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Deforestation, Climate Change and the Sustainability of Agriculture: A Review

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Abstract: This study aims to survey the literature and factual evidence on the nexus between deforestation and agriculture through an assessment of the potential impacts of climate change in the context of the world, India, and the Western Ghats. The Western Ghats region was chosen for this study because of its deep ecological significance. A few underlying themes were created and findings were documented under each theme that ranged from the causes of deforestation, the transformation of forest land for agriculture, the nexus between agriculture, deforestation and climate change, climate-driven agricultural vulnerability and the reconciliation of forest protection with agriculture. These findings suggest that shifting agriculture has been a dominant source of deforestation. The primary climatic impacts on agriculture are seen through crop yield falls. India's arid and semiarid tropical regions have witnessed high climate-driven agricultural sensitivity. This could be on account of the fact that India's tropical forests have witnessed high deforestation. The presence of higher tree densities in areas under Joint Forest Planning and Management in the Western Ghats create the potential for sparing remaining land areas for non-forest uses such as agriculture.

Key words: agricultural sensitivity; agroforestry; climate change adaptability; climate change exposure; deforestation; sustainability

1 Introduction

Agriculture adds approximately USD 6.107×10^{10} to India's aggregate domestic economic output annually (between the first quarter of 2018 and the second quarter of 2021). However, agricultural systems in India and across the world remain exposed to the devastating ecological impacts of climate change, increasing vulnerability, and systemic shocks. A few important factors contributing to the climate-driven vulnerability of India's agricultural system are depicted in Table 1 (projected for 2021–2050). Among the predominant exposure factors, projected fall in July rainfall is the most prevalent among all the regions. Among the predominant sensitivity factors, high net sown area is the most prevalent. Among the predominant adaptive capacity factors, low net irrigated area arises as the most common factor among all the regions. Deforestation is a significant contributor to climate change. Despite this nexus, millions of hectares of forest land are converted for agriculture annually to expand crop production and output. As shown in Fig. 1, shifting agriculture accounted for a reasonable proportion of global annual tree cover loss in 2017, with urbanisation contributing the least.

According to the Intergovernmental Panel on Climate Change (IPCC) 2013 figures, deforestation causes up to 10 percent of anthropogenic carbon dioxide emissions, leading to rising global temperatures. Deforestation could lead to a decrease in rain rate of up to 2 mm day^{-1} over Northern India and an increase in rain rate of up to 5 mm day^{-1} over Southern India, including the Bay of Bengal and the Arabian Sea. Climate change driven by rising temperatures is predicted to decrease crop yield and crop duration. For every 0.5 ℃ rise in temperature, a fall in crop yield to the extent of 0.45 t ha^{-1} and a fall in crop duration was predicted for Indian wheat.

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Table 1 Region-wise analysis of the most important drivers of climate-driven vulnerability of India's agricultural system (2021–2050)

Region (Number of states)	Predominant exposure factor	Predominant sensitivity factor	Predominant adaptive capacity factor	Type of vulnerability
North-East India (1)	Rise in the number of drought years	Low rainfall	Low net irrigated area	Very high
North India (3)	Projected fall in July rainfall, projected rise in minimum temperature, rise in the number of drought years	Low rainfall, high net sown area, high drought proneness	Low density of livestock, low ground water availability, low net irrigated area, high poverty	
Central India (1)	Projected rise in minimum temperature, rise in the number of drought years	Low rainfall, high net sown area, low available water capacity, high drought proneness	Low net irrigated area and ground water availability	
West India (3)	Projected rise in the number of drought years, projected increase in minimum temperature, projected decrease in rainfall in July	Low rainfall, high drought proneness, high net sown area	Low ground water availability, low net irrigated area	
East India (3)	Projected fall in July rainfall, rise in the number of drought years	High net sown area	Low net irrigated area, low ground water availability	
South India (3)	Projected fall in July rainfall, projected increase in minimum and maximum temperature, projected fall in total rainfall	Low rainfall, High net sown area, high drought proneness	Low ground water availability, low net irrigated area	
North-East India (1)	Projected fall in July rainfall	High net sown area	Low net irrigated area	High
North India (6)	Rise in the number of drought years, projected rise in minimum temperature, projected fall in July rainfall, projected rise in maximum temperature	Low rainfall, high drought proneness, high net sown area, low available water capacity	Low groundwater availability, low net irrigated area, low livestock density, high poverty	
Central India (2)	Projected rise in the number of drought years, projected rise in minimum temperature	High net sown area, high drought proneness, low rainfall	Low net irrigated area, low groundwater availability	
West India (3)	Projected rise in minimum temperature, projected rise in the number of drought years, projected fall in July rainfall	High net sown area, low rainfall	Low ground water availability, low net irrigated area	
East India (3)	Projected fall in July rainfall, projected increase in minimum and maximum temperature, projected rise in the number of drought years	High net sown area, flood proneness, low available water capacity, high percentage of area operated by small and marginal farmers, low rainfall	Low ground water availability, low net irrigated area	
South India (3)	Projected fall in July rainfall, projected rise in the number of drought years	Low rainfall, high net sown area	Low net irrigated area, low ground water availability	

Note: This table was adapted from Atlas on Vulnerability of Indian Agriculture to Climate Change, Indian Council of Agricultural Research (ICAR, 2013).

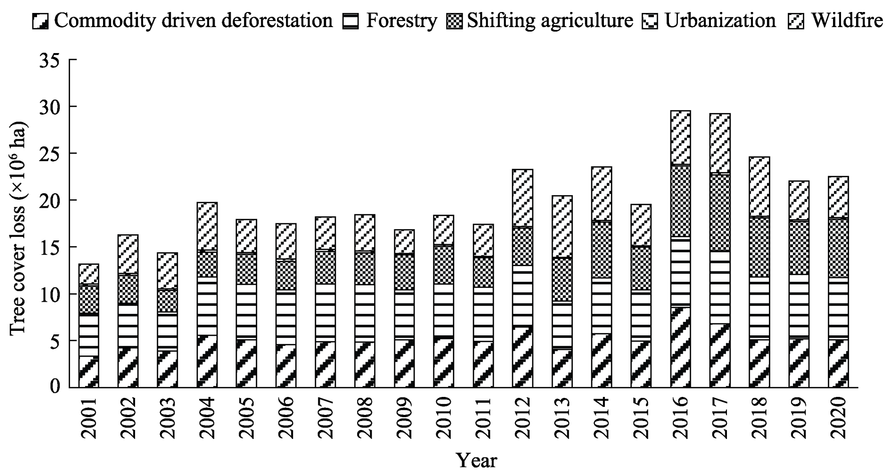

Fig. 1 Global annual tree cover loss by dominant drivers
Note: Source: Global Forest Watch. https://www.globalforestwatch.org/dashboards/global/?location=WyJnbG9iYWwiXQ%3D%3D.

Nearly 46.1% and 22.6% of India's land area are accorded to net-sown area for agriculture and forest, respectively (MoEF, 2009). Despite the negative influence of climate change on agriculture, the diversion of land from forestry to agriculture remains high. This could be due to higher soil fertility and water retention on forest-land which would be suitable for enhancing agricultural productivity. Hence, it is crucial to limit the encroachment of agricultural land into forest zones while also enhancing agricultural output.

The Food and Agriculture Organization of the United Nations has assessed frameworks that integrate forest protection with the development of agriculture in various countries worldwide. Because the two land-use aims are pivotal to support the ecology on one hand and the economy on the other, the application of the stated frameworks in the Indian context requires assessment. The frameworks are driven by the principles of local stakeholder participation, land-use change, and payment for environmental services.

This paper aims to provide evidence on the underlying causes for deforestation, some of the dynamics behind the transformation of land from forest-use to agriculture-use, the nexus between agriculture, deforestation and climate change while highlighting the probable climate change impacts on agriculture, parameters under which climate-driven agricultural vulnerability can be assessed and findings on the reconciliation of land-use for forests and agriculture. Studies in the paper were selected based on their relevance to each of the sub-contexts to be analysed, and their findings were documented to create an emerging storyline. From the selected studies, the respective methodologies, time periods, and regions of focus were also documented to provide information on the scope of the evidence researched. Studies were collected at the global level, in the context of India and in the context of the Western Ghats. The information in Fig. 1 was directly incorporated from the database to project the major drivers of tree cover loss and to highlight shifting agriculture as one of the drivers in one of the years. The information in Table 1 was adapted from the Indian Council of Agricultural Research (ICAR) report to project the most important factors contributing to vulnerability.

2 Projections of deforestation and its underlying causes

Globally, the problem of augmenting growth in the context of deforestation has been studied in line with policy, trade, and population dynamics. An increase in population growth and trade of timber products both increase deforestation. In the Amazon region, the key drivers of deforestation are trade openness and cattle ranching, with significant results of spatially lagged variables indicating the spillover effects of deforestation (Faria and de Almeida, 2013). Yalew (2015) categorically analysed the link between rural poverty and deforestation and stated that high rural poverty creates the potential for forest preservation, as local community power in forest management remains high. The study also extends the dilemma of deforestation to agricultural processes such as shifting cultivation, which has made way for subsistence agriculture and cash crop cultivation in sub-Saharan Africa. The study also pinpoints the relationship between agriculture and deforestation by analysing the contribution of agriculture to gross domestic product (GDP) in high deforestation areas.

Tsiantikoudis et al. (2019) assessed the link between economic growth and deforestation-driven carbon emissions using the Environmental Kuznets Curve (EKC)[①] framework with an N-shaped curve for a country in Eastern Europe. The study also points out that low wages paid to government workers in forest services could cause a greater quantity of deforestation-driven carbon emissions. According to our assessment, this could lead to the potential third phase of the curve. The significance of this finding is in line with the argument that a greater quantity of deforestation-driven emissions indicates a greater quantity of deforestation, and low wages paid to government workers in forest services could disincentivise forest protection.

Insecurity of land tenure has been a major cause for land mismanagement (TERI, 2018). The potential for wealth-generation of India's declining natural resources remains high because of rising resource rents propelled by high extraction rates. Imperfect market structures have been a primary cause of non-optimal resource extraction, which places India in the weak sustainability criterion on account of resource stock declines in the face of rising comprehensive wealth (Agarwal, 2017). Such structures create pressures on the country's forests. India witnessed a 98.7 percent increase in the export of forest products between 1961 and 1971 (Sharma, 1972). This could have been another cause of the decline in the forest area. Government acquisition of private forest property for conversion into national property has been a cause for large-scale tree-felling by private forest property owners to maximise economic returns. India witnessed a rise in fuelwood, charcoal, and sawn wood consumption at compound growth rates of 2.18 and 6.46 percent respectively during 1970–2000 (Malik and Dhanda, 2003), indicating high pressures on its forests.

Rising consumption levels, expanding populations, and agricultural export orientation create grounds for unsatisfied food demand and a subsequent incentive for agricultural expansion into forest zones. This phenomenon is caused by development-induced capital availability. An investment worth USD 3.8×10^9 between Jharkhand's State Government (in India) and mining companies has led to a predicted loss of 57000 ha of forests and a displacement of nearly 9615 families residing in Schedule Areas (Chakravarty et al., 2012). The presence of small landholders does not negate the prevalence of deforestation. Improved opportunities for off-season employment, strong credit markets, and transfers

① The Environmental Kuznets Curve (EKC) represents the hypothesized relationship between economic growth and environmental degradation through the phase of a country's development.

have increased income and rates of deforestation for small landholders. Poor farmer households also lack incentives to account for the environmental effects of their actions, which in turn leads to failures in resource appropriation, policy-making, and local markets. The increasing conversion of forest land for other uses is also a result of improved terms of trade and high real exchange rates for agricultural and forest products.

3 Transitions in land-use from forests to agriculture

Tropical climatic domains have faced the highest reduction in forest area, primarily because of increases in agricultural areas. The highest net reduction in forest area and net increase in agricultural area occurred in low-income nations during the period 2000–2010 (FAO, 2016). The five thousand million ha of land under the management of agriculture exceeds the land area covered by woodland and forests, with almost 13 million ha, primarily from forests being annually converted to agricultural use (FAO, 2002). In the subtropics and tropics, a 62% forest reduction could be attributed to the expansion of commercial cropland along with other land uses (Pendrill et al., 2019).

Nearly 75% of North Korea's forests have been converted to cropland. 69 percent of all converted croplands in the country were originally forested. Deforestation for cropland expansion has led to erosion, runoff, and losses in soil organic carbon, posing risks to crop productivity (Lim et al., 2017).

In India, the total net rate of deforestation has been comparatively steep in the North East in the range of –0.90% and –5.29%, in the Deccan Peninsula at –0.19% to –3.2%, followed by the Western Ghats. India's current estimate of gross deforestation for 2009–2011 is –0.43%, with a global average of –0.6% (Reddy et al., 2013). More than 26.20×10^5 ha of forest were converted for agricultural purposes between 1951 and 1980 (FSI, 1987). A bulk of the woodland that previously covered the Indo-Gangetic Plain was converted to grazing lands or fields (Subramaniam and Sasidharan, 1993). Deforestation has also been attributed to mining and permanent agriculture. Agricultural encroachment has resulted in the loss of mangroves along India's coasts and islands. Overgrazing, expansion of agricultural fields, and shifting cultivation have led to deforestation in the Deccan Peninsula (Reddy et al., 2013). Land clearing, as a means of increasing agricultural productivity, has exacerbated the pressure on forest resources (Haeuber, 1993).

4 Agriculture, deforestation and climate change

Forests play a cardinal role in combating climate change. Approximately 25% of global emissions emanate from the land sector, which, after the energy sector, constitutes the second-highest source of greenhouse gas emissions. Approximately half of these emissions emanate from deforestation and land degradation (IUCN, 2021). One-third of the carbon dioxide released from the burning of fossil fuels which amounts to approximately 2.6×10^9 t, is absorbed by forests every year. Reversing the loss and degradation of forests, along with their rehabilitation can contribute to over a third of overall climate change mitigation, a requirement by 2030, to meet the objectives of the Paris Agreement (IUCN, 2021). On a global scale, issues of changes in water yield, precipitation and surface runoff along with changes in the emissions of greenhouse gases have been analysed in the context of 'slash and burn' forest clearing for agriculture, a mechanism involving the clear-cutting of forestland and burning of remaining vegetation to make land available for cultivation. Oxidation processes of soil organic carbon and the process of soil decomposition on account of 'slash and burn' have led to overall losses in soil organic carbon, a pivotal component for enhancing soil oxygen, water drainage and retention and reducing risks of erosion and nutrient leaching, mechanisms pivotal to the growth of both crops and forests (Tinker et al., 1996). Extensive deforestation in the regions of the northern middle and high latitudes would lead to large decreases in precipitation targeted towards the monsoon regions of the Northern Hemisphere, primarily North America, North Africa, East Asia and South Asia (Devaraju et al., 2015).

The role of forests as carbon sinks is crucial to analyse too. Carbon stocks in forests in India have witnessed an increase to 6621.55 million t from 6244.78 million t from 1995 to 2005. This has translated into an annual increase of 37.68 million t of carbon which is sufficient to offset 9.31 percent of the country's total yearly emissions of the year 2000 (Singh, 2018). Massive deforestation in the northern middle and high latitudes affects the South-Asian monsoon region to the highest extent, with an 18 percent decrease in precipitation over India (Devaraju et al., 2015). Lodh (2017), in his study of the impact of deforestation and desertification on Indian monsoons, concluded that deforestation of any kind in the tropical zones of the Indian subcontinent has a lasting impact on Indian summer monsoon precipitation and circulation. The study also concluded that deforestation and desertification have led to increases in land temperatures owing to lower rainfall over land which is strengthened over the seas. Reduced turbulent flows and anomalous westerly winds, along with subsidence precipitated by lower surface roughness length and increases in albedo, have also occurred due to deforestation and desertification. Reductions in precipitation weaken atmospheric and hydrological water cycles (Lodh, 2017).

Sixty percent of India's cropland, which remains irrigated and rain-fed, could be affected by climate change. This is probably on account of the fact that 60 percent of India's total cropped area remains rainfed and monsoon-dependent as stated by (Mall et al., 2006). High vulnerability to salinisation (increase in the concentration of water salts) and inundation (overflow of water) has impacted climate vulnerability in the country's coastal regions. Minor variations in growing-season temperature over time have affected annual fluctuations in wheat yield, as observed by Mall and Singh (2000). A rise in temperature by 2 ℃ has diminished probable wheat yields in most places in the country. In terms of locational implications of productivity, India's subtropical environments have witnessed smaller decreases in potential crop yields by 1.5% to 5.8%, while its tropical environments have witnessed larger decreases in yields by 17% to 18% (Aggarwal and Kalra, 1994).

The country's Indo-Gangetic plains have witnessed decreasing trends in potential wheat and rice yields owing to increases in minimum temperatures (Pathak et al., 2003). Reductions in agricultural net growth and productivity also occur because of increases in crop maintenance respiration requirements. Increases in crop maintenance respiration requirements have occurred because of increases in minimum temperature driven by warming trends (Aggarwal, 2003). A study by Sinha and Swaminathan (1991) revealed that every rise in winter temperature by 0.5 ℃ results in a 10 percent decrease in the production of wheat in the country's northern high-yielding states. Rainfall shortages have the potential to decrease the supply of irrigation water, leading to a decrease in the area under irrigated crops and a potential increase in the area under rain-fed crops in the following season (Krishna et al., 2004). Such shifts increase rainfall dependence and lead to higher climate change exposure. Reduced crop growing seasons for sorghum have occurred because of the adverse effects of predicted temperature rises that have masked the potential positive effects of increased carbon dioxide. Increases in temperature by 1 °C and 2 °C have, on average, decreased sorghum grain yields by 7% to 12%. A significant reduction in rice yield under irrigated conditions is predicted to occur in northwest India due to reductions in rainfall during the monsoon season. A fall in crop duration across the country is predicted to occur because of temperature increases linked to atmospheric greenhouse gas build-ups. Increases in temperature by 1–2 ℃ without increases in carbon dioxide have resulted in a 3%–17% loss in rice grain yield in different regions (Mall et al., 2006). An estimation of the functional relationship between climate and farm-level net revenue has found an inverted U-shape for the temperature response function, with higher climate change leading to greater losses in farm-level net revenue (Kumar and Parikh, 2001). A 2–3.5 ℃ rise in temperature is predicted to lead to losses in farmer net revenue of 9%–25% (Kumar and Parikh, 1998).

5 Assessing grounds for measuring climate-driven agricultural vulnerability

Vulnerability in the climate change context is defined by the IPCC (2007) as "the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes". Agricultural vulnerability to climate change can be defined in terms of the exposure, sensitivity, potential impact, and adaptive capacity of agricultural systems to climatic extremities.

We first assess findings on adaptive capacity across the globe and in India to analyse existing solutions to vulnerability, before depicting a few factors potentially increasing agricultural exposure and sensitivity in India. Crop insurance based on weather indices plays a major role in mitigating climate change risk. Asia, North America, and Europe account for 55%, 20.1%, and 19.5%, respectively, of the worldwide agricultural insurance premiums. However, Africa accounts for a mere 0.5% due to the lack of involvement of farm households in conceptualising initiatives. Yet insurance providers and policy-makers have the potential to design insurance schemes based on weather indices in a developing country context through an understanding of the maximum willingness to pay on the part of farmers (Fonta et al., 2018). Countries with high irrigation efficiencies would possess the advantage of constant per-area productivity, even with a decline in water availability and a subsequent decline in irrigated areas. Such efficiencies are due to technology adoption (Iglesias et al., 2011) and such measures imply strong adaptive capacity. Water stress-driven rain- fed agriculture has emerged in drought-ridden sub-Saharan Africa. However, drought-tolerant maize varieties have also been developed to cope with drought-driven vulnerability. The invention that implies a high potential for climate change adaptability has however been adopted at below-potential rates of 22 percent owing to the high prices of seeds and lack of access to them. Scaling of the variety has been sought through both market and non-market-based approaches, with the former creating a link between farmers and finance institutions for credit access and the latter targeting seed subsidy programmes (Simtowe et al., 2019). In other regions of Africa, deforestation has been identified as a major driver of climate change. However, shifts to early tree planting, irrigation, water harvesting, and terracing have been identified as major adaptation strategies. An increase in farmers' distance from purchasing markets has led to higher levels of adaptation. However, increases in non-farm income that diminish the risks of climate change, have led to falling adaptation urgency. Access to credit fosters the likelihood of farmers engaging in diversified economic activities, leading to delays in adaptation (Tessema et al., 2013). Hayashi et al. (2018) stated that high unpredictability in the commencement and closure of the rainy season, unpredictability in the duration and quantity of rainfall, and lower nutrient-use efficacy suppress the yields of rain-fed rice. The present study was conducted in Southeast Asia. A relative lack of information and tools has depressed the coping mechanisms of farmers cultivating rain-fed rice. As a solution to this problem, the optimum sowing time can aid in avoiding adverse climatic effects.

India ranks first in terms of value and extent of produce among rain-fed agricultural nations (Zhu et al., 2011). High irrigation potential during droughts surfaces as a result of rainfall surpluses that occur in certain agro-ecological regions. Supplemental irrigation has helped improve the net benefits for crops such as rice, oilseeds, and pulses in certain regions of the country. Decentralisation and equitable intervention in water harvesting and supplemental irrigation schemes could help replace water transfer projects and river linking (Zhu et al., 2011). Such scenarios highlight the country's innate potential for enhancing climate-driven adaptive capacity during periods of low rainfall. Technological and marketing triggers on account of photo- insensitive (light-insensitive varieties that can be grown in every climatic season) varieties of wheat and rice along with assured and remunerative soybean prices have led to changes in the production patterns of major cereals (Sinha and Swaminathan, 1991). Hill states in the country are characterised by lower net sown areas compared to the country's Indo-Gangetic plains and low-lying regions of Gujarat and Maharashtra (certain regions in the two states comprise a part of the Western Ghats). A lower net sown area lowers agricultural vulnerability. Indo-gangetic plains have been characterised by high sensitivity, low exposure, and high adaptive capacity. Greenhouse gas mitigation has been shown to propel adaptive capacity through adoption of agroforestry models. Agroforestry classifies systems in which trees, shrubs, palms, and bamboos are deliberately grown on the same land area as agricultural crops as a means of integrating forestry with agricultural growth. This serves as a model for enhancing environmental sustainability in the face of rising agricultural expansion (Tripathi, 2013). Under the analysis of women's participation in decision-making and gender equality, women have been characterized as being better equipped for behavioural adaptation and policy-support, despite women possessing a higher sensitivity to overall risk on account of their marginal societal positions. The inverse effect of non-farm activities on agricultural vulnerability through the creation of alternative income-generating sources has placed a high share of non-agricultural labour. Livestock-mixed crop-farming systems that have set grounds for poverty reduction have enabled an overall reduction in vulnerability. Livestock possession, which contributes to easier mobility and access to fodder on average, reduces vulnerability (Tripathi, 2013). Altering sowing dates, crop duration until maturity, and supplemental irrigation are some of the response measures to vulnerability driven by changing rainfall patterns. High proportions of land directed towards cropping that face increasing pressures have been protected from vulnerability due to non-farm employment.

The degree of vulnerability can be assessed through findings that predict wage reductions. A fall in wages by 2 percent with every 1 ℃ temperature rise, reducing the welfare effect of a climate shock, has been analysed. Such shock exists because of the low usage of scarce resources. Climate change is also anticipated to trigger a minimum 18 percent reduction in consumption among the country's poor (Guiteras, 2007). The same study pinpointed a medium-term fall in yield by 9 percent and a long-term fall by 40 percent due to climate change and the fact that High Yielding Varieties (HYVs) despite producing higher yields carry a higher sensitivity to climatic fluctuations. The negative climatic impact on agriculture constitutes an overall cost of 1.0%–1.8% of GDP over the medium term (Guiteras, 2007).

Although the Western Ghats are prone to higher rainfall, certain regions covering the states of Tamil Nadu, Karnataka, and Maharashtra are characterised by semi-arid climates (ICAR, 2013). Birthal et al. (2014) found that India's semi-arid and arid tropical areas face higher agricultural sensitivity to climate change than the semi-arid temperate areas. India's annual temperature increase has been relatively high in the arid-semi-arid tropical region. Certain districts in the states of Tamil Nadu, Karnataka, and Gujarat are characterised by more than 100 percent usage of available groundwater. The states of Kerala and Tamil Nadu are characterised by more than 60 percent of small and marginal-farmer land ownership, with certain districts in the state of Kerala being characterised by a high rural population density. On an aggregate basis, larger net sown areas, higher use of ground water, higher rural population density, and a larger number of small and marginal farmers would increase agricultural vulnerability to climate change (ICAR, 2013). The findings indicate that agricultural productivity in the Indian monsoon (Kharif) season is more temperature- sensitive than in the winter (rabi) season. A 1 ℃ temperature rise in the Kharif season triggers a 9.2% reduction in the gross value of output (Birthal et al., 2014).

6 Assessing the grounds to accommodate forest protection and agriculture

6.1 Global findings

Progress towards achieving food security, sustainable agriculture, and sustainable forest management would be instrumental in helping achieve Goals 15 and 2 of the Sustainable Development Goals and Article 5 of the Paris Agreement, in addition to the five strategic objectives of the Food and Agriculture Organisation (FAO) strategic framework. It is essential to understand the basis of reconciling the use of land between forests and agriculture to sustain mutual support and interdependence between the two sectors. Forest conservation protects ecosystem resilience, thereby enhancing sustainable agriculture. Forest environmental services are crucial for agricultural support because of their key roles in supporting water cycles, soil fertility, local climate regulation, and pollination. On the other hand, agriculture supports food security needs and far-reaching development outcomes. This section describes the evidence from existing findings and the literature on paradigms and practices that lay the basis for protecting forests in line with agricultural development. Table 2 below pinpoints this evidence across different countries. Findings are mixed. Not all findings are directed towards forest protection and agricultural development in cohesion. Some findings indicate mechanisms directed towards forest protection or agricultural development alone, and some findings indicate mechanisms that cater to both forest protection and agricultural development. The purpose of this section is to create a body of evidence on the forest-agriculture reconciliation framework. A few mechanisms are vital. For example: The provision of credit for native-forest management and irrigation would account for government support towards forest protection and agriculture. Incentives for fertilizer use would enable agro-forestry systems as fertiliser use increases agricultural productivity on fixed land spaces, making land available for forest protection. The Payment for Environmental Services scheme would set the grounds for public and private contribution to environmental funding.

6.2 Findings in India and the Western Ghats

Das Gupta (2009) stated that India's colonial policy aimed at replacing shifting cultivation with settled agriculture. Shifting cultivation has often been characterised as 'slash and burn' agriculture. The separation between forests and settled cultivation emerged as a policy focus of the time that can be assessed to carry the potential to sustain land use for the two purposes which would have otherwise been in conflict. Gadgil (1990) assessed that India's agrarian societies incorporated the practice of retaining a semi-sacred protected safety forest and a community-controlled supply forest linked to each village. One can conclude that such practices set the grounds for incorporating community agricultural needs with those of forest protection.

Sudha et al. (2006) stated that in the Western Ghats, through joint forest planning and management, high priority has been given to the restoration of degraded patches, the plantation of fuelwood species, and the raising of bamboo and cane. The adoption of plantations on degraded forest land that has been characterised by low canopy cover (< 25%) has proven the deterrence of exploitation of core forests for the purposes of plantation growth. Areas under joint forest planning and management had a higher average tree density than the control plots, with a difference of approximately 1006 ha^{-1}. High tree densities can serve as mechanisms for sparing the remaining areas of land for non-forest use, such as agriculture. The attainable average standing biomass under Joint Forest Management Plantations in the Western Ghats for a 7-year rotation cycle is 5.66×10^5 t, estimated to generate a proximate return to the extent of USD 1.83×10^6 to Village Forest Committees. Such a return can create grounds for enhancing the financial viability of the joint forest management system, along with the targeted ecological and economic processes. Kumar and Takeuchi (2009) stated that the Western Ghats have been characterised by plantation agriculture involving tea, coffee, and spice plantations in association with a broad range of trees. Kumar (1999) stated that the traditional cardamom growth system involves the growth of a commercial crop in natural forests. The crop was grown under tree-shade with

Table 2 Global findings and mechanisms that reconcile forest-protection with agriculture

Country	Region	Mechanisms to reconcile forest-protection with agriculture
Chile	South America	Co-funding of agricultural investment and agroforestry and provision of credit for native-forest management and irrigation by the National Institute for Agricultural Development (INDAP) Incentives for fertilizer-use and build-up of irrigation equipment have aimed at increasing agricultural productivity②
Costa Rica	North America	Development of tree-pasture systems, agroforestry, and forest and watershed protection prioritized for the allocation of payments under the Payment for Environmental Services Scheme. Tree-planting incentives provided for farmers and forest-conservation support in indigenous territories also established under the scheme The provision of shade for coffee crops and livestock under agroforestry systems
The Gambia	Africa	The focus on increasing community-participation in the sustainable management of forests, development of agroforestry and provision of strength to the forestry department under a component of the Gambia National Agricultural Investment Plan
Ghana	Africa	The allocation of land in degenerated areas of forest reserves for the intercropping of food crops in the initial phases of plantation establishment as per a modified taungya system The creation of agroforestry research farms and the inclusion of agroforestry in the Cocoa sector fostered by the drive towards sustainable agriculture
The Republicof Korea	Asia	Recognition of support for food production and the prevention of agricultural disasters through a possible re-establishment of forests in mountain watersheds
Tunisia	Africa	The requirement for special authorization for the harvest of forests designated for the protection of water sources and for the interception of erosion③

Note: Data source: FAO, 2016.

② The increase in agricultural productivity creates the potential for sparing remaining land-area for forest-protection.

③ It is crucial to note that the protection of water sources and the prevention of erosion can aid in agriculture.

little or no dependence on external inputs, such as chemicals and fertilisers. Bawa et al. (2007) stated that the growth of shade coffee beneath forest trees has characterised land-use prac-tices in a certain region of the Ghats. Such systems enhance plantation and crop growth in and near forest spaces.

Agroforestry systems in the Western Ghats have been complemented by the principle of multifunctionality. "Nutrient subsidies" from forest areas have aided farmers in maintaining soil productivity and fertility. The provision of nontimber products, litter, green fodder, wood, and timber has aided farmers with limited access to fertilisers.

Common pool resource regimes that reach balanced outcomes in land-use for forests and agriculture directed through a framework consisting of land-rights, the imposition of fines and penalties for land-use violations and subsidies or incentives for optimal resource-use could aid in maintaining agroforestry models. Partial government intervention within the rights-framework to oversee the allocation of land rights that could be transferable between opposing parties could serve as a solution to internalise external costs to the vulnerable group. Market conditions under which both groups operate would determine the revenue-generating capacity and profitability for each stakeholder belonging to both forest and agriculture groups. Hence, highly competitive market structures can reduce profits. In such circumstances, government intervention to balance competition among forest dwellers and agriculturalists could help both groups augment their savings directed towards preserving their common resource regime. Direct government intervention through legal limits placed on the use of land for agriculture or what can be defined as a 'land ceiling' would help spare the remaining areas for forest regeneration in and around agricultural plots. Such a model could also help expand agroforestry areas.

To highlight the scope of the findings, Table 3 below pinpoints the time periods, methodological tools, and regions of focus in the studies.

Table 3 An analysis of time periods, methodologies and regions of focus

Literature	Time/Period	Methodology	Country/Region
Faria and de Almeida (2013)	2000–2007	Fixed and random effects models, Spatial Autoregressive Model	The Brazilian Amazon
Tsiantikoudis et al. (2019)	1990–2015	Auto-regressive Distributed Lag Model	Bulgaria
Pendrill et al. (2019)	2005–2013	Land-Balance Model Crop-Attribution Model	Countries with a significant proportion of surviving Tropical forests
Lim et al. (2017)	1980s to 1990s, 1990s to 2000s	Environmental Policy Integrated Climate Model based on Geographic Information System (GIS)	North Korea
Fonta et al. (2018)	2014	Probit Model	West Africa
Simtowe et al. (2019)	2015	Probit Model	Uganda
Tessema et al. (2013)	2003–2013	Multinomial Logit Model	Ethiopia
Agarwal (2017)	1993–2012	Ordinary Least Squares (OLS) and Autoregressive Distributed Lag Model	India
Birthal et al. (2014)	1969–2004	Panel Fixed Effects Model	India
Malik and Dhanda (2003)	1970–2000	Ordinary Least Squares (OLS) Model	India
Lodh (2017)	1999–2005, 1982–2002, 1982–1990, 1996–1997	Sensitivity experiments	India

7 Discussion

A considerable extent of deforestation for agriculture has taken place on account of commercial cropping and plantation activity which further drives climate change and in turn harms agriculture. An assessment of the direct impact of deforestation on crop output and productivity would help pinpoint a few extraneous factors leading to declining agricultural productivity in high deforestation areas. One extraneous factor likely to emerge from such models would be temperature and rainfall variations. Regression models that analyse such an impact often control for additional factors that could augment crop productivity such as fertiliser and irrigation in order to isolate the effect of deforestation on crop productivity. Models directed towards predicting the degree of impact of deforestation on crop productivity could take the linear form, such as the Ordinary Least Squares (OLS) model. Models that control for additional factors that impact crop productivity add multiple explanatory variables to the regression. If two or more study regions are included that convert the model to a longitudinal form, the most robust methodologies are those that allow each cross-sectional unit or study region to have its own intercept value, hence bringing in region-wise heterogeneity. The fixed effects panel regression model does so. Often a lot of the variables that could impact crop productivity are eliminated from the model on account of data insufficiency. In such cases, the use of instrumental variables that directly impact deforestation and indirectly impact crop productivity could help reduce such an omitted variable bias. The Panel Generalised

Method of Moments (GMM) Regression aids in such a process. More dynamic models are those that predict both the long-run and short-run effects by including the lagged values of the dependent variable and the explanatory variables in the model. Autoregressive Distributed Lag (ARDL) models would serve the purpose.

From the existing findings, we conclude that a plethora of factors impact agricultural vulnerability to climate change. The key dimensions of climate change vulnerability can be categorised into exposure, sensitivity, potential impact and adaptive capacity. Building an agricultural vulnerability index to climate change in key deforested areas of the world and in the Western Ghats would prove to be a significant indicator of agricultural risk. Estimating the index would involve including appropriate indicators impacting each dimension and tapping sources (government, local stakeholder and secondary sources) that would provide raw data on each indicator. Once the indicator is suitably measured, weights can be assigned to the indicator. The use of weights would help in the estimation of sub-indices and the aggregate index.

Among the findings that support forest protection and agricultural development, the agro-forestry model has emerged as a dominant solution. In order to execute the agro-forestry model through a common pool resource regime, game theoretic models could support future research and policy-making in balancing economic and ecological outcomes specifically in the Western Ghats that remains heavily forested. Coordination and cooperation games aimed at increasing multi-stakeholder support and participation could seek application. A simple experimental game would involve the categorisation of land-use options into low risk and high risk categories and the provision of payoffs to each land-use strategy. Low risk land-use strategies would include more reforestation and high risk land-use strategies would include more agricultural growth, with the former receiving a higher payoff and the latter receiving a lower payoff. Within high-risk agricultural strategies, a sub-division of strategies into high-risk monoculture plantations and commercial polyculture could be accorded a low payoff and low risk diversified cropping systems based on organic and traditional cultivation could be accorded a high payoff. Such incentivisation schemes would help local communities reach balanced land-use outcomes and cater to climate adaptation.

The nexus between forests and agriculture is complex. Climate change has been analysed as an inter-linking phenomenon in our study to bridge the understanding between the two complex land-use aims and to highlight a significant source of vulnerability. The question of the point or phase of development at which a country would begin the transition from high-level resource consumption to resource conservation driven by ecological considerations would depend on its level of overall economic growth, its policies, priorities and the level of support it could gather from the advanced world in the form of funding and aid in making such a transition a possibility. The question about the point or phase of development at which a sole ecological region would be able to make the same transition would depend on state-level legal mechanisms, their monitoring, implementation, and local stakeholder priorities. For India to be able to make that transition, government aid and subsidies directed towards sustainable agriculture in the form of organic farming, inter-cropping and crop rotation would help boost agricultural productivity on fixed land-spaces without the need to encroach into forests. For an ecological zone like the Western Ghats to be able to make that transition, robust state-level policies in each of the six states that the Western Ghats passes through that are in alignment with national land-use policies aimed towards sustainability would be an imperative.

8 Conclusions

This study reviews findings on the interlinkages between deforestation, climate change and agriculture. Findings are driven by both scientific and socio-economic reasoning. With agriculture being a significant driver of deforestation, in turn leading to crop output losses due to the climate change impact, two solutions emerge to resolve the nexus. One would be to cater to crop production through forest protection and the other would be to reduce agriculture's vulnerability to the climate change impact. Transformations in the land sector and in policy making would help achieve the dual outcome of forest preservation and agricultural strengthening. For example, India's policy mandate is to maintain one-third of its land area under forest or tree cover and the country, under the Green India Mission, aims at climate change mitigation through sustainable forest management. Under circumstances where climate change is inevitable, the adoption of climate-smart agriculture would help increase carbon storage and improve food production. Agro-forestry is one land-use model which is a form of climate-smart agriculture. India's agro-forestry policy has recognised the potential for climate-change mitigation through microclimate regulation and carbon sequestration. The policy has recognised the co-existence of tree farming and agriculture and the target of afforestation with nutrition strengthening.

Globally, the aim of enhancing forest protection with sustainable agriculture can be met through the integration of climate-smart agriculture with Reducing emissions from deforestation and forest degradation in developing countries (REDD+) strategies. A few solutions that emerge from the interlinkage are improved emissions accounting for both forestry and agriculture, a Payment for Ecosystem Services scheme to reduce climatic externalities of agriculture and the adoption of low carbon agriculture. It has been pinpointed that improved emissions accounting for agriculture would identify areas suitable for agricultural expansion at the least cost to local climate. While forest protection and agricultural production have always remained disparate, conflicting aims, the integration of the two land-use purposes could help nations achieve their development goals and at the same time restore the ecology and preserve climatic stability. The two outcomes though distinct are crucial and significant to meet.

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森林砍伐、气候变化与农业可持续性：综述

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摘　要：本研究通过总结相关文献探讨了森林砍伐与农业之间的关系，并评估了气候变化对其潜在影响。选择具有重要生态意义的西高止山区作为研究对象，通过整理各个研究主题下的相关结果，我们详细探讨了包括森林砍伐的根本原因，森林土地转化为农业用途，农业、森林砍伐与气候变化之间的关系，气候驱动的农业脆弱性以及如何在保护森林与发展农业之间取得平衡。研究发现，农业的转变已经成为引发森林砍伐的主要原因；气候变化对农业的主要影响体现在作物产量的下降。印度的干旱和亚热带地区对气候变化的敏感性较高，这很可能是由于印度的热带森林遭受了较严重的砍伐。西高止山区联合森林规划和管理区域的树木密度较高，这为剩余土地用于非森林用途（如农业）创造了潜在的机会。

关键词：农业敏感性；农林复合种植；气候变化适应性；气候变化暴露；森林砍伐；可持续性