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Climate Change-Land Degradation-Food Security Nexus: Addressing India's Challenge

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Abstract

Monsoon rains provide relief from the sweltering summer heat conditions, replenish depleted profile moisture to breathe new life in soils. With appropriate management of rain water, Indian summer monsoons boost the level of 'reservoir of life'. Our inability to manage spatial and temporal rainfall variation features of deficit and excess rainfall episodes and their interactions with soil variability is a major cause of uncertainty in agricultural production. In the past, entire focus of national efforts was on rainwater harvesting, storage and distribution through canal networks and greater reliance on ground water pumping to meet immediate crop water demands. These approaches have resulted in wide spread problems of natural resource fatigue and unsustainable water supplies. This paper analyses the complexities of climate change-land degradation-food security nexus and suggests the need for adopting alternate approaches emphasising on *in situ* conservation of rain water and its efficient use such as to reverse the processes that contribute to land degradation in specific landscapes.

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Introduction

Agriculture is practiced in India over a wide range of soil and agroclimatic conditions, and it has provided the basis for co-evolution of different crop production and land use systems to meet food, fibre and other associated needs of the people. Ensuring food security while sustaining the quality of natural resource base was the guiding principle which determined the evolution and adoption of management practices appropriate to mineralogically distinct soils formed in different agro-ecologies. Maintaining the pace of food production at par with population growth rates has always been a matter of serious concern. Notwithstanding rapid and significant gains in food production during the Green Revolution era (1960-1990), concerns for India's food security continue and call for addition of 6 $MT.Yr^{-1}$ food grains to its existing food basket [1].

Recognising that Indian agriculture is monsoon dependent, country adopted a strategy of creating a public network of storage reservoir based canals and development of ground water for reducing its dependence on monsoon rains. Provision of a reliable irrigation source changed the production environment, enabled widespread adoption of high yielding cultivars, enhanced the use of agri-inputs besides converting 22 million hectares (Mha) of forest, pasture and fallow lands to arable lands. While these measures, undoubtedly, contributed to addressing the urgency of increasing food production within a short span, there were unintended consequences as well which now pose additional challenges. Expansion of irrigation provisions and adoption of inappropriate water, soil and crop management practices led to emergence of waterlogging and secondary salinization and ground water pollution problems in some parts of irrigation commands. Over-mining of aquifers for irrigation is threatening even the rural drinking water supplies [2, 3, 4] in the country. Some estimates suggest that production of a large biomass is annually depleting Indian soils of 10-12 million tons of essential nutrients, adversely affecting soil health [5].

Intensive agri-input use strategy improved crop yields but did not improve the factor productivity of agri-inputs. It bypassed humid eastern India and the rainfed drylands where it was not easy to alter the production environments. Farmers relied heavily on use of urea for enhanced yields irrespective of inherent nutrient requirements of the mineralogically different soils. This has led to nutrient imbalances, emergence of multi-nutrient deficiencies, ground water pollution, GHG emissions and decline in crop yields. Organic matter content of most soils has declined. Organic matter plays an important role in development of stable soil structure, maintaining infiltration and regulating the release and uptake of nutrients and acts as food for soil organisms [6]. Declining organic matter is adversely affecting the factor productivity of managed and natural ecosystems. Significant losses in vegetation cover over the arable and forested lands have been reported which point to an on-going process of land degradation [7, 8, 9]. Nearly 37% of the total geographical area of country is, reportedly, at various stages of land degradation [10]. The strategy of achieving food security via intensive use of chemical fertiliser without due diligence on soil health and environmental concerns has proved fundamentally flawed. Many soils in the intensively cultivated Indo-Gangetic plains and elsewhere are now showing signs of resource fatigue [11, 12, 13] and dysfunctional ecoservices rendered by soils and ecosystems [6]. This warrants that food security concerns must be addressed simultaneously with issues relating to soil health and functioning of the ecosystem services.

In common with global community, India is a signatory to millennium development goals (MDGs) which, importantly, aim at eliminating hunger, ensuring food and nutritional security and achieving land degradation neutrality. The objective of this article is to draw attention to current production environment of Indian agriculture, elucidate and highlight the strong nexus that exists between elements of climate change (rainfall, terminal heat stresses), food security and land degradation. It is emphasized that for Indian agriculture to become more resilient to biotic and abiotic stresses, there is need to promote approaches which integrate concerns of enhancing land productivity, gene diversity, water scarcity and climate change. The paper also draws attention for a needed shift from an individual crop to cropping /farming system and land scape based approaches for resolution of the resource problems in different agro-ecologies.

Indian Agriculture: Salient Features

Agriculture sector in India contributes nearly 16% of gross domestic product (GDP), holds 49% share in employment and meets the food demands of 1.3 billion people. India, primarily has two distinct cropping seasons namely the *Kharif* (warm rainy season – June to Oct) and the *Rabi* (post-rainy mild winters - Oct to March). During hot summer months (April- June) very little area is cropped because water availability is at its lowest in the period. Generally, the annual cycle of agricultural operations begins after pre-monsoon showers have been received by mid- June in different regions of the country.

Seasonal Food Grains Production Trends, Area and Growth Rates

In early sixties India produced nearly two-third of the total food grains during the Kharif season from 2/3 of its arable lands, dependent on monsoon rains. The situation has however, changed dramatically by 2000 when almost 2/3 of the total food grains were produced during the *Rabi* season from nearly 1/3 of the total arable lands. Data presented in Table (1) indicate that India's total food grains production grew exponentially and hovered around 3 MT/Yr. during 1950-1990 but slowed-down since then to 1.2-1.8 $MT.Yr^{-1}$ due to fatigue of Green Revolution [14,15]. A closer look at the available production data revealed that area devoted to Kharif food grain crops (rice, coarse cereals and legumes) decreased from 78 to 69.5 Mha during 1965-2016.

In the same period (1965-2016), area under *Rabi* food grain crops (wheat, barley, Rabi maize and sorghum and pulses) has more than doubled, from 25 to 55.4 Mha. Enhanced *Rabi* food grains production was largely dependent on (i) extensive development and use of canal and ground water, (ii) increased availability of quality seed of appropriate crops cultivars, (iii) increased use of fertiliser nutrients, and (iv) adoption of appropriate management practices. Irrigated agriculture is the predominant user of water in India (upto 86%). It has now become almost inevitable that agriculture uses water more efficiently such as to share it with other sectors of national economy.

India's canal irrigation network is not designed to supply water as per demands during the crop season. In absence of good quality canal irrigation systems,

Table 1. Seasonal difference in growth rates of food grains production (million tons/ year) during different time periods in India

Crop seasons	‡Growth Rates (MT/Yr.)				
	Previous study			Present study	
	1966-1990	1991-2006	1967-1991	1992-2007	2007-2016
Kharif	1.61	0.70	1.68	0.66	0.83
Rabi	1.97	0.40^{Ω}	1.56	1.63	1.70
Total Food grains (*Kharif*+*Rabi*)	*1950-1990	*1996-2015	[16]2011-2015		
	2.7^{*}-$3.0^{£}$	1.2	1.8		

Data sources:
‡ Milsi et al. (2010);
*Gadgil (2012)
$^{\Omega}$Values affected by base year production and short time span including several drought years, affecting Rabi production.
[16]Reserve Bank of India database, 2016.
https://www.rbi.in/Scripts/PublicationsView.aspx?id=16463

most farmers (upto 80%) rely on ground water use for timely crop management operations. Over the decades, dependency on groundwater has not declined even in excess rainfall years [17]. This has resulted in significant decline in water tables in many areas [2-3], as well as seems to have reduced the groundwater storage in India. Over drafting of ground water at rates higher than the recharge rates, increases energy consumption for lifting water from the lowered aquifers. Over drafting in coastal areas is resulting in saline water up-coning and water quality decline which threatens the crop productivity. The problem of declining water tables can be tackled through efficient management of rain and canal water supplies, crop substitutions, and adoption of better bet agronomic and irrigation measures.

Agriculture is practiced on a total 194 Mha of gross cultivated area, comprising 95 Mha of irrigated and close to 100 Mha of rainfed agriculture. For food grains production 128 Mha is cultivated to produce 278 million tons of food grains. Several reports indicate that irrigated agriculture is more efficient than the rainfed agriculture in terms of resource utilization and food production. However, rainfed agriculture is important because it has untapped potential for increasing food production through innovations.

Rainfall-Agricultural Productivity-Poverty Nexus

Eastern India receives high rainfall (1000-1700mm/Yr.), increasing in the easterly direction (with longitudes). Most rivers flow from west to east. With the run of the rivers, finer textured alluvial soils are formed. In the Ganges, Brahmaputra and Mahanadi alluvial plains, hydrological situations favour high runoff from the catchment after a rainfall event besides large tracts subjected to inundation during monsoon months from July to September. In Eastern India, nearly 6.74 Mha area remain fallow during Kharif seasons due to flooding [18]. These ecologies give rise to serious land ownership conflicts besides affecting the way crops are grown by the farmers on these lands.

As we move from west to the eastern districts located between 78.83 and 86.13° North longitudes, a strong connection between rainfall, agricultural productivity and poverty begin to emerge (Fig.1). Increasing rainfall decreases agricultural productivity leading to increased poverty of the farm house holds. This is because of the complexities of the ecologies of the C*haur, diara and tal* land (low lands) found along the rivers and their tributaries, which get flooded during monsoon season and fields become available very late for planting of Rabi crops during winter season. In all such agro-ecologies technologies should be targeted appropriately and there is a need for a paradigm shift in the way crops are particularly established and managed [19,21]. Improving crop production in highly risky environment requires a fresh look at seeding and tillage practices, choice of crops and their cultivars for harnessing the full potential of these complex ecologies.

Summer Monsoon Rains (SMR)

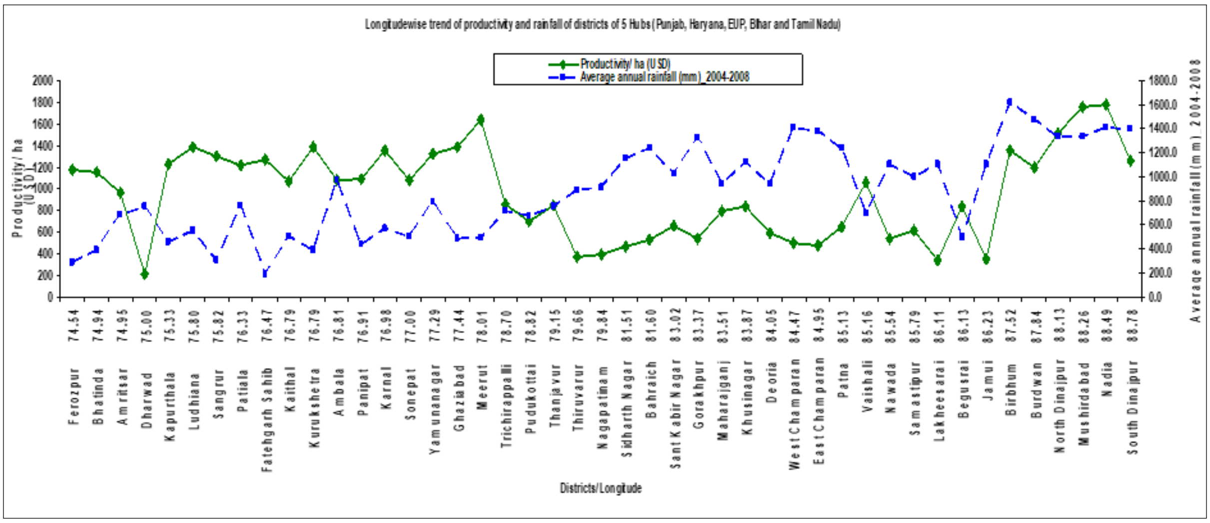

Figure 1. Productivity and rainfall trends in different districts.
(Source: Gupta and Yadav, 2014).

In spite of significant strides in research and development, uncertainty of good crop harvest continues as ever in rainfed dry lands, low lands, black soils and the hilly regions. Large areas remain fallow during Kharif and Rabi seasons. The main source of uncertainty in the Indian agriculture is the high variability in the amount, intensity and distribution of monsoon rainfall events (spatial and temporal variations). One can find areas of negative rainfall shocks (droughts) as well as areas having positive rainfall shocks (excessive) almost every year. The main crisis of Indian agriculture is rooted in our inability to manage spatial and temporal variations related with onset and withdrawal of monsoon rains, and related features across regions. Monsoon features have a significant influence on annual crop production cycles beginning with the Kharif season. Any delay in planting of Kharif season crops, delays field vacation and also delays seeding of succeeding Rabi season crops which reduce crop productivity. For example, late plating in wheat after mid-November reduces its productivity at the rate of 30-45kg/ha/day[22,23].Uncertain monsoon rains results in negative monsoon shocks (drought), deepen water crisis and increase food security concerns. Positive rainfall shocks (excessive rainfall) result in flash floods, adversely affecting crop production.

Unique Features of SMR and Land Degradation

India's summer monsoon rains (SMR) are unique in many ways. Rains are bimodal in nature and more than 85 percent is received through southwest monsoon in the summer season. Winter rains through northeast monsoons constitute only 10-15 of the total rainfall but are important for Indian agriculture. Summer rains are highly variable in space and time and are received in several high intensity storms following the prolonged hot rainless summer periods. Country experiences drought and flood situations in one or the other part at the same time or even at the same place at different periods. South-west summer monsoons usually arrive by mid-June and are active up to September. About 10-15% of the average annual rainfall of 1170 mm is received in few short spells as pre-monsoon showers (May – June). Pre-monsoon showers provide relief from the sweltering summer heat conditions. During peak summers, surface soil layers attain high temperatures of upto 48-50^{o}C or even more. Hot summers desiccate and sterilise the soils and burn soil organic matter. Pre-monsoon rains in summer deep ploughed bare fields, promote slaking and break down of soil aggregates such as to facilitate erosion of fertile soil with runoff water. Thus, in the SAT region, land degradation by erosion is largely a monsoon phenomenon spread over a period of two months involving the loss of some or all of the following: soil, soil productivity, vegetation cover, biomass, biodiversity, ecosystem services, and environmental resilience [24]. Achieving land degradation neutrality and ensuring food security are among the key UN sustainable development goals. Land degradation is an insidious process which becomes obvious only when a considerable damage has already been done. Reversing processes that contribute to land degradation are central to water availability, soil health, adapting to climate change and food security. Poorly managed soils are highly prone to land degradation during the rainy season.

Summer Monsoon Rainfall Variations and Food Production

Summer monsoon rains (SMR) characterised by a range of inter-annual variations, is a reliable facet of Indian weather [15]. The long term (1871-2006) average summer monsoon (Jun- Sep) rainfall has been reported to be 852.4 mm and droughts have been frequent and often widely spread [14].But droughts never cover the whole of the country in one go. For the period between 1960- 2005, mean annual rainfall was reported as 911 mm and 161 mm, for Kharif and Rabi seasons, respectively [8]. Inter-annual summer monsoon variations from the long term mean vary between 70% and 120% with standard deviation of about 10 percent [15]. Summer monsoon anomaly, was defined as the difference between the summer rains of that year and the long term mean, and expressed as a percentage of long term average.

When SMR anomaly is large, most parts in the country have a similar experience of excess water or drought. But when the anomaly is within ±5% (close to its average value), there is a large spatial variation in rainfall- indicating excess in some and deficit rains in other parts. Dips in food grains production during the Kharif season coincide with seasons of major deficit rainfall. A correlation (r =0.76**) of Kharif food grains production with rainfall anomaly suggests that monsoon rainfall has a significant impact on Kharif production [8,15,25,26] and major dips observed in 1967, 1979, 1987, 2002 and 2009 coincided with large deficits in monsoon rains [14,15]. On the other hand, rainfall during the Rabi reason is too little to influence Rabi food grains production (r = 0.11). These researchers have shown that the impact of monsoon variations vis-à-vis SMR anomaly on total food grain production has been asymmetric (non-linear) and reached some significant conclusions as under:

1. Impact of deficit rain fall has not changed over time. The negative impact of deficit rainfall has remained as large at present as it was over the past several decades.
2. Deficit rainfall impacted total food production more than the surplus rainfall, and
3. Before 1980, water was the primary resource limiting food production but in recent times other factors are determining crop productivity in years of normal and excess rainfall (Table 2). Post 1980s, response of positive SMR anomaly on food grains production has declined.

Reduced crop response in seasons of better rainfall was attributed to inability of the farmers to use fertilisers and pesticides well in time. Beside this, the reduced crops responses could be ascribed to processes of land degradation resulting from increased runoff and loss of fertile surface soil.

Monsoon Rains and Water Availability

On an average, a total of 4000 billion cubic meter (BCM) of rain water annually enters the hydrologic cycle over the Indian land mass. This has to find its way into rivers, large storage reservoirs, lakes, tanks and low lying areas (*Tal lands*) and percolate through soils to join the ground water. A significant amount of infiltrated rain water also gets stored as soil moisture in the rootzone to meet evapotranspiration demands of the plants. Due to topographical and other constrainsts, the total utilizable water resource potential was estimated in 2011 at 1137 BCM comprising of 690 and 447 BCM of surface and ground water, respectively [27]. It is estimated that nearly 253 BCM of total rainfall (6.3%) is stored in large reservoirs, 300 BCM is supplied through canal networks and 130 BCM is used through pumping from ground water aquifers [28].Average supply of green water (rainwater stored in soils), estimated at 1070 BCM annually, is about 26% of the total precipitation received over the main land (Gandhi and Bhamoriya, 2011).In spite of a significant contribution of the green water supplies, National Water Policy [29] ignores the importance of green water and emphasizes on building rain water harvesting structures with little attention to rainwater management, it's *in situ* storage and efficient use during

Table 2. Impact of summer monsoon rain anomaly on food grains production (%) for the period (1950-1980) and (1981-2004).

SMR anomaly	Food Grains Production %	
	1950-1980	1981-2004
-25	-19.13	-18.81
-20	-14.41	-13.29
-15	-10.13	-8.65
-10	-6.30	-4.89
-5	-2.93	-2.00
0	0.00	0.00
5	2.48	1.12
10	4.50	1.37
15	6.08	0.73

Source: [15]Gadgil (2012)

the crop season. Engineering bias for creating more and more blue water has encouraged widespread run-off, soil erosion and land degradation. Several recent reports emphasize that additional gains in food systems in 21st century, will likely come through improvements in rainwater management linked green supplies [30, 31]. Although ground water irrigation has been one of the prime drivers of increased food grains production, its use is increasingly becoming unsustainable in many areas due to over-mining. As a result water tables are falling in many parts the Indo-Gangetic plains and elsewhere in the country [3, 4].

Climate Change and Food Security

Evidences presented earlier (section 2.1) have shown that rate of growth in food grains production has considerably decelerated. Besides climate change other factors which have contributed to declines in food grains production include (i) slowdown in expansion of crop lands during Kharif and Rabi seasons, and (ii) declines in solar radiation due to atmospheric pollution. In the arena of food security-climate change research, the most prominent facet is global warming which impacts the amount of rainfall, its intensity and frequency of extreme events. Besides rainfall anomalies, average temperatures have increased by 0.25^{o}C during the Kharif and by 0.6^{o}C during the Rabi season over the last five decades [8]. Temperatures are likely to rise in India by 3-4^{o}C by end of 21st century [32]. Published reports suggest that recent warming has potentially reduced Rabi crop yields by 6% [33, 34], and increased irrigation water demands by about 5% [8]. Thus, projected warming over rainfed dry lands can exacerbate water scarcity and further depress crop production [25, 26, 35].

Recent research findings (Table 3) indicate that rainfall deficits during Kharif, result in larger yield declines than in the Rabi season. Excessive rainfall can also result in higher crop losses in Kharif season [25], possibly due to water congestions and States using canal networks to spread flood water as a flood control measure. Effect of rainfall and temperature anomalies on yields of the Kharif and Rabi crops has also been studied recently for the irrigated and rainfed conditions [25, 36]. It was observed that any deficit rainfall (drier anomaly) and rising temperature anomaly (warmer) can potentially reduce the yields of both Kharif and Rabi crops. Temperature anomaly impacts Rabi crop yields more than yields of Kharif season crops. Yield reductions due to temperature anomaly are likely to be more in unirrigated than in irrigated situations [36].The study also indicated that each additional dry day (days with < 0.1mm rainfall) during the monsoon season can decrease yield of Kharif season crops by 0.2 -0.3% in unirrigated/ irrigated situations.

Carbon Sequestration and Adaptation to Climate Change

Globally, soils have been considered a large carbon sink but Indian researchers have long lived with a notion that carbon status of Indian soils cannot be enhanced under tropical climates. Several studies in recent years have examined the potential of Indian soils to sequester carbon [37-40] through efficient use of fertilizers, zero-tillage, residue management, use of

Table 3. Impact of climate shocks on yield decline of *Kharif* and *Rabi* season crops.

Crop Season & Water provisions	Yield Decline (%)	
	Rainfall anomaly (Drier)	Temperature anomaly (Warmer)
Average *Kharif*	12.8	4.0
Irrigated	6.25	2.7
Unirrigated	14.7	7.0
Average *Rabi*	6.7	4.7
Irrigated	4.1	3.0
Unirrigated	8.1	7.6

Source: [36]Economic Survey of India (2018) amendments, water management, crop substitutions etc. These practices can mitigate more than half of the total GHG emissions in India [41-43]. Recently, it has been indicated that even though soils are almost essential for us to survive climate change, they are unlikely to help remediate this change [44]. Therefore, it would appear that the current emphasis on carbon sequestration as the primary goal of mitigating climate change is somewhat misplaced and an 'inverted' priority. This is because what were considered as secondary benefits (improved rainwater storage, reduced soil erosion, and growing more food) must indeed be viewed as primary objectives of research and development towards better farming.

The chief concerns of the farming community relate to (i) rising farm costs and declining incomes, and (ii) increasing risks on account of weather uncertainties more than climate changes in the long term [45, 46]. Therefore, the role of soils in weather proofing agriculture through moisture infiltration, retention and storage and enhanced availability in periods of intra-seasonal abnormalities in monsoon rainfall, holds tremendous potential. Practices that improve rainwater interception and storage include: minimal soil disturbance (zero tillage), retention of crop residues, use of cover crops, use of farm yard manure etc. [47]. Results of long term experiments conducted for more than 4 decades on Mollisol, Inceptisol, Alfisol and Oxisol group of soils in India have shown that use of organics together with balanced fertiliser nutrient applications, improve SOC, infiltration rates and moisture retention [48-50]. In adapting to climate change, technologies such as small farm ponds linked to canals add to the value of the stored soil moisture and enable farmers, efficiently handle the 'manageable part of climatic variability' by improving the adaptive capacity of agriculture [51]. For reducing the risk and enhancing the resilience of rainfed agriculture, blue water use is considered a must for extracting best productive value of water [52-55]. However over the past decades wherever blue water availability has increased, there is a tendency on the part of the farmers to neglect the importance of green water management which only contributes to unsustainability of irrigated agriculture.

Indian Agriculture: The Challenges

During the Green Revolution era (1960s to 1980s), intensive use of external inputs in agriculture altered the production environments and helped in realizing the yield potential of improved dwarf crop cultivars. In high rainfall eastern India and in arid and semi-arid rainfed dryland regions wherever it was not possible to alter the production environment, benefits of green revolution could not be extended to the farmers. On the whole, enhanced input use strategy leap frogged India's food grains production from 50.82MT/year to 275.8MT/year in past seven decades. Fivefold increase in production has come from a cropped area of 124.9Mha. In the ensuing sections we very briefly outline the key challenges now faced by Indian agriculture.

Declining Land and Water Resources

Over the past many decades, the net cultivated area in the country has fluctuated around 140Mha. In the face of increasing population, there is no possibility of expanding agriculture into new areas. Indeed for a variety of reasons such as increasing urbanization and industrialization, the area devoted to agriculture is likely to decrease. With current crop-water management practices, fresh water needs of Indian agriculture by 2030, are projected around 1500 billion cubic meter (BCM) as against the current water availability of 740 BCM [56]. The projected water demands for agriculture is close to total availability of blue (430BCM) and green water (1070 BCM). In the face of climate change, increasing population and additional water demands from other sectors of national economy, the country is heading for an acute water crisis. Agriculture will be required to (i) use water more efficiently, (ii) spare some fresh water for domestic consumption and also (iii) develop new technologies for re-use of water emanating from domestic use (grey water). All this calls for new investments in adaptive agricultural research.

Declining Food Growth Rates and Poor Adaptation to Climate Change

Total acreage of all the food grain crops is 125Mha. This is about 66 percent of the gross cropped area, as of now. Data presented in earlier sections indicate that the current Kharif food grain production growth rate is 0.83MT/ Yr. which is almost half of that observed during Green Revolution era. Rabi food production is relatively more stable (1.56- 1.70MT/Year).

Higher growth rate in Rabi food grains production [57]is consistent with increased irrigation support and significant yield gains of genotypes bred for irrigated environments until 2000 [58,59]. The lower growth rate of Kharif food grains production can be ascribed to higher biotic and abiotic pressures during the rainy season, low input risk management strategies adopted by the farmers, lesser use of hybrid seed, genotypes successively developed for rainfed upland environments having no-significant yield gains [58], decline in water tables [60] and climate change shocks (moisture deficits/rainfall anomaly shocks). Climate shocks on crop yields are often more prominent in rainfed areas during the Kharif than the Rabi season [25].Declining yields have been reported to be a worldwide phenomenon associated with droughts, declining soil health and overall land degradation [61] and climatic factors [8,14,36,62]. In view of multifaceted nature of threats, there is a need to spread risks in a manner that improve farmers' livelihoods and food security. This calls for encouraging farmers to cultivate a wider diversity with specific traits and gene pool and also harness genotype x tillage x environment interactions to improve crop yields and reduce production costs.

Stagnating Crop Yields

Stagnating crop yields in general, are a consequence of a number of factors affecting crop production. A better understanding of these factors is critical to defining strategies for sustainability of Indian agriculture. Post 2000, declining food production trend in Kharif season and a flattening in the Rabi season, is viewed as the tipping point of Indian agriculture. It has brought into sharp focus issues related with deteriorating soil health, climate change and the declining water availability for irrigation. Timely planting as a stand-alone practice can improve wheat productivity mentioned earlier [22, 23].The troubling report from Ray et al. [63] have indicated that India is becoming a hotspot of yield stagnation with more than a third of its maize, rice, wheat and soybean areas (total area under 4 crops ~ 85 Mha) not witnessing yield improvements for a decade or so (Table 4). It is also observed that yield gaps ($Yield_{max}$ – $Yield_{observed}$) remain large for rice and maize [64]. These large gaps come mostly from low farm yields for rice in rainfed regions of South Asia and rainfed maize regions in the hills. Low productivity of maize in the sub-humid hilly tracts is known to be due to stresses due to moisture and soil acidity, use of open pollinated varieties and non-availability of liming material from nearby sites. Similarly productivity of soybean crop grown primarily on the black soils in Madhya Pradesh is dwindling due to late planting, emergence of micronutrient deficiencies, temporary waterlogging, white fly infestation and weed pressure during the rainy season. Therefore stagnating crop yields or yield gaps in different crops are often a consequence of institutional and technology fatigues and natural resource management problems lacking required location specificity. Therefore, farmers need to move from principles of agronomy to place-based agronomy [65]and try to develop infrastructure and institutions for the myriad value chains that millions of farmers need for the financial incentive to adopt new cropping systems

Table 4. Yield trends of some major crops in India.

Crops	# of districts growing	Total Crop Area. Mha in 2015.16	Number of Districts with Yield growth Trends in Categories		
			Stagnated, Never recovered, collapsed	Increasing slowly, increasing Moderately	Increasing Rapidly
Rice	313	43.39	56		32
Wheat	162	30.23	42	101	19
Maize	343	8.69	133	181	29
Soybean	77	11.67	37	28	12
Total		93.98			

Source: Ray DK et al. (2012)

[64].In order to unlock the production potential in all such districts where yields are not looking up, there is a need to delineate resource management domains, prioritize production constraints and identify appropriate strategies for overcoming the yield barriers [21,51,66,78,79].

Nutrient Mining and Imbalances

Fertiliser nutrients are added to soil to replace those lost through crop off-take and other processes. It must be our endeavour to continuously replenish for any loss. For arresting and reversing soil degradation processes, soil organic carbon, soil microbes and soil moisture retention and nutrient supplies are critical for biomass production. Soil carbon sponge is of great significance for its influence on the soil ecofunctions, enhancing soil productivity, improve nutrient and water use efficiency, reduce production costs and significantly benefit the environment. Use of chemical fertilisers have played a crucial role in realising the potential of modern cultivars. In 2017-18, although a total of 26.7 million metric tons of chemical fertiliser nutrients were consumed in agriculture, yet the overall net nutrient balance was still negative by an order of 12-14 million tons [5]. The N: P: K use ratio which presently fluctuates around 8:3:1, only points to a bias towards excessive use of nitrogenous fertilisers and less use of P and K nutrients. A skewed N: P: K ratio adversely affects soil health in different regions of the country. Imbalanced fertiliser use for long time is known to decrease active fractions of N and C, deplete soil fertility through reduction of labile sources of nutrients, and of particulate organic carbon etc. [1]. In improving the use efficiency of macronutrients, micro-elements play an important role. It is estimated that agricultural crops remove nearly 188 thousand tons of micro-nutrients each year, resulting in emergence of multi-nutrients deficiencies [13].

Reducing our dependence on chemical fertilisers is a laudable objective but has yet to ignite a debate on shifts that will be required from our singular focus on fertilisers. To save on fertilisers, we need to (a) emphasize on the potential agronomic practices that reduce use of synthetic nutrients, and (b) identify and adopt production management systems such as CA that have a targeted effect.

Large Acreage of Kharif and Rabi Fallow Lands

The term fallow lands refer to cultivated areas which are left uncropped in one of the two crop seasons [*Kharif (rainy season) /Rabi (winter season)]* due to inability of the farmers to plant a crop on them due to various reasons. Over past few decades, acreage of total fallow lands in India during the Kharif and Rabi seasons has fluctuated around 25Mha. The acreage of Kharif and Rabi fallows is estimated at around 14 and 11 Mha respectively [18, 66-70]. The problems associated with land fallowing could not be resolved thus far because institutional deficits did not allow a fuller understanding of the problems associated with their cropping. Gupta et al. [66] have pointed out that Kharif and Rabi fallow lands are found in different domains due to distinctly different soil moisture regimes operating in the respective seasons. Whereas seeding practices contribute to Kharif fallows, excessive tillage practices and inadequate soil water conservation practices may add to the acreage of the Rabi fallows in black soil region of Central India Plateau region. In the eastern Gangetic plains, Chhattisgarh and Orrisa, farmers have to leave their field fallow after rice harvest due to excessively wet soils or traditional tillage practices resulting in loss of soil moisture and crop ending up in terminal heat stresses due to delayed Rabi seeding operations [71].

Climate Change Challenge

Climate change has emerged as an overarching challenge to Indian agriculture. Low air quality due to particulate black carbon and dust is known to affect the solar radiation affecting maxima-minima temperatures. Long-lived greenhouse gases (LLGHGs) have had and will continue to have significant negative impacts on crop yields. Research in the last decade has underscored the critical importance of climate changes caused by short-lived climate pollutants (SLCPs) such as black carbon and ozone which impact temperature, precipitation, and radiation. Ozone—is known to be directly toxic to plants. The combined effects of climate change and the direct effects of SLCPs on wheat and rice yields in India has been studied. It has been reported that gains from addressing regional air pollution could counter expected future yield losses resulting from direct climate change effects of

LLGHGs [72]. Wheat yield losses in India due to elevated tropospheric ozone (O_3) and aerosol pollution has been around 30% - two third from ozone and one third due to aerosol pollution [73].

Field surveys conducted in Punjab during 2009-10 revealed that wheat production was affected in the range of 10-26 % due to rise in temperature at reproductive and grain filling crop stages [74]. Heat shocks during grain filling stage in Indian winter wheat has the potential of rendering 40% of the presently favourable wheat growing areas into unfavourable category [75-76]. Global warming also impacts the monsoon patterns, amount, intensity and frequency of extreme rainfall events. High intensity rainfall in short spells is resulting in frequent floods and lot of land degradation through soil erosion and flooding.

Sustainabile Agriculture and Land Management Practices

Sustainable agriculture is envisioned as a continuous process of identification and prioritization of complex natural resource management constraints for enhancing productivity. It requires continuous improvement in strategies, institutional innovations and robust technologies to handle NRM issues. The five broad principles of agricultural research and development contributing to sustainability [51]include (i) more crops per drop, (ii) reduce the use of fertilisers& pesticides, (iii) improve soil health, (iv) adapt to climate change, and (v) increase farmers' income for a decent living. Farmer income touches upon marketing innovations, value chains, equity, effective governance, social well-being and livelihoods of farmers. In recent decade the concept of 'Conservation Agriculture (CA)'has emerged to serve as the common thread to tie the five above inter-connected principles for achieving the goal of sustainable crop production. CA principles as part of sustainable land management systems offers huge potential for nursing depleted arable soils back to health, improve agriculture through enrichment of soil organic matter, reduced erosion, improvement in soil moisture storage, soil structure, reduced surface crusting (e.g. in Red soils) and cracking (e.g. in black soils) besides reducing the costs of production.

Prioritizing the Management Actions

Sustainable agriculture relies on sustainable land management (SLM) principles which ensure achieving land degradation neutrality and sustaining food security [6]. The golden SLM principles include (a) build-up of soil organic matter and related biological activity, (b) improve rain water entry into soils (in situ rainwater storage) and rainwater management, (c) improve rooting depth, soil-water permeability, and (d) commissioning of appropriate soil water conservation measures with greater reliance on vegetative measures. Thus, SLM technologies are agronomic, vegetative, and structural and management measures that help us avoid, reduce and reverse land degradation through restoration or rehabilitation of land and enhance crop productivity [24].

This discussion brings out that our priorities in planning land degradation neutrality interventions should follow a response hierarchy:

Avoidance > Reduction > Reversing degradation/Rehabilitation/ Reclamation

Although all the 3- transects (head end, middle portions and tail ends) have to be handled carefully in the watershed approach, it must be kept in mind that activities must proceed from less affected areas (at the head end) to severely eroded areas (tail end) to be successful.

Ecoregional Approach and Resource Management Domains (RMD)

In 1980s, India established 120 zonal research stations (ZRS) in different agroclimatic zones (ACZ) for solving locally identified problems of land and water resource degradation and crop productivity. In the ACZs, agriculture production and land use systems generally co-evolve in response to shifts in consumer demands, production costs, pricing, procurement policies and infrastructure interventions. Since production systems depend on the quality of resource attributes and available management options at specific locations, integration of biophysical, social and economic parameters is required to characterize land management units, also referred to as resource management domains (RMD). Whereas ACZ refer to homogenous biophysical units, RMD concept integrates socio-economics with biophysical features of zones to define an area by resource issues for successful resource management and to handle the production constraints [77]. Thus, RMD is a relatively homogenous tract of land with common underlying socio-economic characteristics with inherent suitability for specific uses. RMD concept can be used at different levels – (i) understand system ecology issues at regional level (e.g. herbicide resistance in *Phalaris minor* in R-W system of northwest India), (ii) identify production constraints (e.g. late planting of wheat),(iii) priority setting at district/ block level (e.g. declining water table), and (iv) assessment of options for tackling NRM problems at the village / field level (e.g. direct seeding or laser land levelling). Well focussed diagnostic surveys can help unravel the cause-effect chains, institutional arrangement needs and farming system interactions for expanding the range of management options [78]. To address the challenge of resource degradation, climatic risk management and low input use efficiency, RMD concept has been advocated to promotes the use soil test based fertiliser recommendations and address issues related with soil sample over-crowding in testing laboratories and problems associated with timeliness of farm advisories [66,79]. The RMD concept has also been invoked for management of saline environment, offer alternate land use options in Mewat, Haryana [51] and better understand the causal factors leading to seasonal land fallowing and identify the crop-soil-water management practices (CSWMP) for possible double cropping [66].

Land Degradation-Climate Change- Food Security Nexus

Achieving land degradation neutrality and ensuring food security are among the key UN sustainable development goals [6]. Loss of biodiversity and climate change complicate land degradation and soil health issues through loss of organic carbon, temperature rise, GHG emissions, changing rainfall patterns, water scarcity etc. These changes significantly alter the suitability of many areas for biomass production. The nexus (fig.2) calls for approaches and actions that promote soil health, *in situ* soil moisture storage and use of the water to enable farmers grow more crops and provide surface cover to soils to prevent run off and soil erosion.

While summer monsoon rainfall is the life-line for Indian agriculture, runoff water mediated soil erosion processes at the same time result in loss of soil carbon, nutrients, moisture and contribute to reduced biomass production as well as restricting the farmers' choices for diversification (biodiversity). Thus, Indian summer monsoons are both a boon and a bane, contributing to water supplies and land degradation, respectively. Loss of soil organic carbon at elevated summer temperatures and loss of surface soil by beating action of summer monsoon rain drops are by far, the major processes of soil degradation in the Indian subcontinent. Reversing processes contributing to land degradation is central to water availability, soil health, adapting to climate change and food security. It would also appear from fig (5) that rain water management has to be a crucial element of any strategy that enhances gene diversity and sequesters more carbon to offset the climate change effects, builds resilience and reverses land degradation.

Gene Management and Crop Productivity

Success of small holder farmers always depend on manipulations of their on-farm resources through a host of crop-soil-rainwater management practices. These practices included adjusting the sowing dates of crops, cultivar choices, crop rotations, mixed cropping/ farming systems etc. The underlying aim of these practices was always to make efficient use of rainwater. Traditionally,

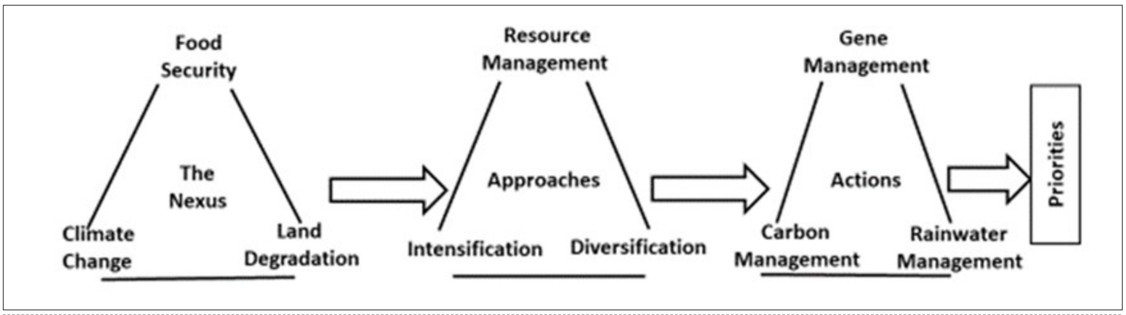

Figure 2. Land degradation-food security- climate change nexus.

many farmers have practised tree-crop-livestock mixed farming systems in the fragile arid environments as a response to frequent climatic aberrations. Arid zone farmers adopt vigorously growing crops such as cluster bean, moth bean, pearl millet, henna and cotton which need less water and also make best use of rainwater made available in short spells. These crops are not only responsive to use of external inputs but are also attuned to make good use of prevailing nutrient, moisture and thermal regimes of soils. Use of appropriate land races in crop improvement programs can further enhance gene diversity (gene management) and make agriculture more resilient to biotic and abiotic stresses. High heterogeneity and uncertainty of rainfall patterns in rainfed environments make crop improvement scientist's task extremely difficult. For rainfed agriculture, any crop improvement strategy must focus around efficient use of limited and uncertain soil moisture storage supplies which need a better understanding of rainfall variability, soil properties and moisture and nutrient release patterns of the soils.

In the drought prone, high temperature rainfed environments of the SAT region, farmers generally cover their risks through mobile household livestock capital. Since livestock need fodder to survive and be productive, preferred crop improvement objective should be to increase plant biomass over harvest index, develop some stress tolerance, harness the genotype x tillage x environment interactions and reduce production costs. Such an approach will greatly promote the primary livestock industry of rainfed dryland regions in the country. Clark-Sather et al. [81] have indicated that mulching the crops whose water demands are attuned to seasonal rainfall cycles, allow for enhanced rain water use during periods of peak rain fall. In adapting to climate change, technologies that focus on 'manageable part of climatic variability' also play an important role in improving the adaptive capacity of agriculture [51, 66]. Hoff et al. [82] indicated that improved nutrient management and supplemental irrigation can further enhance the crop choices.

Crop Production and Resource Conservation

Crop production and conservation of natural resources are parallel objectives but often pursued in isolation through fragmented schemes of the local governments. Production management systems require promoting adoption of soil, water, and crop management strategies that build soil organic carbon and improve resource use efficiency together with enhanced production. Conservation agriculture (CA) is one such innovative approach to management of production systems, which is close to organic farming. CA allows use of agrochemicals and its yield potential is hardly debatable, unlike the organic farming. The concept of CA rests on four broad entwined management principles: (a) drastic reduction in soil disturbance and adoption of direct sowing, (b) maintenance of a continuous vegetative soil cover; (c) sound crop rotations and (d) avoid free-wheeling to reduce soil compaction. CA based production systems mimic natural agroecosystems and hence result in numerous environmental benefits such as decreased soil erosion and water loss through runoff, decreased carbon dioxide emissions and higher carbon sequestration, organic matter build-up, efficient nutrient cycling, reduced fuel consumption, increased water productivity, reduced flooding, enhanced recharge of underground aquifers [6], reduced compaction in the subsoil, and cracking in black soils. CA has the targeted effect in reducing the use of synthetic fertilisers through slowed soil organic matter (SOM) decomposition, reduced soil erosion during rainy season through residue retention and brown manuring (green manure crop knocked down through herbicide to provide surface mulch) and avoidance of summer deep plowing. CA is carbon efficient and sequesters more organic carbon which is central to continued delivery of soil ecofunctions [41, 42,83,84].

Globally, there is a fair degree of consensus that conservation agriculture principles can be an important component of any national strategy to produce more food at lower costs, improve environmental quality and preserve natural resources [6,85,86]. No-till CA promotes crop intensification, employment opportunities, inclusive economic growth and small farmers benefit most from it.

Low yields are linked to poor soil health and inefficient water management practices. For improvement in yields of different crops, there is an urgent need to improve agriculture water productivity through a mix of improved water application, soil moisture and tillage management practices linked with soil health [23, 87].

Given the fact that surface flooding is the most used water application method in India and elsewhere, there is an urgent need to promote the use of lay-flat gated pipes to surface irrigate the crops established in permanent ridge-furrow planting system [88, 89]. Pressurised sprinkler systems must be promoted in rolling toposequences. Drip system is best under marginal conditions of soil, water quality and climate. Although drip systems save little more water than gated-pipes and sprinklers, in our experience, the latter are easily moveable and more farmer friendly in operations.

Direct dry seeding practice has the potential of improving the rain water productivity, reduce soil erosion hazards and make planting season independent of rainfall predictions [66]. Dry seeding of rice eliminates puddling to save at least 25 cm irrigation water besides improving the productivity of succeeding wheat crop [23, 87]. Practices such as laser assisted precision land levelling, zero tillage, dry seeding, surface seeding, mulching, cultivars with early vigour, etc. save irrigation water, reduce evaporative losses, improve infiltration, soil water storage and crop productivity [6,87,90,91]. Molden et al. [91] have suggested that in areas with low water productivity such as in South Asia, reducing evaporation and improving soil health are still the important options for increasing water productivity. Addams et al. [56] have pointed out that India's base case 2030 water supply-demand gap could be solved with agricultural measures, provided there is a strong shift in favour of conservation agriculture and a will to invest in water management.

Summary and Conclusions

Hot summers followed by summer monsoon rains result in loss of organic carbon and fertile surface soil with runoff rainwater. Indian agriculture therefore, must promote approaches that integrate concerns of land degradation during monsoon season, declining water availability, gene diversity and climate change. In weather proofing agriculture, soils can play a tremendous role through moisture storage, its retention and enhanced availability in periods of intra-seasonal abnormalities during monsoon rains. Making Kharif crop sowing time independent of the onset of monsoon rains is equally important for the Indian sub-continent and to reduce crop losses due to land fallowing, late planting, soil moisture and terminal heat stresses beside providing a surface cover against monsoon rain-enhanced soil erosion to prevent loss of fertile surface soil. Practices that improve rainwater storage include: direct dry seeding, minimal soil disturbance (zero tillage), retention of crop residues, use of cover crops, and use of farm yard manure etc..

Indian agriculture made some rapid strides during the green revolution era but food gains and its growth rates have subsided after 2000s due partly to fatigue of natural resources and poor R&D investments. Additional food has to now come through increased productivity routes. In spite of developments of large canal networks, rainfed agriculture has continued to be important involving large acreage, however, the untapped potentials for increasing food production through innovations in agricultural practice such as efficient rainwater management, carbon and gene management. For improving productivity in the rainfed areas, crop water demands need to be attuned to seasonal rainfall cycles and allow for enhanced rain water use during periods of peak rainfall. Plant breeding strategies for rainfed dryland systems should focus on increasing plant biomass, develop crop stress tolerance and harness genotype x tillage x environment to improve crop yields and reduce production costs. This can be achieved through a shift from crop based to resource based research and developmental planning. Conservation agriculture is likely to be at the center stage of such a change to reduce production costs. Targetting technologies appropriate to enhanced efficiencies of resource management domains can reduce the acreages of fallow lands besides improving stagnating crop productivity. The primary goal of climate smart agriculture should be to improve rainwater storage, retention and availability in periods of intra-seasonal abnormalities and reduce soil erosion through conservation agriculture. From the discussion in the paper, it emerges that national water policy should also focus on *in situ* rain water storage and rain water management practices in addition to rain water harvesting. The paper indicates that conservation agriculture principles can be important components of the national strategy to produce more food at lower costs, improve environmental quality and preserve natural resources. For overcoming stagnating crop yields, farmers need to translate principles of agronomy to placed-based agronomy for better understanding of NRM issues in specific resource domains.

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