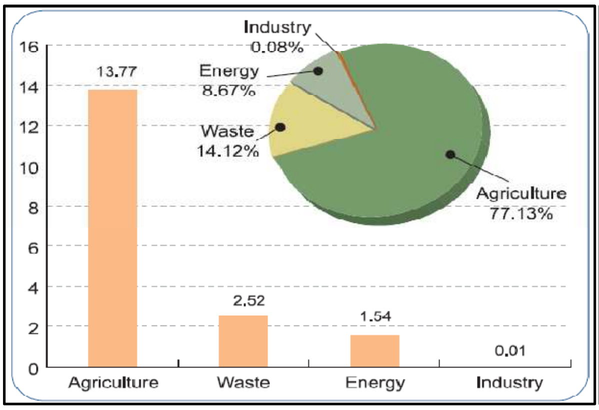


Fig.20: CH4 emission distribution in million tons from rice cultivation in 2007.

Here

MA- Multiple aeration, SA- Single aeration and CF- Continuously flooded

Total CH_4 emitted in 2007 was 20.5 million tons. The energy sector emitted 4.27 million tons of CH_4. The industry sector emitted 0.15 million tons of CH_4. 13.77 million tons and 2.52 million tons of CH_4 were emitted from agriculture and waste sectors respectively. CH_4 emissions from the agriculture sector is the largest and it is 77.1% of the total CH_4 emitted in 2007 (Fig.21). Within the agriculture sector CH_4 emitted due to enteric fermentation in livestock constitutes more than half (56.6%) of the total of CH_4 emitted in 2007.The total N_2O emissions from India in 2007 were 0.24 million tons. The energy sector emitted 0.06 million tons of N_2O. The industry sector emitted 0.02 million tons. The agriculture sector emitted 0.15 million tons and the waste sector contributed 0.02 million tons to the total N_2O emitted in 2007.The agriculture sector alone contributes more than half (60%) of the total N_2O emitted from the country.N_2O from agricultural soils alone constitute 58% of the total N_2O emitted in 2007 from all sectors. (Fig.22).



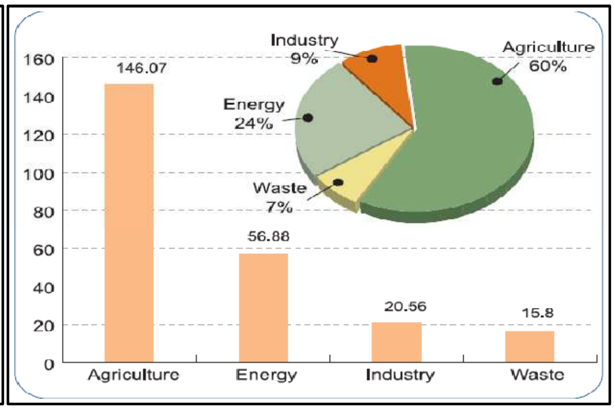


Fig. 21:CH_4 emission and distribution by sector in **Fig. 22:** N_2O emitted by sector in '000 tons in 2007. million tons

Data on global warming potential (GWP) during the life cycle of various food items on fresh and dry weight basis. On an average, CH_4 contributed 71% of the GWP for food consumption whereas CO_2 and N_2O contributed 16% and 13%, respectively (Fig.23a). As Indians mostly consume fresh foods produced locally, 87% of the emission came from food production followed by preparation (10%), processing (2%) and transportation (1%) of food (Fig.23b).

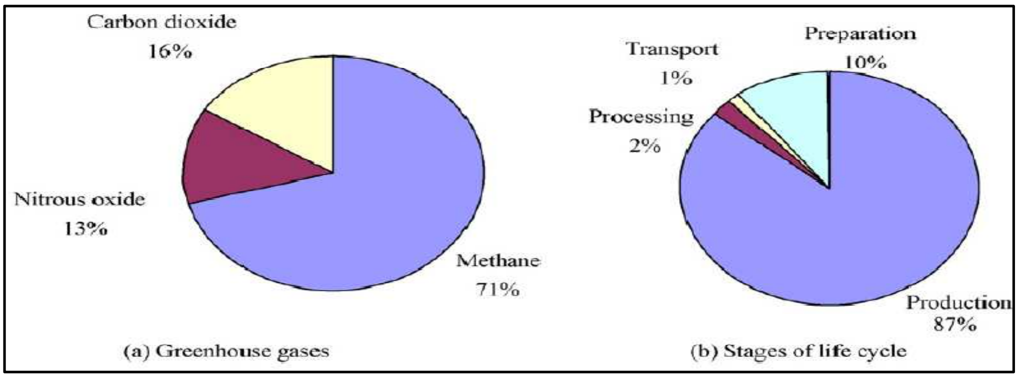


Fig.23: Relative contribution of (a) various greenhouse gases and (b) various stages of life cycle of Indian food items towards global warming.

A balanced diet is one which contains different foods in quantities and proportion that the need for calories, minerals, vitamins, carbohydrate, fat and other nutrients is met to withstand short duration of leanness.For the developed countries per capita GWP for food consumption is about 1200–1500g CO_2 eq. i.e., 2 times that of Indian emission[171].In a common lacto-vegetarian meal rice contributed the largest amount of GHG (49%) followed by milk (22%) (Fig. 24a). In a non-vegetarian meal contribution of mutton was the largest (35%) towards GHG emission, closely followed by rice (34%) (Fig. 24b). Kramer *et al.*,[88] showed that meat and dairy products account for 28% and 23% of GHG emission, respectively in Dutch food.

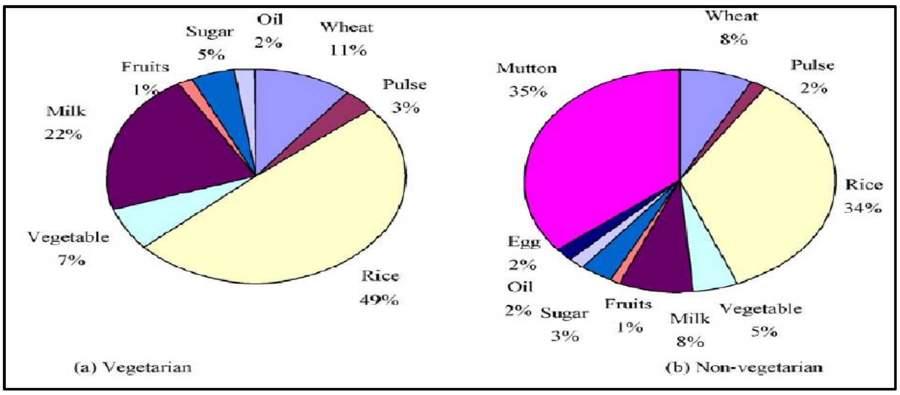


Fig. 24: Relative contribution of various food items to greenhouse gas emission in balanced vegetarian and non-vegetarian diets.

b) Reduction of Greenhouse Gases through conservation agriculture

Positive changes in agronomic practices like tillage, manuring and irrigation can help reduce greatly the release of greenhouse gases into the atmosphere. Adoption of zero tillage and controlled irrigation can drastically reduce the evolution of CO_2 and N_2O. Reduction in burning of crop residues reduces the generation of CO_2, N_2O and CH_4 to a significant extent. Saving on diesel by reduced tillage and judicious use of water pumps can have a major role to play. Changing to zero tillage would save 98 liters diesel per hectare Naresh *et al*[123]. With each liter of diesel generating 2.6 kg, about 3.2 Mt CO_2/annum (about 0.8 MMTCE) can be reduced by zero-tillage in the 12 million ha under rice-wheat systems in the Indo-Gangetic Plains alone. Intermittent irrigation and drainage will further reduce CH_4 emission from rice paddies by 28% to 30% as per the findings at IARI (Delhi) and at Pantnagar. Use of calcium nitrate or urea instead of ammonium sulphate and deep placement instead of surface application of nitrogenous fertilizers can increase its efficiency and plant uptake thereby reducing N_2O emission. Tillage and crop residues retention have a great influence on CH_4 and N_2O emission through the changes of soil properties (e.g.,soil porosity, soil temperature and soil moisture etc.)[1,199]. In some experiments,conversion ofconventional tillage (CT) to no-till (NT) can significantly reduce CH_4 and N_2 Oemission[40,112]. Wang *et al.,*[191] indicated that the major differences in CH_4 production zone resulted from the disturbed depth by the different tillage methods. Therefore, the CH_4 production zone may vary according to the adopted tillage method. Wang et al., 1998 also reported that the main oxidation zone of CH_4 was the root surface and the interface between soil and water. The rice residues retention may have increased the soil oxide layer. In this study, NT significantly increased the SP at 0−5 cm depth and thus had a larger oxide layer than other treatments, which may be beneficial to the oxidization of CH_4. Regina *et al.,*[147] indicated that CH_4 oxidation rate was higher when there were more macro-pores or fewer micro-pores in the soil.

Table 3: Carbon dioxide emissions over a 19-day period after tilling wheat stubble with different methods

Tillage method	Cumulative CO_2 Loss (t/ha)
Mould board plough	9.13
Disk harrow	3.88
Chisel plough	3.65
No- tillage	1.84

Source: Reicosky[150]; Reicosky and Lindstrom[149]

Maintenance of mulch under conservation tillage systems increases the ability of soil to sequestrate CO_2 and reduces emissions, protecting the atmosphere. In some soils, following several years under a conservation tillage system, organic matter content has been shown to increase by as much as 2000 kg/ha/year. Increased organic matter also improves the soil's nutrient and water holding capacity. As shown Table 3, tillage increases oxidation of soil organic matter content releasing large quantities of CO_2, whereas conservation tillage can reduce CO_2 emission by up to 80%.Conservation tillage has an even more direct impact on greenhouse gas levels. It can reduce the number of trips needed to produce a crop and lowering the horsepower requirement for crop production; it reduces the amount of fuel used in farming. Mulch tillage light to moderate tillage passes that leave more than 30 percent residue cover after planting saves approximately 2.0 gallons per acre[78].Across the 46.7 million acres of mulch-tilled cropland, that represents a savings of 93.4 million gallons of diesel. Jasa *et al.,*[77] figured the advantage of no-till over moldboard plowing to be a fuel savings of 3.9 gallons per acre. Extrapolating that out over the nation's 65 million acres of no-till crops, a savings of 253.5 million gallons of diesel is realized. Combining those two figures, conservation tillage saves 353.8 million gallons of diesel per year. Kern and Johnson[85] determined no-till could reduce fuel consumption by 3.5 to 5.7 gallons per acre, depending on the number and type of tillage trips eliminated the soil type and moisture content.

Crop inputs, no-till emitted less CO_2 from agricultural operations than did conventional tillage, with 137 and 168 kg C/ha/year, respectively[131]. Larney *et al.,*[100] suggested that although relative increases in soil organic matter were small, increases due to adoption of NT were greater and occurred much faster in continuously cropped than in fallow-based rotations. Hence intensification of cropping practices, by elimination of fallow and moving toward continuous cropping is the first step toward increased C sequestration. Reducing tillage intensity, by the adoption of NT, enhances the cropping intensity effect. Changing from conventional tillage to no-till is therefore estimated to both enhance C sequestration and decrease CO_2 emissions[196]. The benefits of NT systems on carbon sequestration may be soil/site specific, and the improvement in soil organic matter may be inconsistent in fine textured and poorly drained soils[194]. Studies conducted in Europe, based on EU 15th implementation report provided that 70% of the farmland was under direct seeding and minimum tillage, leading to a reduction in CO_2 emissions of more than 135 MT per year. This amount represents almost 40% of the annual CO_2 emission reduction target until 2012, which was established at 346 MT CO_2 yr^{-1}.This study assumes that the sequestration of 1 ton of carbon is equivalent to 3.7 tons of CO_2 and that the consumption of 100 litres of fuel produces an emission of 303 kg of CO_2. It is also assumed that direct seeding results in an increase of soil carbon of 0.77 t ha^{-1} yr^1 and minimum tillage of 0.5 t ha^{-1} yr^{-1}. In total, conservation agriculture reduces energy consumption between 15%-50%, reduces the working time by over 50%, and increases energy efficiency between 25% -100%.Saharawat *et al*[154].,reported that the Simulated CH_4 emission in rice ranged from 25 to 59 kg ha^{-1}, and the transplanted rice after conventional puddling FP (T_1) had the largest emission followed by unpuddled transplanting (T_2). Emission of N_2O from soil in rice as well as in wheat varied between 0.10 and 0.12kg N_2O-N ha^{-1}.Fertilizer contributed 0.24 and 0.37 kg N_2O-N ha^{-1} in rice while it was between 0.42 and 0.54 kg N_2O-N ha^{-1} in wheat. Farm machinery including pump used for irrigation emitted 389 to 507 kg CO_2-C ha□$^{-1}$ in rice and 58 to 81 kg CO_2-C ha^{-1} in wheat. Off-farm practices such as production of fertilizer contributed 117 to 199 kg CO_2-C ha^{-1} in rice and 222 to 252 kg CO_2-C ha^{-1} in wheat. Production of biocides contributed 47 to 82 CO_2-C ha□$^{-1}$ in rice, while its contribution was negligible in wheat. Application of fertilizer and biocide contributed about 40 kg CO_2-C ha^{-1} in rice-wheat system. Ladha *et al.,*[91] indicated that different RCTs in rice-wheat system had pronounced effects on the GWP, which varied between 2799 kg CO_2 equivalent ha^{-1} in raised-bed system (T_3) and 3286 CO_2 equivalent ha^{-1} in FP (T_1). Compared to the FP (T_1) all the technologies reduced the GWP by 3 to 28%.

CONCLUSIONS

Food production in India must increase by 2.5 per cent each year to meet the demand of the growing population and to reduce malnutrition. A significant part of it has to come from rice- wheat crop based production systems. This assumes special challenge as the data on rice- wheat yield trends indicate plateauing or progressive productivity decline in Punjab, Haryana,and Western Uttar Pradesh. For future productivity growth to keep pace with the increasing demand, it is necessary to address the problem at various levels. It will be important to make investment in developing appropriate technologies, and enable the farmers to take advantage of these in combination with their own ingenuity and age old wisdom. On croplands, tillage is the most important practice, which can have a major effect on the carbon pool, either negative with conventional plowing or positive, when No-tillage is applied. No-tillage practices claim to reverse historical carbon loss from soils,thereby reducing CO_2 in the atmosphere through storage in soil sinks - a process known as sequestration. Carbon sequestration and an increase in soil organic matter will have a direct positive impact on soil quality and fertility. There will also be major positive effects on the environment, and on the resilience and sustainability of agriculture. This information can be used by extension and private-sector consultants to promote the use of no-tillage, bed planting and laser land leveling production systems that result in increased soil carbon, improving soil quality and productivity in the long term and enhancing profitability of producers. The response of soil chemical fertility to tillage is site-specific and depends onsoil type, cropping systems, climate, fertilizer application and management practices. However, in general nutrient availability is related to the effects of conservation agriculture on SOC contents. The needed yield increases, production stability, reduced risks and environmental sustainability can only be achieved through management practices that result in an increased soil quality. The above outlined evidence for the improved soil quality and production sustainability with well implemented conservation agriculture systems is clear, although research remains inconclusive on some points. At the same time, the evidence for the degradation caused by tillage systems is convincing for biological and physical soil quality. Therefore, even though we do not know how to manage functional conservation agriculture systems under all conditions, the underlying principles of conservation agriculture should provide the foundation upon which the development of new practices is based, rather than be considered a parallel option to mainstream research activities that focus on improving the current tillage-based production systems.

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