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Gazing at Long-term Linkages Between Agricultural Land Use and Population Growth in India: An Inverted 'U-Shape' Relationship

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Gazing at Long-term Linkages Between Agricultural Land Use and Population Growth in India: An Inverted 'U-Shape' Relationship

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Abstract

This study investigates the linkages between changes in agricultural land use and population growth in India. We have employed long-term time series and a panel dataset of 1869 samples (267 districts * 7 time points from 1961 to 2021) to determine this. We theorize that there is an inverted 'U-shape' relationship between changes in population growth and agricultural land. Our findings suggest a positive impact of population growth on the change in cultivated land. However, this relationship was not static during 1961-2021. We found a two-stage split relationship with a breakpoint in 1981. Prior to the 1980s, there was a 12% expansion in cultivated land in response to a unit increase in population growth. During the post-1980s, with a unit decline in population growth, there was a 5% reduction in cultivated land. The findings were reaffirmed through several robustness checks: analyses using alternative outcome variables, alternative break points in a segmented regression model, and spatial modeling. From a policy perspective, this study advances the need for the reduction of population growth rate in high-fertility states and the adoption of superior technology for agricultural intensification and diversification to stop cropland expansion at the cost of environmental sustainability.

Keywords: Population Growth; Agricultural Land; Land-Population Relationship; Dynamic Panel Data Analysis; Spatial Econometrics; Malthusian-Boserupian Debate

JEL Classification: J11, Q15, Q56

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1. Introduction

Has population growth changed the agricultural land? Did the change in the share of agricultural land and productivity induce population growth? Does a decline in population growth reduce the expansion of agricultural land? These questions have no clear and scientific answers. One difficulty in answering these questions is the lack of robust empirical research addressing land use and population growth. Research has previously focused on case studies, which often depend on the individual level of interaction between the physical and human world. Although the case studies illuminate the particular intricacies of the population and land use relationship, these are not comparable across varying geographies (Jolly & Torrey, 1993; Hoffmann, 2021).

Our study, using an Indian context, will attempt to examine the long-term contested discussions between optimists and pessimists regarding their concern for population growth and food production. Current interest is shifting toward population and land use with a reduction in per capita land in increasing world population scenarios. Whether Malthus' view about food insecurity owing to increasing population and limited land is accurate or Boserup's thoughts of technological transformation in agricultural land use to sustain the growing population seem correct, these issues remain debatable. At its outset, this study is an attempt to work for a resurgence of population and land debates through the theoretical framework of the Boserupian school of thought (Turner & Fischer-Kowalski, 2010).

Malthusian thought concerns the ecological limit of the land, as increasing populations will demand more land for sustenance with food and other essential materials. Boserup, on the contrary, argued that increasing population pressure will innovate and intensify the methods for increasing production from limited land. Boserup viewed population density as the major determinant in innovating modern farm technology for better food production with changes in land use systems. In many countries, including India, farm technology was implemented due to increasing population pressure, although land encroachment for agriculture has also been carried out. Thus, both intensification and extensification of agricultural land occurred simultaneously.

The core of this study is to theoretically and empirically document how the "man-land" interaction evolved in an Indian context. Although several studies have investigated the relationship between population and agricultural land, most of them have established a correlation at a point in time or merely postulated theoretical arguments. Only limited studies have assessed the dynamic relationship between population growth and agricultural land, using panel data over a long period in the Indian context. We have investigated the relation of population growth, instead of size and density, with the share of agricultural land use for the last six decades in Indian districts. Some studies have found a multiphasic response between population pressure and agricultural land use change, even though they show the role of increasing population in the tradeoff between extensification and intensification of agricultural land (Bilsborrow, 1987; Turner & Ali, 1996; Codjoe & Bilsborrow, 2011). Our study not only analyzes population growth as one of the major determinants for agricultural land use change but also attempts to capture the response of agricultural land use through India's demographic transition during the last six decades.

Modern debates on land and population are concerned with the environmental degradation of the land due to the use of degradative materials to raise agricultural production and fulfill the demand for food amid population pressure. This debate has its roots in the

Malthusian-Boserupian debate of limited land for food production and increasing population size. The relevance of this study is to highlight the Malthusian-Boserupian debate of land and population growth with a unique empirical approach, which employs a long-term district-level panel data analysis in an Indian context. This study contributes significantly to the literature on population, development, and environment. In particular, the major contributions of this paper are fourfold. First, the study formulates a theoretical framework to study the long-term relationship between population and agricultural land. Second, it employs a cutting-edge econometric approach using long-term panel data to test the study hypothesis, i.e., whether the population growth rate influences the increase or decrease in cultivated land. Third, using a spatial econometric regression model, it addresses the geographical heterogeneity of the population growth rate and agricultural land use. Finally, the main findings are reaffirmed using several robustness checks, including analyses of alternative outcome variables, alternative break points in a segmented regression model, and analysis in light of land reforms in Indian states.

The findings of the study suggest that population growth is one of the major determinants in the expansion and reduction of agricultural land. We found a two-stage split relationship between population growth and agricultural land with a breakpoint during the 1980s. Prior to the 1980s, the impact of the population growth rate on cultivated land was positive and significant. There was an expansion of cultivated land in response to the exponential increase of the population. During the post-1980s, there was a gradual reduction in cultivated land with a decline in the population growth rate and an intense rise in agricultural productivity. At the outset, the study suggests, from a policy standpoint, that to prevent cropland expansion at the expense of environmental sustainability, population growth in high-fertility states should be reduced, and innovative and superior technologies should be adopted early in the agricultural intensification process.

The paper is organized as follows. The next section (Section 2) discusses the background and literature review. Section 3 describes the trend of population growth rates and agricultural land use in India. Section 4 discusses the theoretical framework of the study. Section 5 illustrates the empirical approach of the study, i.e., the hypothesis, data sources, panel construction, and variables. Section 6 describes the econometric approach of the study. The results are detailed in Section 7. Section 8 depicts the results of various econometric models with robustness checks, while Sections 9 and 10 deal with the discussion and conclusion of the study, respectively.

2. Background and Literature review

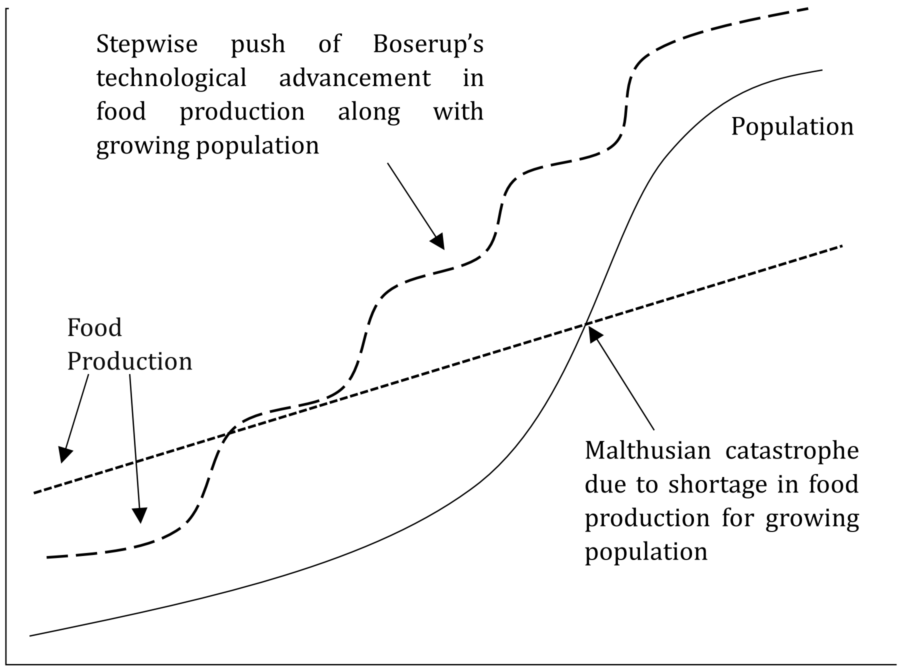
To sustain the growing population, food production must keep up with growing demand and there are two ways to do so: either expanding agricultural land or intensifying the agricultural land cultivation. Malthus was concerned about the limited availability of agricultural land. He said that with increasing population, agricultural land use expands to raise food production (Malthus, 1973). The new lands acquired for agricultural practice will be less productive than land already in practice because most fertile land is already in use. However, he was unaware of the rapid development of agriculture after the Industrial Revolution. The concern of biological and agricultural scientists in the 20th century was the ecological limits of food production. They hardly believed any future expansion in agricultural production is possible with the technological advancement. Thus, they have warned about food insecurity and environmental degradation because of rapid population growth (Ehrlich et al., 1977; Ehrlich & Holdren, 1971; Raven, 1990) and this would result in the Malthusian catastrophe when the food supply could no longer support an expanding population (Figure 1). Nevertheless, after two centuries of uninterrupted expansion in population and food production, as well as economic advancement, it is difficult to imagine a disaster caused by overpopulation alone (Johnson, 1997).

Neoclassical economists, on the other hand, promulgated and emphasized technological advancement and the substitution of scarce resources with more abundant ones to persist high quality of living with limited resources (Simon, 1981; Stiglitz, 1979). Boserup's investigation of agricultural systems of African and Asian countries concluded that with evolution and innovation in farm technology (e.g. fertilizers, soil conservation, irrigation system, farming machinery) and innovative use of finite resources (e.g. cropland intensification, terrace farming, fallow shortening), rapid increase in population could be sustained with increased food production (Boserup, 1965, 1970, 1981). According to Boserup, population expansion will spur innovation in agriculture (Figure 1). However, she was criticized on the grounds that extreme conditions of poverty and slow economic development would not allow for innovation, as was the situation for many African and Asian countries (Dasgupta, 1992). Boserup and Simon were also criticized for their simplistic conclusion, that technological progress would resolve the Malthusian problem and would stay ahead of population growth (Brander, 2007).

Amid these arguments and counterarguments in the later 20th century, four reports were published by the United Nations (1953, 1973) and the National Academy of Sciences (1971, 1986), two by each. Both organizations were pessimistic in their earlier reports, suggesting negative consequences of population growth. On the contrary, later reports were somewhat revisionist in thinking and made a guarded assessment of the net impact of population on development (Kelley, 2001). The 1993 report of NAS directly addressed the issue of population and land use in developing countries (Jolly & Torrey, 1993). This report said that rapid population growth affects land use in the long run and is disadvantageous for environmental sustainability and human well-being.

Recent arguments between these two perspectives have evolved towards sustainable land use considering the rising threat of climate change and environmental damage in developing nations due to high population density. Sustainability and living standards are key themes in modern population growth and resource management literature. This debate on sustainability is beyond the scope of this study as it focuses more on the relationships between finite land and growing population pressure. The earlier literature in the global and Indian context addresses the two important questions that have been discussed below. Most of the earlier literature classifies the response of agricultural land to population growth as extensification or intensification. We classified the literature with population-induced land use changes, whether extensification or intensification, and the limited possibility of land use changes. Some studies also concluded the simultaneous response of agricultural land as extensification or intensification, which is also discussed.

Figure 1. Pessimists vs Optimists: Theoretical differences in arguments of population change and food production



Source: Martín i Oliveras, Martín-Arroyo Sánchez, & Revilla Calvo (2017)[3]

2.1. Does population growth change the agricultural land?

2.1.1 Extensification of agricultural land

Population-induced changes in agricultural land can be either extensification (conversion of non-agricultural arable lands into agricultural land) or intensification (using tools and labor to increase production on the same land). Malthus' view is one of the earliest descriptions of cultivated land extensification due to increasing population (Malthus, 1973). He further said that the increasing number of people need to be migrated to new lands for agricultural extensification without population checks. But this is a temporary solution, he added. Among the early researchers, Clark (1967) and Perkins (1969) provided extensive studies on agricultural land extensification in response to population growth. Clark compared land use change and population growth between developed and developing countries, showing how much land is needed for developing nations to maintain the same food and calorie intake as developed countries. However, Clark's data were mostly concentrated on developed nations, and his major limitation was the interpolation of empirical data from the developed to the developing world. Perkins showed how China's growing population, which increased from 75 million to 647 million between 1400 and 1957, led to an expansion of agricultural land from 25 million hectares to 112 million hectares. Although he also found some evidence of small-scale intensification, the primary response was extensification.

Stonich (1989) found that in Honduras, population growth leads to smaller land holdings (the land-to-man ratio decreases), forcing the growing population to migrate to highlands

[3] Martín i Oliveras, A., Martín-Arroyo Sánchez, D. J., & Revilla Calvo, V. (2017). The wine economy in Roman Hispania: Archaeological data and modellization. Universitat de Barcelona, CEIPAC. http://ceipac.ub.edu/biblio/Data/A/0940.pdf

to clear forests for setting up new farms to sustain the population. Similar results were found by Cruz (1999) in the Philippines, where a rapidly increasing rural population with unequal land distribution leads to smaller land holdings and significant agricultural land extensification, causing massive deforestation. Bilsborrow & Stupp (1997) used agricultural and population census data for Guatemala to link population growth in origin places with deforestation for agricultural land by out-migrants in destination places. Similarly, increasing population growth rates in Kenya also induced out-migration and agricultural land extensification in destination areas by forest clearance (Bilsborrow & Okoth Ogendo, 1992). A study by Maertens et al. (2006) in Indonesia found that with increasing population, there is a differential effect on agricultural land extensification based on the location of land (upland or lowland). A recent study by Knauer et al. (2017) in Burkina Faso, using satellite images, found that with a 3% annual population growth, there was a 91% increase in rainfed agricultural land with massive forest loss. Gray & Bilsborrow (2020) also found similar land clearance evidence in the Amazon region.

2.1.2 Intensification of agricultural land

In earlier studies of population and land use intensification, Ester Boserup (Boserup, 1965, 1981) provided comprehensive insights on global trends in land use change and population growth. Boserup (1965) postulated that population growth is independent of food production and that the pressure of an increasing population drives land use change through land intensification in five stages: forest fallow, bush fallow, short fallow, annual cropping, and multi-cropping. She showed that with increasing population pressure via rural population density, people focus more on land-saving and land-intensifying methods. This intensification occurs with innovations in cultivation tools, an increased labor force, changes in land tenure systems, and rural investments. However, some economists disagreed with her theory and said that only cropping intensity increases more in response to population pressure rather than innovation in agriculture (Grigg, 1979).

A historical study by Blaikie & Brookfield (1987) in Papua New Guinea found many agricultural innovations through time as the population increased. In Kenya, Tiffen et al. (1994) found results opposite to the Malthusian presumption of extensification due to population growth. With a sevenfold increase in population between 1900 and 2000, the population sustained itself through land intensification in the following stages: grazing, shifting cultivation, sedentary agriculture, cattle-plowing, and integrating crops with livestock. Pender (2001) has clearly explained this evolutionary relationship between population growth and agricultural land use patterns. Pender points out eight broad stages of this relationship, starting with the extensification of cropland, followed by the shortening of fallow periods, adoption of labor-intensive methods, labor-intensive land investments, capital investment, knowledge intensification, mixed land use, change in occupation and migration, and ends with a change in fertility decision of household. In Vietnam, shifting cultivation with limited land availability induced deforestation and agricultural extensification, but the introduction of individual rights in the late 1980s led to agricultural land intensification and forest restoration (Tachibana et al., 2001). A recent study by Eckert et al. (2017) used Google Earth and Landsat images to study land use change in Kenya from 1987 to 2016. They found that the period from 1987-2000 was associated with the extensification of agricultural land, while since 2000, intensive agriculture has been more common with improved irrigation facilities. Other studies have shown similar conclusions about the effect of population pressure (density or growth) on agricultural land intensification (Josephson et al., 2014; Ricker-Gilbert et al., 2014; Dias et al., 2016; Spera, 2017).

2.1.3 Simultaneous presence of extensification and intensification

A few studies depict both extensification and intensification at the same time in response to population growth. Bilsborrow (1987) uses Davis' (1963) theory of multiphasic response in the Malthusian and Boserupian debate on the extensification and intensification of agricultural land. He stated in the presence of population pressure, land extensification has been witnessed in many countries, but land intensification also parallelly worked in those areas with increasing use of fertilizers, high-yielding seeds, increased irrigated areas etc. (Bilsborrow, 1987; Codjoe & Bilsborrow, 2011; Bilsborrow & Geores, 2019; Gray & Bilsborrow, 2020). Studies in consideration of the population density of developing countries, especially China and India, showed that along with increasing cropland, adopting intensive farming systems pushed food production manyfold (Hayami & Ruttan, 1987; Pingali & Binswanger, 1987). Bilsborrow & Geores (1994) and Heilig (1994) also concluded a weak but positive relationship between population growth and irrigated land-fertilizer use through temporal changes of country-level data. Carswell (2002) studied part of Uganda for 50 years and found that fallow lands were increased rather than decreased due to population growth. This happened with land extensification, clearing swamps, and intensification through inter-cropping, crop rotation, and higher production.

2.2 Does limited agricultural land control population growth?

Some scholars counter the idea that population pressure leads to an increase in agricultural productivity and intensification. Higher population densities do not always result in increased agricultural productivity, particularly in locations where farmers own less land and the area is resource-deficient (Lele & Stone, 1989). According to Dasgupta (1992), under extreme poverty and low development rates, people suffer from a vicious cycle of poverty, population growth, environmental degradation, and extreme poverty, making Boserup's postulations inapplicable in these settings. The financial cost of bringing new land into cultivation is also substantially higher, preventing developing countries from expanding their land base. According to Scherr & Yadav (2001), land degradation poses a severe threat to food production and rural livelihoods in high-population-density areas of developing countries. They emphasize the importance of land management and land-improving investments through new policies to sustain the growing populations by meeting food demand. Diversification in agricultural land use is possible when basic calorific sufficiency through food is attained, and the goal for quality and diversity in food accessibility demands control of population growth. Studies by Magazzino et al. (2023) and Magazzino et al. (2024) show how population growth, especially in urban areas, and rapid changes in agricultural land use increase greenhouse gas emissions, posing a serious threat to the climate. Growing populations induce pollution through agricultural land use change and intensification, which poses significant challenges for developing nations with limited resources. Financial investment in agriculture is required for the adaptation of sustainable technology and innovations in developing countries (Magazzino et al., 2021; Magazzino & Santeramo, 2023).

The well-known Maasai tribes of East Africa have serious issues with limited available land relative to their large population size due to pre- and post-colonial policies (Sindiga, 1984). The land available for the Maasai does not allow them to be self-sufficient and economically sustained. Carswell (2002) describes the simultaneous presence of extensification and intensification in parts of Uganda but also expresses concern about future agricultural changes as further extensification has reached its limits and all possible means of intensification have already been applied. In developing countries, an increase in population leads to fragmentation of household holdings and increased landlessness, forcing rural populations to either out-migrate to urban areas for new job opportunities or to other arable and forest areas for agricultural establishment, resulting in extensification in these regions (Bilsborrow & Okoth Ogendo, 1992; Bilsborrow & Stupp, 1997; Bilsborrow, 2022). Thus, due to the limited availability of arable land, Malthus' thoughts on out-migration to new lands and other countries are well-predicted.

2.3 Population and Agricultural Land Use Studies in India

Many studies have investigated land use changes in India, but their emphasis is mostly on land use change rather than land use-population interactions (Roy & Roy, 2010; Tian et al., 2014). The land cover of India has altered dramatically, particularly the forest cover. From 1880 to 2010, forest cover decreased by 29%, while agricultural area rose by 51% (Tian et al., 2014). Cropland conversion is faster than cropland extension in India and other emerging nations (Richards & Flint, 1994).

The scant-known literature on population and land use interactions is limited to either local areas or mostly uses cross-sectional designs. For instance, a comparative case study undertaken by the United Nations in 1975 in districts of Punjab and Orissa revealed that positive population growth is connected with agricultural transformation by increasing production (United Nations, 1975). However, they also demonstrated that the limited possibility of labor intensification in agriculture in those areas generates labor surplus and forces off-farm employment search. Boyce (1987) used data from 1901 to 1980 for West Bengal and Bangladesh to study agricultural output upon the growth of the population and concluded that agricultural growth took about 30 years to respond to population growth; while Mukhopadhyay (2001) empirically tested the reverse causality and found that agricultural production does affect population growth in India in about 5 years. Another study in India using district-level panel data from 1951 to 1991 showed that population density positively induced agricultural intensification (Mishra, 2002). However, while the work was focused on agricultural intensification, no discussion on agricultural land extensification was conducted. A study by Deb et al. (2013) in the northeastern states of India found that increasing population pressure on agricultural land among tribal shifting cultivators led to various innovations and adaptations for increasing productivity.

The major conclusions from the above studies are as follows: positive population growth is associated with both the expansion of cropland and the intensification of agricultural systems. The studies either show the effect of population growth on land extensification and intensification separately or document the coexistence of both processes. Studies in India have focused on agricultural intensification in response to changing population scenarios. Recent studies using satellite data have only focused on cropland expansion without connecting it to population growth. Long-term studies on agricultural land use change and population growth are also missing in Indian literature. Thus, a long-term study at the district level (as household and community level data for the long term is not available) is needed in the Indian context to understand the dynamics of population and agricultural land. India has witnessed a major demographic transition in the last 70 years. Over the period, India's population growth rate increased rapidly, slowed down, and has been declining since the 1980s. This transition in population growth rate needs to relate to changing agricultural land use to better understand Malthusian and Boserupian ideas in the Indian context.

3. Description of Agricultural Land and Population Growth in India

Before formulating a theoretical framework for the study, we have described the long-term trends in agricultural land and population in India. Figure 2 illustrates that since 1951, the rate of population growth has been significantly increasing, leading to an increase in the percentage of cultivated land[4], to support the growing population. The population growth rate was increasing until the late 1960s, but remained high and stable until the 1980s, resulting in rapidly expanding absolute population numbers between 1951 and 1981. Since the 1980s, there has been a continuous drop in the population growth rate. The decline in cultivated land was also coupled with a decrease in overall agricultural land[5]. In 1951, the proportion of cultivated land out of total agricultural land was nearly 73%, but fast population growth increased it to 84% by the late 1960s (Figure 3). However, since the 1970s, this share has remained constant with few variations[6]. It also indicates that land expansion was much higher till the late 1960s. Figure 2 also shows that the decline in the population growth rate is followed by the reduction in the use of cultivated land.

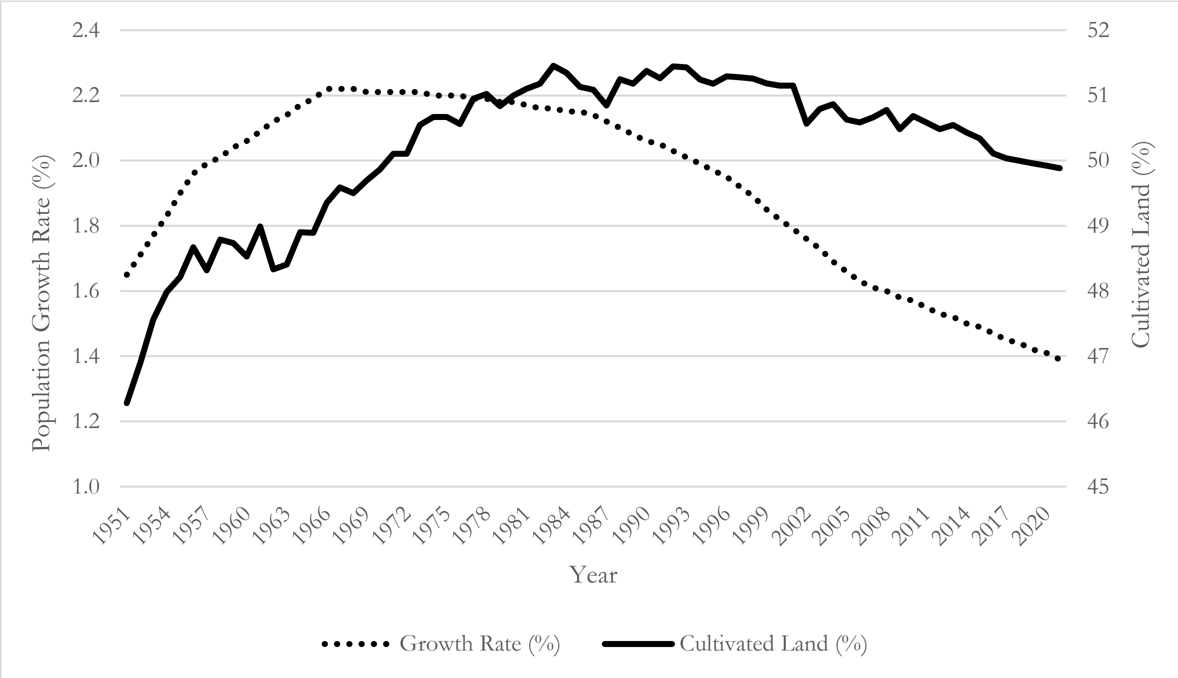
Along with the expansion of cultivated or agricultural land, India witnessed agricultural intensification with the Green Revolution. Figure 4 shows the yield of major crops as an indicator of agricultural intensification. Crop yields have been steadily increasing since 1951, with some fluctuations, though they gained rapid momentum from 1966 onwards with the introduction of high-yielding seeds and other modern agricultural intensification methods. This intensification in agriculture is also associated with economic development in India, as it made intensification methods economically viable. Economic growth helps to slow and further reduce the population growth rate by improving job opportunities, educating the population, and reducing gaps in social groups. Although the pace of economic development was slow until the 1990s, new liberal economic policies accelerated it, as illustrated in Figure 4 with India's per capita Gross Domestic Product. It can be said that agricultural development occurred as a result of rapid population expansion, as well as economic development, particularly after the 1990s.

[4] Net Sown Area + Current Fallow. Cultivated Land is a type of agricultural land which is always in operation. Other agricultural lands have some periods of inactivity.

[5] Agricultural Land is the combination of 'Cultivated Land' with 'Land under Miscellaneous Tree Crops and Groves', 'Culturable Waste Land', and 'Fallows other than current fallow'.

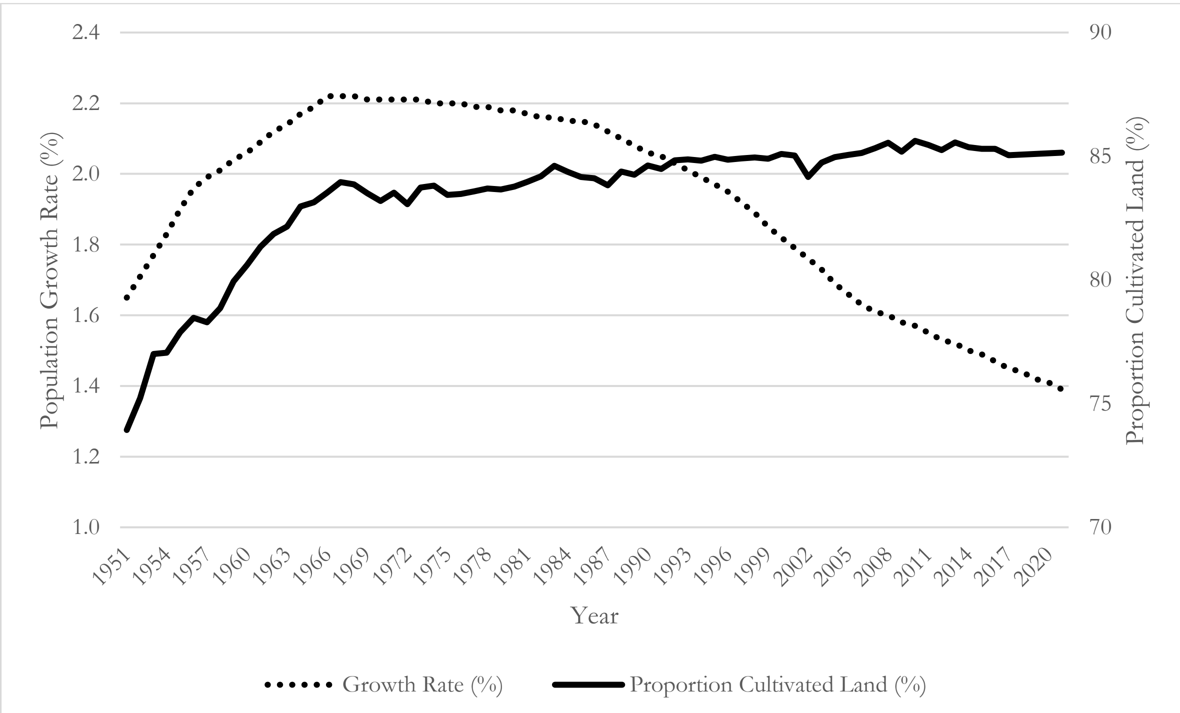
[6] It can be said that until the late 1960s, an increase in cultivated land occurred in two ways; first within the total agricultural land by using the culturable waste land and other available fallows, second by increase in total agricultural land itself. The first type of increase is the extensification of operational agricultural land (cultivated land) to non-operational agricultural land (agricultural land other than cultivated land). The second type of increase is the extensification of the non-agricultural arable lands.

Figure 2. Trend in population growth rate and cultivated land in India, 1951-2021



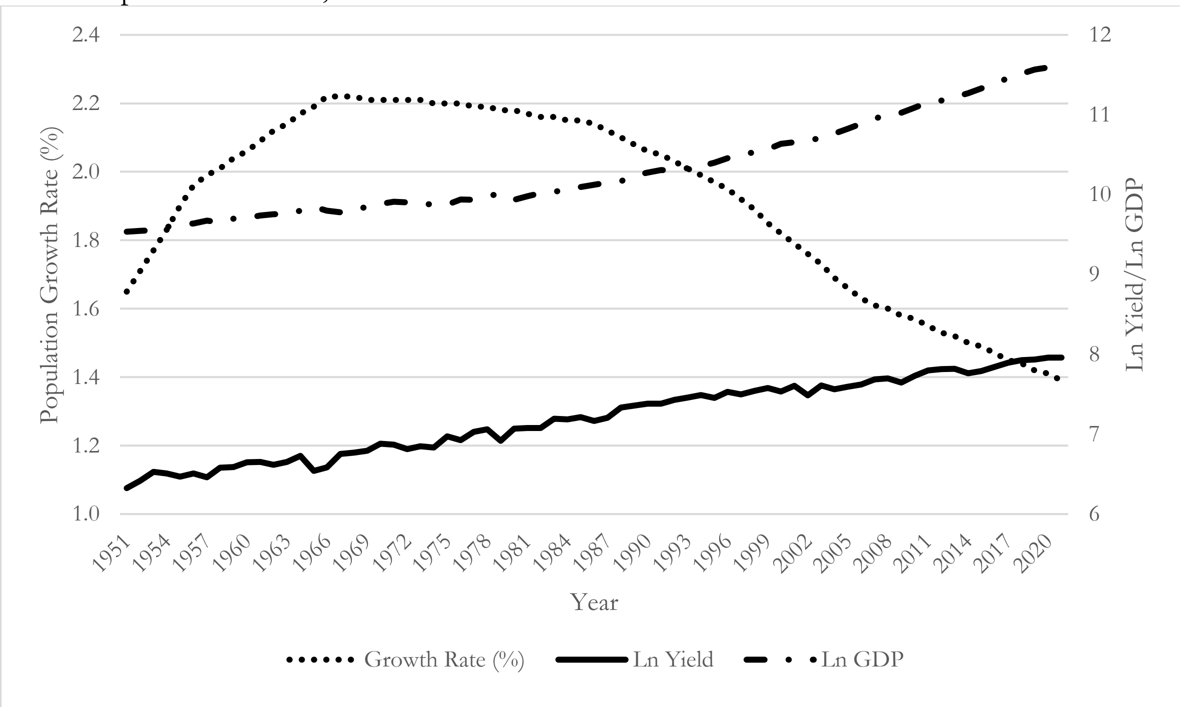
Source: Authors' construction with data collected from the Census of India (Census of India, n.d.) and Directorate of Economics and Statistics (DES, n.d.)

Figure 3. Trend in population growth rate and proportion cultivated land out of total agricultural land in India,1951-2021



Source: Authors' construction with data collected from the Census of India (Census of India, n.d.) and Directorate of Economics and Statistics (DES, n.d.)

Figure 4. Trend in population growth rate, yield of major crops, and per capita gross domestic product in India, 1951-2021



Source: Authors' construction with data collected from the Census of India (Census of India, n.d.) and Directorate of Economics and Statistics (DES, n.d.).

4 Theoretical Framework

The relationship between humans and land, more specifically population growth and agricultural land, is evolutionary. The term "evolutionary" is important since this relationship is not static; it varies over time based on demographic transitions. The theoretical framework presented in this study is primarily based on a synthesis of two distinct transitional systems: demographic and agricultural, as shown in Section 3.

The relationship between land use change and population growth in our theoretical framework forms three stages (Figure 5). In the first stage, starting with the dawn of civilization, access to unoccupied and unutilized arable land drives population growth. This stage is associated with the first stage of the demographic transition model (Thompson, 1929; Notestein, 1945; Davis, 1945). Assurance of food necessitates human acquisition of arable land. To secure food for survival and avoid famine, humans accessed additional land, which demanded more labor for farming. This need for labor was fulfilled by increasing household size. However, as mortality had a high prevalence in pre-industrial societies, both population growth and agricultural land expansion were slow. This stage would end with a decrease in mortality and a consequent population boom. This stage also witnessed some expansion in agricultural land due to population pressure. Although a clear distinction from the following stage is difficult, all countries experienced this stage before the 1800s, particularly during the pre-Industrial Revolution period. India experienced this stage before its independence, and the country's mortality rate started steadily declining from the 1940s (Goli & Arokiasamy, 2013; Dyson, 2018).

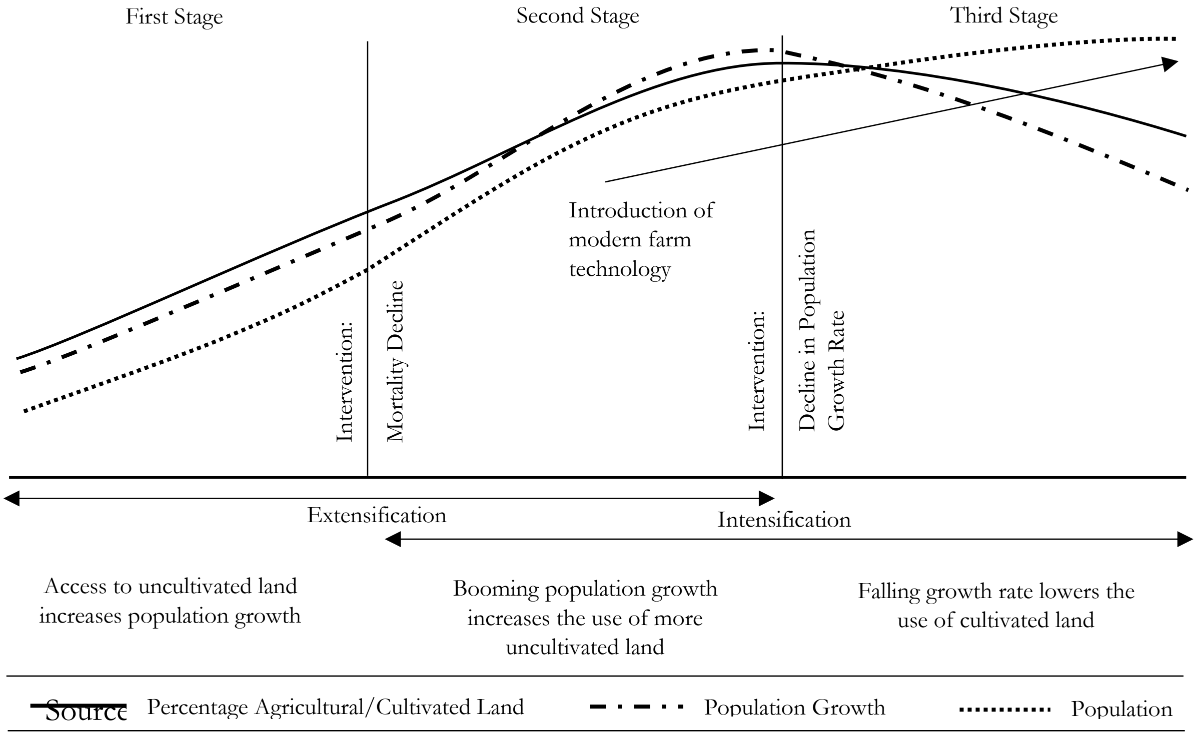
The second stage is more crucial. Due to a reduction in mortality, the population expanded with persistently high fertility, increasing the use of agricultural land. This stage relates to the second stage of demographic transition. With a booming population, the rate of extensification of agricultural land was high. Early population growth following mortality reduction stimulated economic development by increasing labor force participation in agriculture (Keyfitz, 1992; Coale & Hoover, 2015). Land scarcity due to the exponential rate of population growth necessitated agricultural intensification. There were two forms of agricultural intensification: labor-intensive and technology-intensive (Boserup, 1965; Pender, 2001). At this stage, only labor intensification was carried out. India witnessed this period before the 1980s, with very high fertility and low mortality (Goli & Arokiasamy, 2013; Dyson, 2018). During this period, both agricultural land extensification and intensification coexisted (Bilsborrow, 1987). However, with such a high population growth rate, extensification was widely practiced. In this stage, technology-intensive land intensification was in its initial phase, and with persistent high population growth, intensification methods were insufficient to halt cropland expansion. A decline in the population growth rate toward the end of this stage reduced the pressure on land, leading to a slowdown in cropland expansion.

Finally, in the third stage, which is related to the third stage of the demographic transition model, the population growth rate began to drop due to a fertility decline, combined with socioeconomic development and a reduction in the demand for farm labor, attracting agricultural workers to non-farm sectors. Technological innovation (both in agriculture and family planning techniques) helped to overcome the issues of limited land and overpopulation. The absolute number of the population still increased due to population momentum (the population growth rate declined but remained positive). At this stage, the rate of agricultural intensification surpassed the rate of population growth. This stage marked a reduction in both agricultural land use (cropland contraction and reforestation) and population growth. The reduction in agricultural land share was slower than the decline in the population growth rate because agricultural production still needed to support the increasing absolute number of people. With further advancements in demographic transition, like stable population growth rates and stationarity in the population, the need for more croplands will be reduced. However, it can be said that to cease the extensification process and further reduce the use of croplands, the population growth rate must decline first, along with the presence of modern intensive agriculture systems, thereby forming an inverted 'U-shape' relationship.

In these three broad stages, the relationship between agricultural land and population growth changes from one stage to another. In the first stage, land use impacts the population with a rising positive growth rate, while in the second stage, population growth influences land use with increasing positive growth in both land and population. Lastly, in the third stage, population growth again influences land use change, but with a declining population growth rate. Specifically, the population growth rate declines faster than agricultural land, as intensification and mechanization occur and the demand for agricultural land and labor diminishes.

Due to data limitations, this study only examined the second and third stages highlighted in the theoretical framework (Figure 5). As a result, for convenience, the 'second and third stages' are referred to as the 'first and second phases' throughout the text.

Figure 5. Theoretical framework showing co-evolution of agricultural land and population growth transitions



5 Empirical Approach

5.1 Hypothesis:

Hypothesis 1: Changes in population growth rate would change the agricultural land use share.

Hypothesis 2: Population growth and agricultural land use change have a split relationship, and the effect of population growth rate would be higher in the first phase than in the second phase of 'the transition in agricultural land and population growth relationship'.

5.2 Data:

Data for this study has been collected from multiple secondary sources of different time points, which are categorized into two broad sub-sections: Socio-economic & Demographic Data and Agricultural Data (Table 1).

The sources are Primary Census Abstracts and Census Tables of the Census of India (Census of India, 2001, 2011b), India District Database constructed by Vanneman & Barnes (2000) for district-level socio-economic and demographic data, Gridded Population of the World (GPW) version 4.11 for the year 2020 (Center for International Earth Science Information Network (CIESIN), 2018), Directorate of Economics and Statistics, Ministry of Agriculture & Farmers Welfare (DES, n.d.), and District Level Database by ICRISAT (ICRISAT & TCI, n.d.). Category and period-wise detail data sources are given in Table 1.

Table 1. Data sources by type of variables

Data	Period	Variables	Sources
Demographic and Socio-economic Data	1961-1991	Total Population, Urban Population, Agricultural and Non-Agricultural Workers	India District Database (Based on Census of India)
	2001-2011	Total Population, Urban Population, Agricultural and Non-Agricultural Workers	Primary Census Abstracts and Census Tables, Census of India
	2021	Total Population	Center for International Earth Science Information Network
		Urban Population, Non-Agricultural Workers	Projected by Authors (Linear Extrapolation)
Agricultural Data	1961-2021	Land Use Statistics	Directorate of Economics and Statistics, Ministry of Agriculture & Farmers Welfare
	1961-2021	Crop Area (Hectare), Production (Tonnes), Irrigated Area (Hectare)	Directorate of Economics and Statistics of Ministry of Agriculture & Farmers Welfare, ICRISAT, and Indian District Database, District Census Handbooks of Census of India

Notes: Reference for data sources are given in section 5.2

5.3 Panel Construction

To enhance and establish a relationship among the variables of interest, we have constructed a district-level panel using 267 districts and 7-time points from 1961 to 2021, which accounts for 1869 samples. The base year for the panel data is 1961, the first census year after state (or provincial) boundary reorganization. There were a few changes in district boundaries after 1961, which have been adjusted in the creation of the panel. There were three types of changes in district boundaries: the creation of a new district by merging two or more districts, and also the creation of a new district by bifurcation of an existing district, and the creation of a new district by bifurcation of two or more districts. In the first condition, we used the merged district, and districts before unification were merged to form the panel. We have simply merged the newly created districts with their parent districts for the second condition. In the third situation, we have merged the all-parent districts and the newly created districts altogether to secure the unchanged boundary for this broad merged district[7]. To do this exercise, we have used the publication by the Census of India (Census of India, 2004, 2011a) and earlier literature (Kumar & Somanathan, 2017; Liu et al., 2021). The primary panel consisted of 280 districts with 7 time points. However, in the final analysis, we have considered only major states[8] of India, which accounts for 267 consistent districts throughout the panel years from 1961 to 2021.

[7] For example, Udaipur, Chittorgarh and Banswara in Rajasthan were three separate districts from 1961 to 2001. But creation of Pratapgarh in 2011 from parts of these three districts led to merge of all four districts to create an unchanged boundary for this panel unit.

[8] Andhra Pradesh, Assam, Bihar, Chhattisgarh, Gujarat, Haryana, Himachal Pradesh, Jammu & Kashmir, Jharkhand, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Odisha, Punjab, Rajasthan, Tamil Nadu,

Census was not conducted in the state of Assam in 1981 and in the state of Jammu & Kashmir in 1991. Values for these two states in particular years are calculated by linear interpolation. For district-level panel data, statistics of the latest available year are considered for 2021. All the data are collected from multiple sources, as mentioned in Table 1.

5.4 Variables:

5.4.1 Main variables:

The two key variables of this study are population growth rate (%) and cultivated land (%). The population growth rate is assumed to follow an exponential rate of increase which is why the decadal population growth rate is calculated exponentially[9].

Land use statistics in India have the 9-fold classification of lands[10]. We have used cultivated land as one of the major variables. Cultivated land consists of net sown area and current fallow land. The percentage of cultivated land is calculated by dividing the total cultivated land (hectares) by the total reported area (hectares). The reason for selecting cultivated land as the dependent variable is that the area under cultivated land is under continuous use throughout the year, rather than other cultivable areas like 'other fallows' (not used for cultivation for 1-5 years) or 'culturable waste' (not used for last 5 years or more).

Both population growth rate and cultivated land are alternatively taken as outcome and explanatory variables to understand the bi-directional relationship. But cultivated land as a predictor has no significant results, so we have put the results of models with population growth rate as dependent and cultivated land as independent variables in the appendix section.

5.4.2 Other explanatory variables:

Control variables are the combination of agricultural and socio-economic variables (table 1), which are the log yield of major crops[11], irrigated area out of total reported area (in %), cropping intensity (in %), agricultural population density (persons/hectare of agricultural land), urbanization (in %), and non-farm workers (in %).

The percentage of agricultural land used is directly influenced by the yield, irrigated area, and cropping intensity within a given district. An increase in irrigation facilities would eventually lead to an expansion of cultivated land. On the other hand, an increase in cropping intensity will increase productivity. As productivity can be affected by other factors (fertilizer, use of tractors, etc.) that are not available at the district level, we directly take the production yield to control those factors as well.

Telangana, Uttar Pradesh, Uttarakhand, and West Bengal. See Appendix A for the final district boundary map.

[9] $\{\ln (P_t / P_{t-n})\} * 100$, where ln = Natural Logarithm, P = Population, t = time, n=interval

[10] Forests, Area Under Non-agricultural Uses, Barren and Un-culturable l Land, Permanent pastures and other Grazing Land, Land under Miscellaneous Tree Crops and Groves not included in Net Area Sown, Culturable Waste Land, Fallow Lands other than Current Fallows, Current Fallows, Net Sown Area. All these 9 types of land are aggregated and termed as Reported Area.

[11] Rice, Wheat, Jowar, Bajra, and Maize

Population density accounts for the pressure of increasing population on land. Agricultural population density has been specifically chosen as this will control for the pressure of population on cultivable areas. Urbanization plays an important role in the development of a country. Urbanization acts as a pull factor for agricultural laborers who would move to urban areas for better job opportunities. The advent of modern agricultural technology leads to job losses among agricultural laborers, compelling them to seek better employment opportunities in urban regions (Boserup, 1965; Keyfitz, 1992; Coale & Hoover, 2015). Additionally, as population growth and land use have a relationship of rural population with land, the variable urbanization will also account for the ruralness of the district. Similarly, the proportion of non-farm workers also reflects the level of reduction in labor dependency in agriculture of a specific area or district. In the absence of the Census for the last year of the panel (2021), we have linearly extrapolated the census variables (Urbanization, Nonfarm Workers).

5.4.3 Summary statistics

Summary statistics are given in Table 2. We have calculated the decadal population growth rate from census data for each district. The exponential growth rate formula was implemented to calculate the population growth rate. The mean decadal growth of the population is 19.4% from 1961 to 2021. A few districts also experienced negative growth rates. Cultivated land is the percentage of cultivated area out of the total reported area. The mean area cultivated per district for the study period is 55.1%, with the minimum cultivated area in a district being 0 (especially fully urban districts) to a maximum of 91.1%. The average agricultural population density of Indian districts in the study period is 17.9 persons per hectare of agricultural land. The average yield for major crops in India is 1284 kg per hectare[12]. The minimum and maximum yield values show that there is heterogeneity in agricultural productivity among Indian districts. The yield of crops has been consistently increasing in India (Figure 4) over the years. In the case of irrigated areas in districts, there is a huge variation in India from 0 to 92.2% with a mean of 20.5%. The mean value is very low compared to the upper range of distribution. This is due to the lack of irrigation facilities in dry areas and high irrigation density in the north-western states of India. Meanwhile, cropping intensity suggests that multi-cropping is practiced in India in limited areas, with a mean value of 133.3% and a range of 100% to 277.6%. The average urban population and non-farm workers throughout the study period are 22% and 31%, respectively. Urbanization and non-farm workers vary widely in Indian districts, from fully rural districts to fully urban centers and metropolises. Almost all the described variables except population growth rate and yield have a huge variation throughout the country within the study period. For year-wise summary statistics and box plots of the variables, please see Appendix B.

Table 2. Summary statistics of the variables

Variables	Calculation	Observations	Mean	SD	Min	Max
Decadal Population Growth Rate (%)	$\{\ln (P_t / P_{t-10})\} *100$	1,869	19.35	6.89	-17.18	52.52

[12] $e^{7.16} = 1284.025$

Cultivated Land (%)	(Cultivated Land/Reported Area) *100	1,869	55.10	20.53	0.00	91.10
Agricultural Population Density (/hectare)	Total Population/Agricultural Land	1,853	17.93	321.79	0.07	12442.37
ln Yield	Natural Logarithm of Yield (kg/hectare)	1,866	7.16	0.99	0.00	9.01
Irrigated Area (%)	(Net Irrigated Area/Reported Area) *100	1,869	20.54	20.58	0.00	92.16
Cropping Intensity (%)	(Gross Sown Area/Net Sown Area) *100	1,851	133.34	26.43	100.00	277.57
Urbanization (%)	(Urban Population/Total Population) *100	1,869	22.02	16.47	0.00	100.00
Non-Farm Workers (%)	(Non-Agricultural Workers/Total Main Workers) *100	1,869	36.89	18.51	8.72	100.00

Source: Authors' construction; Notes: ln = Natural Logarithm, P = Population, t = time

6 Econometric Approach

We employed the following strategies to understand and evaluate our hypothesis of population growth and agricultural land use change. We have taken two major approaches, panel data regression and spatial panel data regression models. They are as follows,

6.1 Dynamic Panel Data Regression Model

OLS estimation is inconsistent if an explanatory variable is correlated with an unobserved component of the dependent variable. The main variables of the study, population growth rate and percentage cultivated land can be correlated with various unobserved components. Further, because both the variables have a trend and transitioned in different phases in the study period a serial correlation problem might affect the OLS or other panel models. Finally, our target is to find whether the change in population growth rate can change the percentage of cultivated land use, thus we are inclined towards the first difference approach rather than other models in panel data models. The basic first difference approach also has the limitations of serial correlation and endogeneity. The dynamic panel data model also uses the first difference approach and considers the unobserved component and serial correlation by using a lagged dependent variable as a regressor in the model and also lagged variables as the instrument for all the variables (Cameron & Trivedi, 2005). Thus, it also incorporates the instrumental variable model as well. In this study, we have used the Arellano-Bover/Blundell-Bond linear dynamic panel data model with a two-step estimator to account for the potential endogeneity issues. In this approach, instead of traditional instruments, lagged variables are used as instruments. The model specification is as follows:

$$\Delta cl_{it} = \theta_0 + \alpha \Delta cl_{it-n} + \gamma \Delta gr_{it} + \beta \Delta X_{it} + \Delta \epsilon_{it}$$

Where, cl is cultivated land (%), gr is population growth rate (%), θ_0 is intercept, X is a vector of other explanatory variables, t is the time, n is the number of lags, $\alpha, \gamma,$ and β are the coefficients.

From the time series figures (Figure 2) we know that there is a structural discontinuity in both population growth rate and percentage of cultivated land. To assess the period-specific effect, we have applied a segmented regression approach within the dynamic panel model. As our theoretical framework suggests that population growth rate is the determinant for the cultivated land use change, we have divided the population growth rate into two periods (before and after the breakpoint of Figure 2) to separately observe the effect of population growth on cultivated land in two phases and a separate intercept for the later period has also been added to fulfill the segmented regression conditions.

6.2 Spatial Dynamic Panel Durbin Model

To address the spatial heterogeneity of population growth rate and cultivated land use, which has existed in Indian districts throughout the panel years, we have used the Spatial Dynamic Panel Durbin Model with spatial fixed effects. The model is a spatially weighted regression model which consists of both spatial lag and error model characteristics for a panel dataset. Moreover, along with addressing the spatial lagged values of dependent and independent variables, it also accounts for the lagged dependent variable as a separate independent variable. In the given sum, the spatial dynamic panel Durbin model incorporates time and space dependency of dependent and independent variables, as well as both spatial lag and error panel models. Thus, the model simultaneously controls for spatial dependency, spatial heterogeneity, and time dependency in our analysis. In this model, both dependent and independent variables are spatially lagged, and as a consequence, no additional endogeneity problem emerges from the estimation point of view (Belotti et al., 2017; Arbia et al., 2021). The model is as follows:

$$cl_{it} = \tau cl_{it-n} + \psi W cl_{it-n} + \rho W cl_{it} + \beta X_{it} + D X_{it} \theta + \alpha_i + \gamma_t + \mu_{it}$$

Where, cl is cultivated land (%), X vector of explanatory variables including population growth rate, W is the spatial matrix for the autoregressive component, D is the spatial matrix for the spatially lagged independent variables, α_i is the individual fixed or random effect, γ_t is the time effect, μ_{it} is a normally distributed error term, t is time, n is the number of lags, $\tau,\ \psi, \rho, \beta$ and θ are the coefficients. For all the econometric analysis STATA version 16 has been used and maps are created using ArcGIS 10.4.

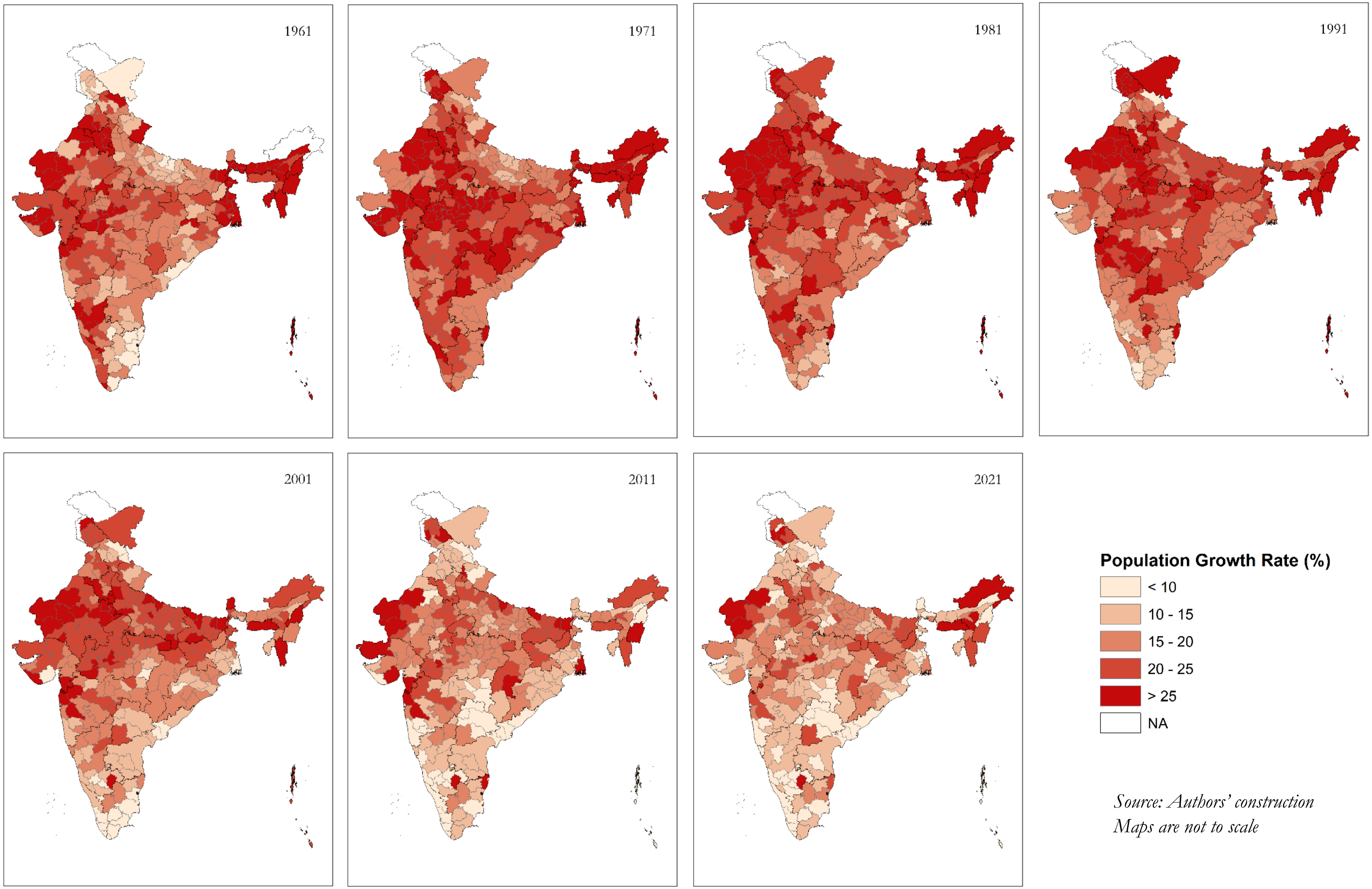
7 Results

7.1.1 Trends and Heterogeneity Pattern in Population Growth and Cultivated Land among Districts

Using maps, figure 6 depicts the district-level decadal population growth rate from 1961 to 2021. From 1961 to 1971 and 1981, all districts' population growth rates increased, even though population growth rates varied by region. Eastern states (West Bengal and Assam) and western India (with an elongated cluster from north to south) had higher population growth rates than other areas in 1961. Population growth rates in all districts were much greater in 1971, 1981, and 1991 as compared to other periods. This surge in population growth was aided by lower mortality in all regions of India following independence. Southern and eastern coastal states began to slow their population growth rate in 1991, with a major decrease in population growth rate beginning in 2001. The population growth rate of Indian districts began to decline from the southernmost states, which were later joined by the eastern coastline states and other southern states, while higher population growth rate regions were pushed towards the north.

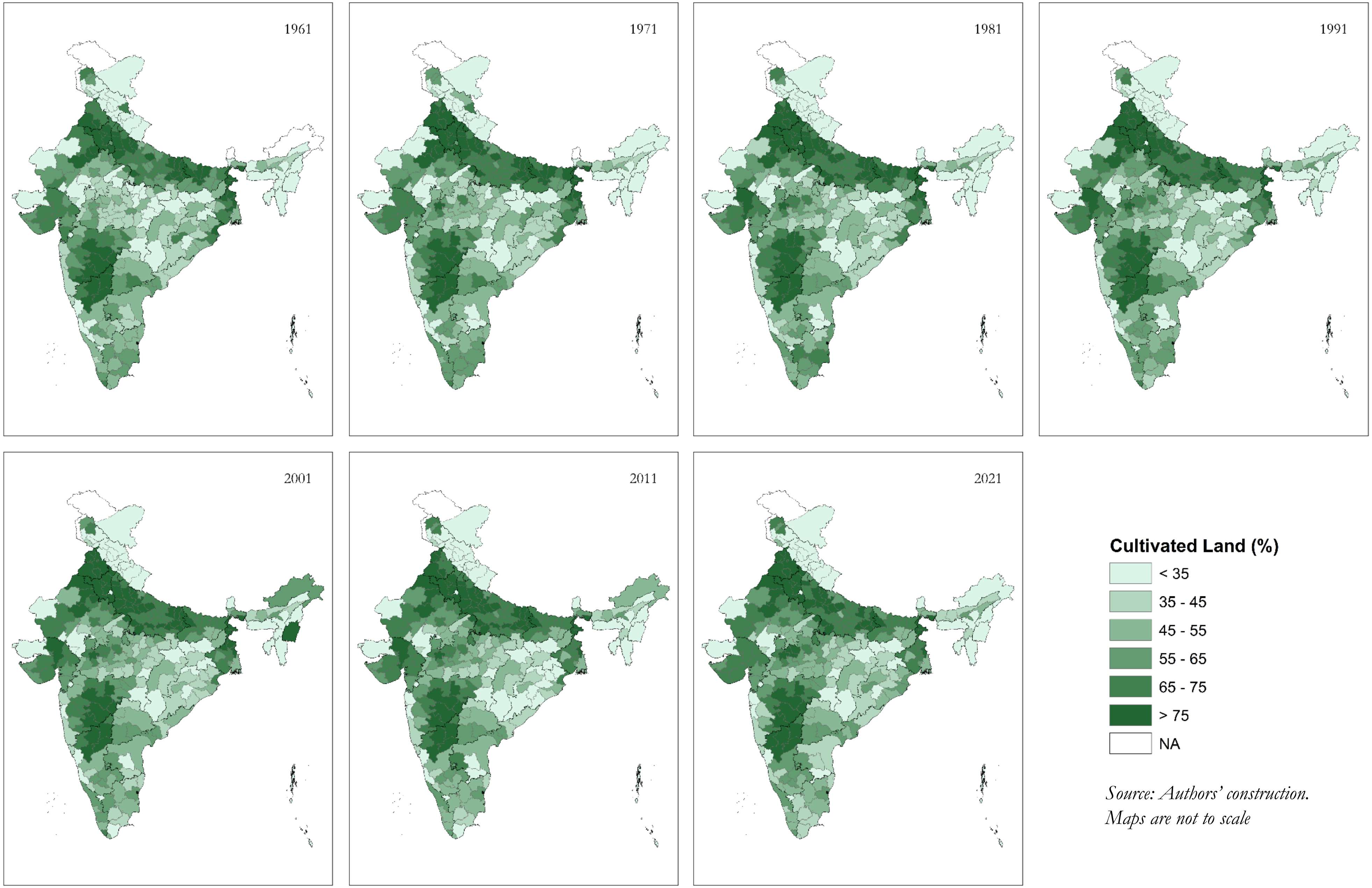
Figure 7 depicts maps of the percentage of cultivated land in Indian districts that vary in spatial terms. A substantial proportion (>65% out of the total reported area of the district) of cultivated land in India is concentrated in a few areas, namely the Ganga plain regions, central Maharashtra and northern Karnataka, north-eastern Rajasthan, and Gujarat plains. A moderate proportion of cultivated land (45-65%) is found in southern states, as well as in northern and western Madhya Pradesh. The lowest share of cultivated land within districts are in north and northeastern hilly areas, the central and eastern plateaus, and the western desert areas. The unequal distribution of cultivated land is intricately connected with population density patches in India, and this should have been the primary reason for the early population expansion in highly cultivated areas. The cultivated areas across districts have heterogeneous changes varying over the six decades (1961-2021), ranging from substantial changes in the share of cultivated land area in densely populated districts to negligible changes in sparsely populated districts. However, due to the high spatial variation in cultivated land in Indian districts, it is difficult to depict these changes alongside the spatial variation in these maps. Changes from year to year can be easily captured with a first difference of variables, and the regression results of section 7.2 depict the effect of change in population growth on change in cultivated land use.

Figure 6. District-wise decadal population growth rate, 1961-2021



Source: Authors' construction
Maps are not to scale

Figure 7. District-wise percentage cultivated land, 1961-2021



Source: Authors' construction.
Maps are not to scale

7.1.2 Spatial Clustered Trends in Population Growth Rate and Cultivated Land Use

To understand the spatially clustered trends of population growth rate and percentage cultivated land among the districts from 1961 to 2021 we have implemented the K-Means cluster analysis method and classified the population growth rate and cultivated land in 3 major clusters of districts. We have used GeoDa version 1.2 and converted the long format panel into the wide format. Table 3 shows the cluster centers for each cluster. All three clusters for each variable can be classified into three categories i.e., early transition districts, late transition districts, and other extreme value districts. Figure 8 shows the maps for clustered areas for each variable.

For population growth rate, cluster 1 suggests late transition districts majorly concentrated in India's northern, central, western, and south-central regions (Figure 8). The population growth rate in these districts increased till 1981 and then fell in 1991 (Table 3). Cluster 2 depicts the early transition districts with growth rates that started declining in 1981, majorly concentrated in India's southern and east coastal states. Cluster 3 of the population growth rate shows districts with a very high rate of growth majorly located in eastern and western borders.

Clusters of percentage cultivated land also show similar trends. Cluster 1 is in India's major agricultural areas, i.e., northern Indo-Gangetic belt, central dry agricultural belt, and western canal irrigation belt (Figure 8). The region has 70% of land for cultivation on average (Figure 7). This region's cultivated land percentage increased until 1981, remained unchanged till 1991, and then declined steadily (Table 3, section B). Cluster 2 is concentrated in central and eastern plateau areas and the states of Kerala and Tamil Nadu. Cluster 2 increased until 1991 and then fell since then. Cluster 3 shows the extreme regions with a very low percentage of land for cultivation, mostly located in mountainous and desert areas of the country.

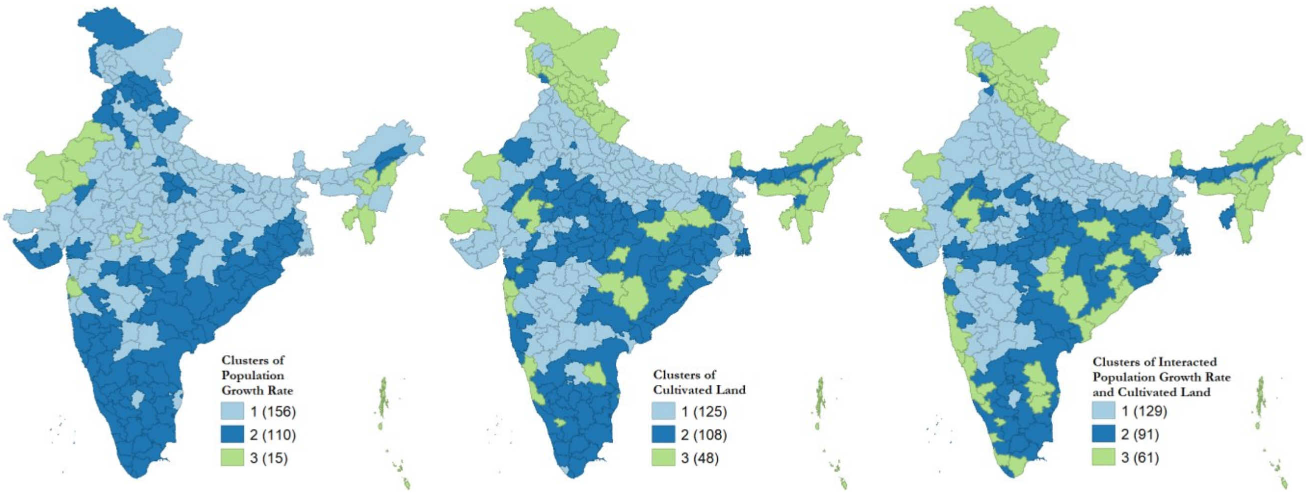
Further, we have used an interacted variable of population growth rate and percentage cultivated land to see the spatial coevolution of these two variables. Cluster 1 depicts the late transition districts, which are majorly concentrated in Indo-Gangetic plains in the north, central dry agricultural areas, and western canal-irrigated agricultural areas. This region has also been documented to have a higher population growth rate. Cluster 2 is concentrated in the southernmost states and eastern and central plateau regions. This region shows early transition districts mostly dominated by population growth rate (Table 3, section A). Cluster 3 is mostly located in mountainous and hilly regions with some scattered areas of plateau regions.

Table 3: Year-wise cluster centers for population growth rate and cultivated land

Clusters	1961	1971	1981	1991	2001	2011	2021
(A) Population Growth Rate							
Cluster 1	20.03	23.39	24.08	23.69	22.08	18.99	17.15
Cluster 2	19.12	20.80	18.95	17.11	13.88	10.13	8.87
Cluster 3	38.25	31.84	37.36	32.99	31.79	21.98	20.22
(B) Cultivated Land							
Cluster 1	70.53	72.39	73.50	73.43	73.36	73.09	72.05
Cluster 2	44.59	46.81	47.42	48.28	47.75	47.17	48.17
Cluster 3	18.24	19.44	17.96	18.19	21.34	19.43	19.06
(C) Interaction of Population Growth Rate and Cultivated Land							
Cluster 1	1394.29	1560.91	1686.49	1644.08	1555.69	1297.18	1116.32
Cluster 2	953.64	1127.31	1044.77	1000.86	847.73	648.33	541.24
Cluster 3	427.38	529.42	482.51	432.52	420.86	295.04	299.43

Source: Authors' construction

Figure 8: Spatial Clusters of Population Growth Rate and Percentage Cultivated Land



Source: Authors' construction

7.2.1 Dynamic Panel Regression Results

We have applied the Arellano-Bover/Blundell-Bond linear dynamic model with a two-step GMM estimator to our panel data, yielding the results presented in Table 4. The dynamic panel model has the benefit of employing the first differences of variables with lagged dependent variables as an instrument. It operates on the assumption that there is no serial autocorrelation, and it also eliminates the possible endogeneity problem by applying lagged variables as instruments. Considering cultivated land as the dependent variable, table 4 shows that the increasing population growth rate is significantly affecting the cultivated land even after controlling all other variables. In each of the models from 1 to 6, the 'a' indicates panel up to 2011 (which has values based on observed data), and 'b' indicates panel up to 2021 (which has two extrapolated variables for 2021). Models are arranged in order of increasing number of explanatory variables to get consistent results.

A lag of the dependent variable has been taken by the models, which find the possible effects of independent variables on the dependent variable after extracting the effects of its own lagged values. In all the models, the population growth rate has significantly affected the cultivated land. In models 1a & 1b, the population growth rate is considered as the sole explanatory variable. From model 2a onwards, we have used the agricultural population density as a covariate which controls for the increasing population pressure on agricultural land. In models 2a and 2b, after controlling for agricultural population density, one unit change in population growth rate would affect the percent cultivated land by 12% and 10%, respectively. After controlling for agricultural variables in models 3a & 3b one unit change in population growth rate would affect the percent cultivated land by 8.5% and 9% units. Similarly, in models 5a and 5b, after controlling for all variables considered for the study, one unit change in population growth rate would affect cultivated land by 5.7% units and 6.5%, respectively. These results signify that an increase in the population growth rate would increase the cultivated land use within a district and vice-versa. As the population growth rate declines in later periods, it has a significant effect on the reduction of cultivated land use. The segmented regression results in the next section more clearly depict this. Apart from population growth, agricultural population density, crop yield, irrigated area, and percentage of non-farm workers are significant determinants of cultivated land use in our models.

All the models satisfy the specification tests except for the Sargan test in models 1a and 1b. Both panels 'a' and 'b' are found similar in most of the models. AR tests show that there is no significant serial correlation in the second order, which is desirable. Sargan test confirms that overidentifying restrictions are valid. We also tested population growth rate as a dependent variable against cultivated land as an explanatory variable to check for a reversal effect but found no evidence of it. These results are included in Appendix C. However, we found that urbanization, education, and log yield are major determinants of the population growth rate in India.

7.2.2 Dynamic Panel Regression with Segmented Regression Approach Results

Following the theoretical framework (Figure 2), the first and second phases[13] of the land-population relationship are examined using models 1 to 5 in Table 5. To get the period-specific effect of the population growth rate on cultivated land, we have used period-specific population growth rates and an additional intercept for the period of 1991-2021[14] following the segmented regression methods. Here, the population growth rate of the full panel (1961-2021) is segmented into two periods by predicting a breakpoint. The predicted breakpoint was 1981, and two segmented periods are pre-breakpoint (1961-1981) and post-breakpoint (1991-2021). In Table 5, the population growth rate was found to be significantly affecting cultivated land for both periods. In model 1, a unit change in population growth rate would affect the percentage of cultivated land by 20% and 8% for the period 1961-1981 and 1991-2021, respectively. In model 5, after controlling for all the variables, one unit increase in population growth rate would increase the share of cultivated land by 12% between 1961 and 1981, and a unit decline in population growth rate would reduce the percent cultivated land by 5% from 1991 to 2021. AR tests show no second-order correlation and the Sargan test confirms that there is no overidentification by instruments

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[13] Referred to as the second and third stages in the theoretical framework. For convenience, they are mentioned as the first and second phases in the results, as mentioned earlier.

[14] Constant in the models are the intercepts for the period 1961-1981, while for intercepts for the period 1991-2021, we need to add both model constant and intercept (1991-2021) e.g., in model 1 of Table 4, the intercept of period 1991-2021 would be (0.755 + 22.978) = 23.733

Table 4. Results of Arellano-Bover/Blundell-Bond linear dynamic panel regression model showing the effect of population growth rate on cultivated land.

Variables	Model 1a	Model 1b	Model 2a	Model 2b	Model 3a	Model 3b	Model 4a	Model 4b	Model 5a	Model 5b
Cultivated $Land_{t-1}$	0.706*** (0.067)	0.670*** (0.063)	0.633*** (0.077)	0.605*** (0.072)	0.674*** (0.088)	0.629*** (0.077)	0.678*** (0.078)	0.629*** (0.069)	0.614*** (0.09)	0.574*** (0.078)
Population Growth Rate	0.133*** (0.025)	0.111*** (0.020)	0.117*** (0.025)	0.101*** (0.020)	0.085*** (0.032)	0.090*** (0.028)	0.065* (0.035)	0.052* (0.031)	0.057* (0.03)	0.065** (0.027)
Agricultural Population Density			0.001*** (0.000)	0.001*** (0.000)	-0.01*** (0.001)	-0.011*** (0.001)	0.001** (0.000)	0.000** (0.000)	-0.011*** (0.001)	-0.011*** (0.001)
Log Yield					0.645* (0.362)	0.855** (0.372)			0.687 (0.52)	1.014** (0.506)
Irrigated Area					-0.079*** (0.028)	-0.074*** (0.028)			-0.004 (0.035)	-0.025 (0.033)
Cropping Intensity					0.016 (0.014)	0.012 (0.009)			0.008 (0.014)	0.005 (0.01)
Urbanizatio n							-0.032 (0.037)	-0.003 (0.024)	-0.034 (0.037)	-0.01 (0.023)
Nonfarm Workers							-0.026 (0.021)	-0.035* (0.018)	-0.055** (0.023)	-0.05*** (0.019)
Constant	13.940*** (3.932)	16.543*** (3.626)	18.56*** (4.558)	20.529*** (4.135)	11.942** (5.593)	13.251** (5.387)	18.729*** (4.489)	21.523*** (4.039)	17.689*** (6.268)	17.709*** (5.977)
Groups	267	267	265	266	265	266	265	266	265	266
Observations	1335	1602	1323	1588	1319	1583	1323	1588	1319	1583
Instruments	10	12	11	13	14	16	13	15	16	18
AR (1)	-3.029***	-3.259***	-2.835***	-3.106***	-3.039***	-3.243***	-2.972***	-3.203***	-2.843***	-3.126***
AR (2)	-0.807	-0.980	0.134	-0.166	0.104	-0.217	-0.037	-0.315	0.054	-0.045

Sargan Test	13.308*	15.052*	9.976	10.899	10.443	12.460	6.976	7.226	4.651	5.638
Wald Chi^2	120.087***	132.056***	82.803***	96.103***	3167.812***	881.397***	108.979***	125.082***	731.015***	2093.542***

Source: Authors' construction

*Notes: dependent variable: Cultivated Land (%); *** p<.01, ** p<.05, * p<.1; Standard Errors are in parenthesis*

Table 5. Results of split period-wise Arellano-Bover/Blundell-Bond linear dynamic panel regression model showing the effect of population growth rate on cultivated land.

Variables	Model 1	Model 2	Model 3	Model 4	Model 5
Cultivated Land$_{t-1}$	0.721*** (0.062)	0.649*** (0.066)	0.621*** (0.066)	0.652*** (0.064)	0.621*** (0.065)
Population Growth Rate (1961-1981)	0.202*** (0.071)	0.167** (0.069)	0.151*** (0.057)	0.139** (0.069)	0.122** (0.057)
Population Growth Rate (1991-2021)	0.079*** (0.023)	0.076*** (0.023)	0.082*** (0.027)	0.050** (0.024)	0.052** (0.025)
Agricultural Population Density		0.001*** (0.000)	-0.01*** (0.001)	0.001** (0.000)	-0.01*** (0.001)
Log Yield			0.802** (0.357)		1.200** (0.470)
Irrigated Area			-0.059** (0.028)		-0.042 (0.030)
Cropping Intensity			0.009 (0.010)		0.004 (0.01)
Urbanization				-0.012 (0.023)	-0.013 (0.023)
Nonfarm Workers				-0.027 (0.017)	-0.047** (0.019)
Intercept (1991-2021)	2.327 (1.502)	1.707 (1.498)	1.287 (1.382)	1.973 (1.39)	1.473 (1.312)
Constant	11.922*** (3.859)	16.777*** (3.974)	12.924*** (4.985)	18.199*** (3.899)	12.841** (4.992)
Groups	267	266	266	266	266
Observations	1602	1588	1583	1588	1583
Instruments	14	15	18	17	20
AR (1)	-3.526***	-3.344***	-3.270***	-3.420***	-3.376***
AR (2)	-1.076	-0.335	-0.260	-0.411	-0.180
Sargan Test	13.020	10.084	13.593	7.011	6.033
Wald Chi^2	157.880***	135.301***	1021.863***	163.700***	2217.414***

Source: Authors' construction

*Notes: dependent variable: Cultivated Land (%); *** p<.01, ** p<.05, * p<.1; Standard Errors are in parenthesis*

7.3 Robustness Checks

7.3.1 Model estimates with agricultural land as an alternative measure of cultivated land

As an alternative dependent variable for testing robustness, we used the percentage of agricultural land[15]. In Table 6, models 'a' and 'b' indicate panels up to 2011 and 2021, respectively. The results indicate that all the models confirm that the population growth rate is significantly affecting the change in the percentage of agricultural land. In final model 5a with panel up to 2011, after

[15] Agricultural land, as earlier mentioned is a combination of cultivated land and other lands (Land under Miscellaneous Tree Crops and Groves not included in Net Area Sown, Culturable Waste Land, Fallow Lands other than Current Fallows).

controlling all the variables one-unit shift in population growth rate affects the agricultural land by 7%. All the models have satisfied the AR test specifications and Sargan test validity.

Table 6. Results of the Arellano-Bover/Blundell-Bond linear dynamic model showing the effect of population growth rate on land using an alternative dependent variable (i.e. agricultural land)

Variables	Model 1a	Model 1b	Model 2a	Model 2b	Model 3a	Model 3b	Model 4a	Model 4b	Model 5a	Model 5b
Agricultural $Land_{t-1}$	0.869*** (0.087)	0.826*** (0.085)	0.851*** (0.104)	0.801*** (0.101)	0.843*** (0.091)	0.755*** (0.087)	0.864*** (0.104)	0.806*** (0.100)	0.86*** (0.098)	0.756*** (0.086)
Population Growth Rate	0.085*** (0.027)	0.064*** (0.024)	0.082*** (0.027)	0.065*** (0.024)	0.076** (0.032)	0.066** (0.028)	0.060* (0.031)	0.054** (0.027)	0.068** (0.032)	0.062** (0.029)
Agricultural Population Density			0.000** (0.000)	0.000* (0.000)	0.005 (0.006)	0.004 (0.006)	0.000* (0.000)	0.000* (0.000)	0.005 (0.007)	0.003 (0.006)
Log Yield					-0.378 (0.711)	-0.364 (0.555)			-0.371 (0.685)	-0.305 (0.592)
Irrigated Area					0.055 (0.05)	0.038 (0.039)			0.069 (0.05)	0.033 (0.04)
Cropping Intensity					-0.029 (0.02)	-0.016 (0.012)			-0.033 (0.021)	-0.017 (0.013)
Urbanization							-0.068* (0.04)	-0.023 (0.027)	-0.076 (0.047)	-0.01 (0.027)
Nonfarm Workers							0.020 (0.024)	0.003 (0.018)	0.021 (0.03)	0.002 (0.022)
Constant	6.345 (5.265)	9.590* (5.146)	7.639 (6.371)	11.287* (6.118)	13.737* (7.845)	18.24*** (6.707)	8.029 (6.780)	11.618* (6.464)	13.891* (7.52)	18.238*** (6.484)
Groups	267	267	265	266	265	266	265	266	265	266
Observations	1335	1602	1323	1588	1319	1583	1323	1588	1319	1583
Instruments	10	12	11	13	14	16	13	15	16	18
AR (1)	-3.592***	-3.669***	-3.547***	-3.614***	-3.375***	-3.226***	-3.276***	-3.288***	-3.263***	-3.143***

AR (2)	-0.032	-0.423	1.266	0.523	1.079	0.479	1.164	0.463	1.017	0.463
Sargan Test	6.441	12.094	6.417	11.967	8.505	17.368**	6.184	12.922	8.573	19.432**
Wald Chi^2	206.255***	221.127	387.748***	528.186***	178.637***	194.694***	432.238***	946.745***	181.748***	222.215***

Source: Authors' construction

*Notes: dependent variable: Agricultural Land (%); *** p<.01, ** p<.05, * p<.1; Standard Errors are in parenthesis*

7.3.2 Model estimates with an alternative break point in population growth rates

The trend in cultivated land use reveals that it has been shrinking since 1993 (Figure 3). To test the validity of our results, we used 1991 as the alternative breakpoint rather than the previously used 1981. In Table 7, the population growth rate has been considered for two separate periods (or phases), i.e., 1961 to 1991 and 2001 to 2021. Most of the models of Table 7 show that the population growth rate of both periods is significantly affecting the cultivated land, which is in line with our earlier results. In model 1, one unit change in population growth rate would change the cultivated land by 12.7% and 4.8% for the period 1961-1991 and 2001-2021, respectively. In model 5, after controlling for all the variables, a unit change in population growth rate would affect the cultivated land by 7.6% and 6.1% for the period 1961-1991 and 2001-2021, respectively. It should be noted that the coefficient of the earlier period in Table 7 is lower than the coefficient of the earlier period in Table 5. It is due to spatial heterogeneity in the time of decline in population growth rate. Until 1981 both the population growth rate and cultivated land use increased all over India. However, the decline in population growth rate since 1981 is followed by the decline in cultivated land use since 1991, with a lag of 10 years (see Figure 2). This lag in decline slightly lowers the coefficient in the earlier phase of Table 7 compared with Table 5. All the models satisfied the specification tests of dynamic panel regressions.

Table 7. Results of the Arellano-Bover/Blundell-Bond linear dynamic model showing the effect of population growth rate on cultivated land using alternative breakpoints in population growth rate trends

Variables	Model 1	Model 2	Model 3	Model 4	Model 5
Cultivated Land$_{t-1}$	0.703*** (0.065)	0.622*** (0.071)	0.612*** (0.071)	0.607*** (0.074)	0.565*** (0.073)
Population Growth Rate (1961-1991)	0.127* (0.069)	0.088 (0.063)	0.089** (0.040)	0.074 (0.065)	0.076* (0.042)
Population Growth Rate (2001-2021)	0.048* (0.024)	0.06** (0.025)	0.069** (0.028)	0.048* (0.025)	0.061** (0.026)
Agricultural Population Density		0.000** (0.000)	-0.011*** (0.001)	0.000* (0.000)	-0.011*** (0.001)
Log Yield			1.075*** (0.411)		0.998** (0.483)
Irrigated Area			-0.05* (0.03)		-0.022 (0.031)
Cropping Intensity			0.008 (0.009)		0.005 (0.009)
Urbanization				-0.004 (0.025)	-0.012 (0.022)
Nonfarm Workers				-0.042 (0.034)	-0.046* (0.026)
Intercept (2001-2021)	1.248 (1.405)	0.203 (1.269)	-0.14 (0.883)	0.711 (1.069)	0.219 (0.856)
Constant	14.479*** (4.205)	19.991*** (4.39)	12.797** (5.302)	22.57*** (5.126)	17.84*** (5.941)
Groups	267	266	266	266	266
Observations	1602	1588	1583	1588	1583
Instruments	14	15	18	17	20
AR (1)	-3.287***	-3.141***	-3.231***	-3.108***	-3.129***

AR (2)	-1.038	-0.283	-0.182	-0.224	-0.020
Sargan Test	11.399	7.560	8.454	6.981	5.685
Wald Chi^2	139.252***	103.472***	1747.458***	114.709***	2222.276***

Source: Authors' construction

*Notes: dependent variable: Cultivated Land (%); *** p<.01, ** p<.05, * p<.1; Standard Errors are in parenthesis*

7.3.3 Model estimates with two lags for cultivated land

In Table 8, we used two lags for the dependent variable, i.e. cultivated land, for an additional robustness check of the main results, which used single lag models. The second lag of the dependent variable is not significant here. We have used only the models with all the control variables. In models 1a and 1b, a unit change in population growth rate would affect the cultivated land by 5.7% and 6.2%, respectively.

Table 8: Results of Arellano-Bover/Blundell-Bond linear dynamic model showing the effect of population growth on cultivated land with two lags of dependent variable.

Variables	Model 1a	Model 1b
Cultivated Land$_{t-1}$	0.687*** (0.143)	0.605*** (0.116)
Cultivated Land$_{t-2}$	-0.066 (0.084)	-0.118 (0.076)
Population Growth Rate	0.057* (0.034)	0.062** (0.031)
Agricultural Population Density	-0.02*** (0.004)	-0.022*** (0.003)
Log Yield	0.011 (0.365)	0.455 (0.418)
Irrigated Area	0.067** (0.027)	0.047** (0.021)
Cropping Intensity	0.003 (0.018)	-0.003 (0.011)
Urbanization	-0.028 (0.041)	-0.003 (0.024)
Nonfarm Workers	-0.049** (0.022)	-0.053*** (0.019)
Constant	20.89* (10.662)	25.999*** (8.76)
Groups	265	266
Observations	1054	1318
Instruments	15	17
AR (1)	-3.391***	-4.195***
AR (2)	0.212	0.806
Sargan Test	2.826	5.329
Wald Chi^2	244.985***	245.689***

Source: Authors' construction

*Notes: dependent variable: Cultivated Land (%); *** p<.01, ** p<.05, * p<.1; Standard Errors are in parenthesis*

7.3.4 Spatial Dynamic Panel Durbin Model Results

Table 9 depicts the results of the spatial dynamic Durbin model with fixed effects to accommodate both spatially lagged dependency and geographical heterogeneity, along with the possible endogeneity problem in the data. The benefit of employing the spatial dynamic panel Durbin model is it incorporates both spatial and time dependency (lagged values) in the model. The model will help to understand neighborhood effects and district-specific effects (main effect) after controlling for lag values of the dependent variable. In table 9, 'a' indicates panel up to 2011, and 'b' indicates panel up to 2021. In models 1a & 1b, one unit change in population growth rate (in main effect) would affect cultivated land by 7.2% and 7.5%, respectively. Similarly, in models 5a & 5b, after controlling for all the variables, a unit change in population growth rate would change the cultivated land (in main effects) by 7.7% and 8.2%, respectively. This indicates that even in the presence of spatial dependency and heterogeneity population growth rate is still influencing the cultivated land use change within any district.

7.3.5 Model estimates according to land reform policies of the states

India has observed multiple land reform legislations across states since independence. Land reforms aimed to reallocate the land among different socio-economic groups and enhance the poor's access to land. Situations where cultivators own the land exhibit better performance in terms of agricultural production and investment than conditions where land ownership lies with landlords (Banerjee & Iyer, 2005). Thus, land reform offers ownership of land to more households, thus promoting technological progress in land use as cultivators own and sown the smaller lands which often drive for intensification over extensification. We have used cumulative land reform legislation scores from Besley & Burgess (2000) to differentiate land reform states. States that score more than the national score (2.910) are considered land-reformed states and vice versa. table 10 shows the results of land reform and population growth interactions. In table 10, 'a' indicates panel up to 2011, and 'b' indicates panel up to 2021. In both models, irrespective of whether states have experienced 'land reforms' or 'no land reforms', the population growth rate significantly influences the percentage of cultivated land. In model 1a, one unit change in population growth rate changed cultivated land by 4.3% and 8.2%, respectively, for states with land reforms and no land reforms. In model 1b, one unit change in population growth rate changed cultivated land by 6.1% and 8.3% for states with land reforms and no land reforms, respectively. Though the effect of the population growth rate for states with no land reforms is slightly higher, in both conditions, it is significantly increasing cultivated land. The AR test and Sargan test show that the models are valid and robust.

Table 9. Results of Spatial dynamic panel Durbin model showing the effect of population growth rate on cultivated land

Variables	Model 1a	Model 1b	Model 2a	Model 2b	Model 3a	Model 3b	Model 4a	Model 4b	Model 5a	Model 5b
Main Effects (x)										
Cultivated $Land_{t-1}$	0.451*** (0.075)	0.475*** (0.061)	0.446*** (0.076)	0.473*** (0.061)	0.440*** (0.078)	0.469*** (0.064)	0.454*** (0.077)	0.471*** (0.061)	0.437*** (0.081)	0.461*** (0.065)
Population Growth Rate	0.072* (0.038)	0.075** (0.032)	0.068* (0.035)	0.074** (0.031)	0.071* (0.037)	0.076** (0.031)	0.072** (0.034)	0.078** (0.032)	0.077** (0.038)	0.082** (0.032)
Agricultural Population Density			0.000* (0.000)	0.000** (0.000)	0.000 (0.001)	0.000 (0.000)	0.000 (0.000)	0.000*** (0.000)	0.000 (0.001)	0.000 (0.000)
Log Yield					0.227 (0.481)	0.049 (0.331)			0.136 (0.548)	0.034 (0.381)
Irrigated Area					-0.004 (0.109)	0.012 (0.076)			0 (0.11)	0.016 (0.077)
Cropping Intensity					0.023 (0.042)	0.012 (0.027)			0.022 (0.042)	0.01 (0.026)
Urbanization							0.013 (0.029)	-0.007 (0.025)	0.01 (0.031)	-0.005 (0.025)
Nonfarm Workers							-0.067 (0.047)	-0.058* (0.035)	-0.063 (0.047)	-0.057* (0.032)
Spatially Lagged Effects (W*x)										
Population Growth Rate	-0.004 (0.048)	-0.02 (0.044)	-0.002 (0.047)	-0.019 (0.044)	0.000 (0.06)	-0.012 (0.056)	-0.075 (0.05)	-0.082* (0.045)	-0.062 (0.065)	-0.066 (0.055)
Agricultural Population Density			0.000 (0.001)	0.000 (0.001)	0.000 (0.001)	0.000 (0.001)	0.000 (0.001)	0.000 (0.001)	0 (0.001)	0 (0.001)

Log Yield					-0.429	0.328			0.25	0.682
					(0.716)	(0.602)			(0.796)	(0.682)
Irrigated Area					-0.038	-0.058			-0.023	-0.052
					(0.093)	(0.066)			(0.09)	(0.066)
Cropping Intensity					0.015	0.004			0.009	0.002
					(0.042)	(0.029)			(0.042)	(0.027)
Urbanization							-0.088	-0.031	-0.083	-0.033
							(0.055)	(0.047)	(0.054)	(0.046)
Nonfarm Workers							0.053	0.042	0.03	0.031
							(0.059)	(0.046)	(0.057)	(0.044)
ϱ	0.405***	0.391***	0.407***	0.392***	0.385***	0.391***	0.391***	0.375***	0.356***	0.365***
	(0.060)	(0.054)	(0.06)	(0.054)	(0.061)	(0.052)	(0.062)	(0.056)	(0.058)	(0.051)
σ^2	14.790***	14.414***	14.738***	14.393***	14.618***	14.295***	14.685***	14.294***	14.527***	14.177***
	(3.080)	(2.684)	(3.076)	(2.682)	(3.049)	(2.677)	(3.092)	(2.703)	(3.059)	(2.696)
Observations	1335	1602	1335	1602	1335	1602	1335	1602	1335	1602
Groups	267	267	267	267	267	267	267	267	267	267
R^2 (within)	0.179	0.223	0.180	0.223	0.190	0.228	0.191	0.234	0.203	0.240
R^2 (between)	0.950	0.954	0.950	0.954	0.958	0.964	0.943	0.952	0.942	0.959
R^2 (overall)	0.907	0.911	0.908	0.911	0.913	0.920	0.902	0.909	0.899	0.916
Log-likelihood	-3627.122	-4342.2911	-3624.8688	-4341.2416	-3617.5303	-4336.3220	-3621.4764	-4333.5498	3610.6000	-4326.3357

Source: Authors' construction

*Notes: dependent variable: Cultivated Land (%); ϱ is coefficients of spatially lagged dependent variables; W is the weight matrix; *** p<.01, ** p<.05, * p<.1; Robust Standard Errors are in parenthesis*

Table 10. Results of the Arellano-Bover/Blundell-Bond linear dynamic model showing the effect of population growth on cultivated land for two groups of states: with land reforms and with no land reforms.

Variables	Model 1a	Model 1b
Cultivated $Land_{t-1}$	0.544*** (0.086)	0.535*** (0.078)
Population Growth Rate*Reformed	0.043** (0.021)	0.061** (0.025)
Population Growth Rate*Non-Reformed	0.082* (0.044)	0.083** (0.039)
Agricultural Population Density	-0.011*** (0.002)	-0.011*** (0.002)
Log Yield	0.784 (0.488)	1.058** (0.474)
Irrigated Area	-0.008 (0.03)	-0.024 (0.027)
Cropping Intensity	0.009 (0.012)	0.005 (0.008)
Urbanization	-0.029 (0.031)	-0.006 (0.021)
Nonfarm Workers	-0.054*** (0.02)	-0.049*** (0.017)
Constant	20.994*** (6.276)	19.731*** (5.958)
Groups	257	258
Observations	1279	1535
Instruments	17	19
AR (1)	-3.143***	-3.514***
AR (2)	-0.134	-0.269
Sargan Test	2.111	2.169
Wald Chi^2	261.108***	215.169***

Source: Authors' construction

*Notes: dependent variable: Cultivated Land (%); *** p<.01, ** p<.05, * p<.1; Standard Errors are in parenthesis*

We have also checked the robustness of the results using a full sample with all the districts, which is presented in Appendix D. The results based on the full sample are also in tune with our main findings.

8 Discussion

This study empirically examines the effect of population growth rate on change in cultivated land use by using long-term panel data. The study is both confirmatory as well as exploratory in nature. In particular, this study explored the nature of the relationship between 'population and land' at different stages of the demographic and land use transition with our proposed theoretical framework (Section 4). The study successfully tested two hypotheses: (1) the increase in population growth leading to expansion of cropland in the absence of agricultural technology and crop intensification, and (2) the relationship between 'population growth' and 'the size of cropland' pose a split relationship subject to change in agricultural technology and crop intensification. Besides robust econometric approaches such as dynamic panel data regression models, the evidence put out in this study is also validated using the spatial dynamic panel Durbin model, identifying spatial clusters and several robustness checks. The study also tested the heterogeneity of the findings by land policy environment and reforms across the states of India. The discussion of key findings of the study in the context of existing literature is organized as follows:

(a) The rise in population growth rate had a significant effect on the expansion of cultivated land

The first key finding of the study is the expansion of cultivated land was mostly affected by the increase in the pace of population growth. The demography history since Malthusian days has hinted that population growth is the primary reason for expanding cultivation of agricultural land, although Marxian theorists pose population expansion as being a result of the agricultural revolution (Boserup, 1965; Birdsall et al., 2001). Although contemporary evidence suggests that under demographic transition, the population growth rate eventually increases and decreases with various behavioral and developmental changes in society, its links with agricultural land are not widely documented (Arizpe et al., 2019; Bongaarts, 2023). In this context, this study documents robust empirical evidence on the effect of population growth rate on the expansion of cultivated land. The evidence documented in this study is in line with the limited existing studies in the global and other developing country contexts. Most of the existing studies have fostered that the decrease in population growth rate is attributed to socio-economic development, while the reduction in cultivated land use is contingent upon a prior decline in population growth rate, even in the presence of agricultural technology (Ramankutty et al., 2018).

(b) The population growth rate poses a split association with cultivated land from 1961 to 2021

The second important finding of this study is that the population growth rate poses a split relation with cultivated land from 1961 to 2021. Our segmented regression models provide significant results for both phases: in the first phase, the effect of population growth rate was higher than in the second phase, which supports our second hypothesis, and findings are in tune with previous literature (Bilsborrow & Okoth Ogendo, 1992; Mishra, 2002). Our results also explain that the declining population growth rate in the second stage also affects cultivated land use positively. This implies that in the initial phase, a rapidly increasing 'population growth rate' contributes to the increase in population size (and density), prompting a corresponding expansion in agricultural land utilization and agricultural intensification. However, in the subsequent phase, as the 'population growth rate' experiences a gradual decline (while remaining positive), population size and density continue to grow at a slow pace. During this period, the 'rate of growth in agricultural intensification' surpasses the 'rate of population growth'[16] which enables agricultural technology to effectively support food security without expanding agricultural land (Ausubel et al., 2013). Consequently, agricultural land expansion ceases and begins to contract with the rise and fall in population growth rates from 1961 to 2021, with a predicted breakpoint in 1981. India's highest recorded population growth rate was in 1971 (2.22% per year), but it remained unchanged until 1981 (2.20% per year), then it began to decline. Following a lag of roughly ten years, the percentage of cultivated land began to decline in the 1990s. Before 1981, the Indian population growth not only increased farmland but also worked as a catalyst for a major shift in agricultural technology via the Green Revolution (Ausubel et al., 2013; Goli & Arokiasamy, 2013; Dyson, 2018). Even in this phase of agricultural technology development, these findings support the hypothesis that a decrease in the rate of population growth rate precedes and is a necessary condition for a decrease in land used for agriculture. Further, the findings foster an 'inverted U-shaped' relationship between population growth rate and agricultural land use in India.

(c) The sustainability of the population and environment is a prerequisite for a decline in population growth and cropland and the rise of ecologically friendly agricultural intensification and productivity

The third key finding is the mediating role of crop intensification and productivity guiding the relationship between population growth rate and cultivated land expansion. The findings assert that the role of population growth weakens on expanding cultivated land with increasing agriculture intensification and rise in productivity. These findings assume importance in the

[16] See Appendix E

context of existing evidence that any population's food security and sustainability can be achieved by increasing agricultural productivity by using modern green farm technology, rather than expanding land usage (Ausubel et al., 2013; Barretto et al., 2013). This is because the rate of increase in 'agricultural intensification or productivity' must be higher than the 'rate of population growth' (Appendix E) for population sustainability (Lam, 2011; Bilsborrow, 2022; Lam, 2023). Thus, we can infer from the findings of the present study that the rise in ecologically friendly agricultural intensification and rise in productivity for population sustainability is the key implication advancing out of this study. Moreover, as the population growth rate in India declines (James & Goli, 2016), it creates an opportunity for a reduction in cultivated land.

(d) *Other findings: expansion of urbanization and non-firm sectors and decline in population growth and cropland*

In developed countries where food security is not a major problem, the use of agricultural land is reducing due to an increase in agricultural productivity, conversion of cropland to forest areas, and urbanization (Ewers et al., 2009; Sali, 2012). Although the context of a developed country cannot be strictly compared to that of developing countries, these factors are also true for countries that are rapidly developing, such as India. Thus, we are advancing an additional significant finding from this study that the expansion of education and urbanization, which expands the non-farm works, helps in the decline of population growth rate and thereby cultivated land. Though urbanization contributes to a significant reduction in croplands (Del Mar López et al., 2001; Van Vliet et al., 2017). Also, with the reduction in agricultural land in the country due to increasing agricultural productivity, forest cover increases by reserving cropland for forest, thus contributing to environmental sustainability (Lambin & Meyfroidt, 2011). Furthermore, urbanization, education, and the non-form sector contribute to economic development, thereby helping in controlling population growth as well. The existing evidence also suggests that originally, an expanding population heralded economic development (Coale & Hoover, 2015), but later stages of this economic development rescued the population from the 'Malthusian Catastrophe' by sustaining agricultural productivity as well as lowering population growth rate in India, which in turn lowers the expansion of agricultural land (Liu et al., 2008; Ewers et al., 2009; Lambin & Meyfroidt, 2011; Sali, 2012; Manoharan & Varkey, 2022).

(e) *Validation of the findings in the context of existing theoretical arguments*

The above findings can be placed in the existing classical arguments from Boserup and Malthus. Boserupian perspective is generally concerned with scenarios of expanding population to cause the intensification of agriculture with limited land availability, but in the present study, lowering the population growth rate alleviates population pressure in the long run, which reduces the use of agricultural land. Furthermore, a growth in population density (along with population size) would stimulate more labor-intensive farming practices, and the introduction of new farm technologies might help to support the rising population while also easing the shift of agricultural laborers to other sectors. Labor shifts from agriculture to industries would also aid agriculture by increasing the manufacturing of modern tools for cultivation (Boserup, 1965, 1981). The declining population growth rate, along with access to modern farming technology, increases productivity and crop intensification, thus reducing cultivated land. However, it cannot be concluded that population growth acted as an impetus, as Boserup claimed, even though it is the primary cause of the green revolution.

In this scenario, both Malthusian and Boserupian perspectives acted independently. In the mid-1960s, India experienced severe food shortages due to a series of famine years. Despite this fact, the 1971 Census results show that the famine did not affect population growth (Dyson, 2018). However, it raised the risk of starvation. It should be noted that the origins of the 1960s famines were caused by climatic variations in the country, such as drought, not by population explosion.

Yet this raised concerns about probable future famines that would have a serious impact on the population (Dasgupta, 1977). This terrifying threat to the population functioned as a Boserupian stimulant, introducing high-yielding seeds from Mexico and necessary changes in infrastructure like irrigation, fertilizer use, agricultural research, etc. Thus, the Malthusian vision of disaster through food scarcity served as a push factor in the Indian setting to develop new farm technology for population sustainability (due to high population expansion), but technological intervention, as viewed by Boserup, did not let the population be starved. Both the Malthusian-Boserupian postulations acted as feedback mechanisms to each other. The modern population and land use debate is beyond their postulations (Bilsborrow, 1987; Turner & Ali, 1996; Codjoe & Bilsborrow, 2011). There are several studies which concluded that intensification did happen in India due to population pressure (Mishra, 2002; Lam, 2011; Bilsborrow, 2022), and our study further extends this debate on how population growth reduction with intensive agricultural practice could reduce the use of croplands.

9 Conclusions and Policy Implications

In conclusion, we state that using long-term panel data and robust econometric tools the study found population growth was one of the dominant drivers driving the usage of cultivated land throughout the last 70 years of India's demographic and economic history. However, the influence of population growth on cultivated land consumption is not static; in India, two distinct phases of this relationship exist. The phases separated around the 1980s with the onset of a declining population growth rate in the country. In the first phase, a rapidly increasing population growth rate drives the expansion of cultivated land with the least use of agricultural technology and crop intensification, while the declining population growth rate in the second phase insists the use of cultivated land declined, with the help of introduction of modern farm technology, rise in crop intensification and productivity, albeit slowly. It can be argued that while the Malthusian catastrophe arrived indirectly in the mid-1960s in India as a threat of famine and food shortage, these concerns were resolved by technological advancements in agriculture and a rise in productivity, as Boserup perceived. Though there are some intermittent influences, such as a drop in the population growth rate due to socioeconomic development and a rise in the non-farm sector, the population growth rate remains the most important factor influencing changes in cultivated land usage in India.

From a population, agricultural land, and environmental policy point of view, the study advances that the uncontrolled expansion of agricultural land has been putting huge carbon footprints in the country, akin to what has been observed globally. The food-producing industry causes 25% of the greenhouse gas emissions in the world, and out of this, half of food emissions come from land usage and crop production (Ritchie, 2019). Thus, a reduction in population growth rate in high fertility states along with the rise in ecologically friendly agricultural intensification and productivity helps in population and environmental sustainability in the country. The finding assumes more importance in the Indian context, where the country has poor adaptive capacities to environmental hazards. The country is also not at the forefront in terms of adopting green and organic farming technologies and protecting ecological balances. Finally, we advance that population stabilization coupled with a reduction in the expansion of cultivated land and unsustainable agricultural practices contributes to sustainable development in most populous countries of the world.

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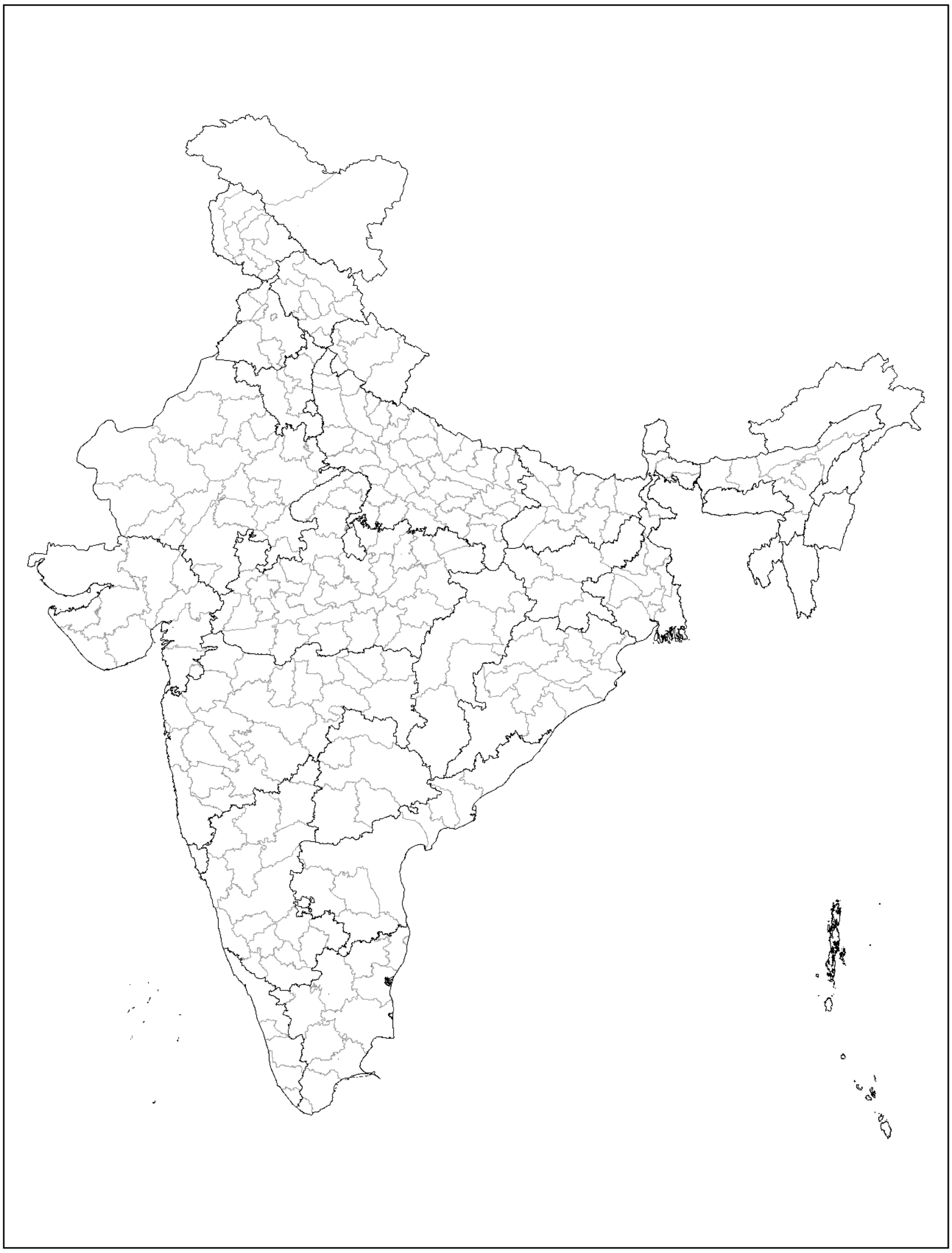
Supplementary (For online Publication only)

Appendix A

Figure A1. Consistent district boundaries, 1961-2021



Source: Authors' construction; Notes: Figure illustrates 280 consistent district boundaries over 1961-2021. In the analysis, only 267 consistent district boundaries have been used as part of the major states of India.

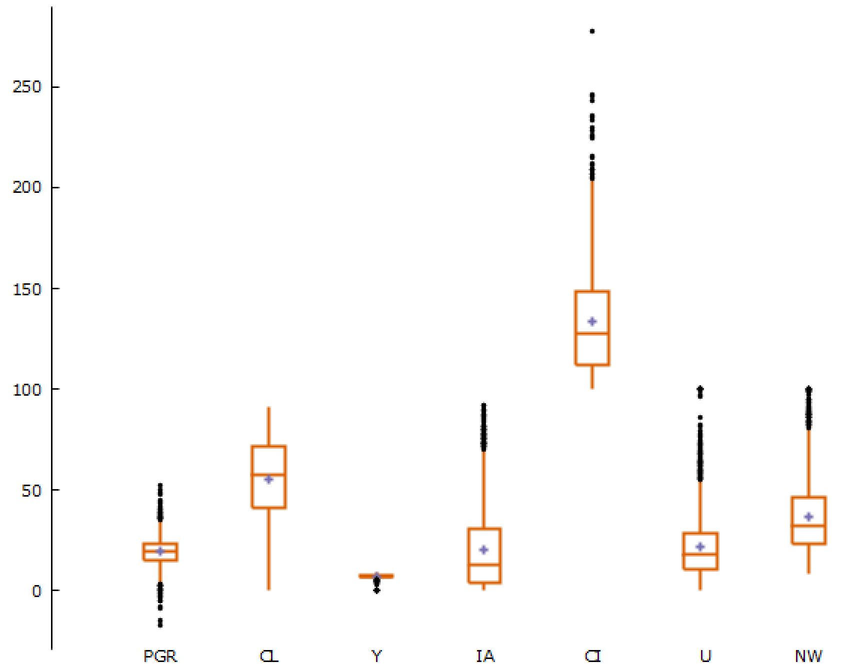
Appendix B

Table B1. Year-wise summary statistics of districts

Variables	Mean (Standard Deviation)						
	1961	1971	1981	1991	2001	2011	2021
Decadal Population Growth Rate (%)	20.26 (7.64)	22.47 (5.18)	22.36 (5.05)	21.25 (5.41)	19.11 (6.58)	15.62 (6.85)	14.38 (6.44)
Cultivated Land (%)	53.14 (20.31)	55.05 (20.33)	55.4 (20.93)	55.78 (20.72)	55.68 (20.63)	55.3 (20.72)	55.35 (20.17)
Agricultural Population Density	3.76 (13.31)	5.48 (29.95)	8.55 (65.69)	12.04 (105.06)	28.26 (350.01)	55.05 (763.85)	12.29 (45.49)
Log Yield	6.56 (0.94)	6.73 (0.81)	6.92 (0.84)	7.13 (0.96)	7.39 (0.91)	7.62 (0.91)	7.78 (0.92)
Irrigated Area (%)	10.48 (12.10)	13.21 (15.06)	16.61 (17.87)	20.55 (19.66)	24.21 (21.94)	27.71 (22.57)	30.99 (23.63)
Cropping Intensity (%)	118.58 (16.41)	122.08 (18.52)	127.71 (20.39)	132.46 (24.61)	137.66 (26.53)	141.74 (27.23)	153.19 (31.01)
Urbanisation (%)	15.77 (13.99)	17.20 (14.27)	20.09 (14.65)	22.14 (15.14)	23.57 (15.67)	26.43 (17.41)	28.96 (19.38)
Nonfarm Workers (%)	30.37 (15.17)	27.87 (14.84)	31.02 (15.39)	32.72 (16.03)	42.56 (17.51)	45.45 (18.43)	48.22 (20.12)

Source: Authors' construction

Figure B1: Box plot showing the distribution and outliers for variables



Source: Authors' construction

Notes: PGR = Population Growth Rate; CL = Cultivated Land; Y = Yield of Major Crops; IA = Irrigated Area; CI = Cropping Intensification; U = Urbanisation; NW= Nonfarm Workers

Appendix C

To understand reverse causation, Table C1 places alternatively the population growth rate as a dependent variable of cultivated and agricultural land. After attempting various combinations of independent variables and lags of dependent variables, the following two models passed the specification tests. The models are based on panels up to 2011. In none of the models, the representative land variable was found to be significant.

Table C1. Arellano-Bover/Blundell-Bond linear dynamic model (dependent variable – population growth rate)

Variables	Model 1	Model 2
Population Growth Rate$_{t-1}$	0.429*** (0.113)	0.432*** (0.114)
Population Growth Rate$_{t-2}$	0.143* (0.083)	0.142* (0.082)
Cultivated Land	-0.042 (0.051)	
Agricultural Land		-0.037 (0.051)
Agricultural Population Density	-0.002*** (0.000)	-0.002*** (0.000)
Log Yield	-1.489*** (0.429)	-1.494*** (0.430)
Urbanisation	-0.024 (0.078)	-0.018 (0.076)
Nonfarm Workers	0.013 (0.049)	0.017 (0.049)
Education	-0.163*** (0.049)	-0.167*** (0.049)
Constant	26.104*** (5.548)	25.981*** (5.433)
No. of Groups	265	265
No. of Observation	1056	1056
No. of Instruments	14	14
AR (1)	-4.087***	-4.106***
AR (2)	1.486	1.513
Sargan Test	8.016	8.237
Wald Chi^2	1068.903***	1278.600***

Source: Authors' construction

*Notes: dependent variable: Population Growth Rate (%); *** p<.01, ** p<.05, * p<.1; Standard Errors are in parenthesis*

Appendix D

For the robustness of the results in Table 3 of the main paper, we have run the same set of models using the full sample, which consists of 280 districts over the panel. The results show, in all the models, that the population growth rate significantly affects cultivated land, which re-affirms our earlier models with major states of India.

Table D1. Results of Arellano-Bover/Blundell-Bond linear dynamic panel regression model showing the effect of population growth rate on cultivated land – Full Sample

Variables	Model 1a	Model 1b	Model 2a	Model 2b	Model 3a	Model 3b	Model 4a	Model 4b	Model 5a	Model 5b
Cultivated $Land_{t-1}$	0.551*** (0.089)	0.529*** (0.079)	0.501*** (0.101)	0.487*** (0.087)	0.552*** (0.11)	0.52*** (0.098)	0.511*** (0.101)	0.504*** (0.084)	0.499*** (0.096)	0.494*** (0.096)
Population Growth Rate	0.105*** (0.027)	0.100*** (0.021)	0.093*** (0.026)	0.096*** (0.021)	0.097*** (0.025)	0.110*** (0.031)	0.073** (0.031)	0.073** (0.034)	0.079*** (0.025)	0.103*** (0.031)
Agricultural Population Density			0.000** (0.000)	0.000*** (0.000)	-0.012*** (0.002)	-0.012*** (0.002)	0.000* (0.000)	0.000** (0.000)	-0.012*** (0.002)	-0.012*** (0.001)
Log Yield					0.697** (0.352)	0.882** (0.365)			0.668** (0.335)	0.947*** (0.34)
Irrigated Area					-0.037 (0.031)	-0.031 (0.032)			0.010 (0.033)	-0.012 (0.034)
Cropping Intensity					-0.005 (0.013)	-0.006 (0.01)			-0.007 (0.013)	-0.007 (0.01)
Urbanization							-0.019 (0.047)	0.020 (0.023)	-0.027 (0.04)	0.018 (0.023)
Nonfarm Workers							-0.015 (0.022)	-0.028 (0.018)	-0.033 (0.022)	-0.031* (0.018)
Constant	22.682*** (5.145)	23.967*** (4.388)	25.834*** (5.806)	26.571*** (4.802)	19.571*** (6.797)	19.703*** (6.219)	26.777*** (5.769)	26.713*** (4.784)	24.163*** (5.995)	21.418*** (6.226)
Groups	280	280	278	279	278	276	278	279	278	279
Observations	1397	1677	1385	1663	1381	1658	1385	1663	1381	1658
Instruments	10	12	11	13	14	16	13	15	16	18

AR (1)	-2.430**	-2.129**	-2.314**	-2.079**	-2.495***	-2.203**	-2.353**	-2.120**	-2.368**	-2.162**
AR (2)	-0.979	-0.052	-0.236	0.191	-0.105	0.285	-0.266	0.209	-0.080	0.265
Sargan Test	5.186	5.752	4.062	4.378	4.363	6.636	3.918	3.784	2.997	4.801
Wald Chi^2	41.155***	67.074***	58.396***	111.718***	274.127***	357.701***	50.045***	106.570***	292.832***	604.793***

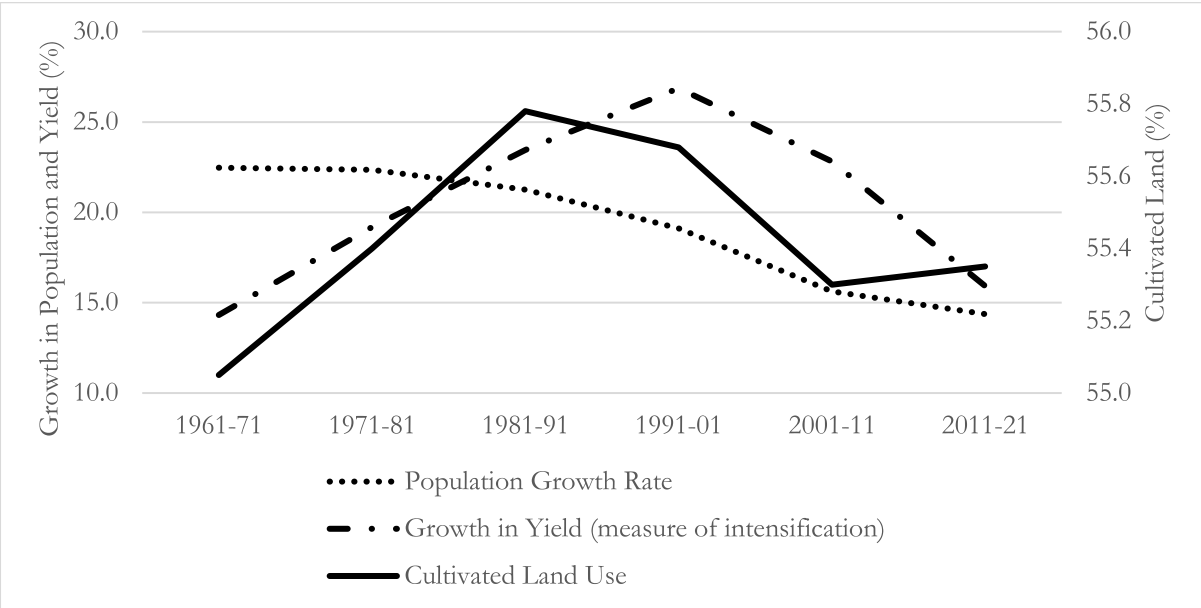
Source: Authors' construction

*Notes: dependent variable: Cultivated Land (%); *** p<.01, ** p<.05, * p<.1; Standard Errors are in parenthesis*

Appendix E

In the theoretical framework, we argue that the percentage use of cultivated land will decline after the population growth rate starts declining and the growth rate in agricultural intensification exceeds the population growth rate. Figure E1 shows the yearly mean values of three variables i.e., population growth rate (%), percentage cultivated land, and growth in yield of major crops (%), overall districts from 1961-71 to 2011-21. From 1971 to 81, the population growth rate started declining, and in that period, growth in the yield of major crops exceeded the population growth rate. This fulfills the two conditions we have postulated. Following this, the percentage of cultivated land started declining from 1981-91.

Figure E1: Trend in Population Growth Rate, Growth in Agricultural Yield and Cultivated Land Use



Source: Authors' construction
Notes: Values are the year-wise mean of district-level measures of the three variables.

Appendix F

We have implemented a machine learning approach to compare in-sample and out-of-sample errors for different predictors. Since we are interested in changes in land use and population growth over time, we have used the first difference variables rather than the original variables. We randomly split the samples into two sets, with 80% in the training set and 20% in the test set. The panel used is up to 2011. We have used five predictors: ordinary least squares (OLS), principal component analysis (PCA), neural networks, random forest, and boosting. All five models were run for the training set, and then the mean square error (MSE) for the training and test samples was calculated.

Table F1 shows the MSE of the training and test samples for the five predictors. The results indicate a very small difference in MSEs, between the training and test samples. The training sample MSE is lowest for the random forest model, while the test sample MSE is lowest for the

OLS model. Finally, we have shown the OLS model with the full sample in Table F2, and the results demonstrate that the population growth rate significantly affects cultivated land use.

Table F1: Mean Square Error of Training and Test Samples

Predictor	Train Sample MSE	Test Sample MSE
Ordinary Least Square	25.139	24.388
Principal Component Analysis	25.286	24.974
Neural Network	25.608	24.587
Random Forest	13.118	24.707
Boosting	24.688	25.509

Source: Authors' construction;

Table F2: Results of ordinary least square regression showing the effect of population growth on cultivated land with the first difference

Variables	Model 1
Population Growth Rate	0.043* (0.023)
Agricultural Population Density	-0.018*** (0.006)
Log Yield	0.637** (0.294)
Irrigated Area	0.061*** (0.022)
Cropping Intensity	-0.017 (0.012)
Urbanization	-0.039 (0.043)
Nonfarm Workers	-0.113*** (0.024)
Constant	0.675*** (0.202)
No. of Observation	1318
Wald Chi^2	8.031***

Source: Authors' construction

*Notes: dependent variable: Cultivated Land (%); *** p<.01, ** p<.05, * p<.1; Standard Errors are in parenthesis*