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ORIGINAL ARTICLE

Dynamics and determinants of land change in India: integrating satellite data with village socioeconomics

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Abstract We examine the dynamics and spatial determinants of land change in India by integrating decadal land cover maps (1985–1995–2005) from a wall-to-wall analysis of Landsat images with spatiotemporal socioeconomic database for ~630,000 villages in India. We reinforce our results through collective evidence from synthesis of 102 case studies that incorporate field knowledge of the causes of land change in India. We focus on cropland–fallow land conversions, and forest area changes (excludes non-forest tree categories including commercial plantations). We show that cropland to fallow conversions are prominently associated with lack of irrigation and capital, male agricultural labor shortage, and fragmentation of land holdings. We find gross forest loss is substantial and increased from ~23,810 km^2 (1985–1995) to ~25,770 km^2 (1995–2005). The gross forest gain also increased from ~6000 km^2 (1985–1995) to ~7440 km^2 (1995–2005). Overall, India experienced a net decline in forest by ~18,000 km^2 (gross loss–gross gain) consistently during both decades. We show that the major source of forest loss was cropland expansion in areas of low cropland productivity (due to soil degradation and lack of irrigation), followed by industrial development and mining/quarrying activities, and excessive economic dependence of villages on forest resources.

Keywords Land use change · Drivers · Causes · Deforestation · Agriculture · Food security

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Introduction

India's per capita land availability is ~0.25 ha per person compared to the global average of ~2.3 ha per person (Census of India 2011). India's cattle density is ~62 heads per km^2 compared to the global average of ~10 heads per km^2 (Robinson et al. 2014). This high human and animal pressure, coupled with increasing standards of living (Hubacek et al. 2007; United Nations 2014; World Bank Group 2015), has placed tremendous pressure on India's land resources for food, fiber, fuel, and shelter causing extensive environmental degradation (Table 1).

The pressure on India's land resources is expected to further intensify in the future, with the growing economy (Hubacek et al. 2007; United Nations 2014; World Bank Group 2015) and human population (United Nations 2015), expected increase in demands for animal products (Alexandratos and Bruinsma 2012), and climate change (Singh et al. 2002; Krishna Kumar et al. 2004; O'Brien et al. 2004; Lobell et al. 2008, 2012; Auffhammer et al.

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Table 1 Comparison by numbers: the role of land-use and land-cover change (LULCC) on key environmental problems compared between world and India for present/past period

Environmental problem	Role of LULCC	
	World	India
Human land use	55% of land area	83% of land area
Climate change	20–24% of GHG emissions	25–30% of GHG emissions
Biodiversity loss	14% of species richness	22% of species richness
Land degradation	8–41% of land area	~57% of land area
Water use for agriculture	70% of withdrawal	91% of withdrawal
Nutrient excess in crops (water pollution)	56% of nitrogen; 48% of phosphorous	74% of nitrogen; 71% of phosphorous

The comparison indicates that LULCC contribution to environmental problems in India is of greater magnitude compared to global case. See Table S1 for details

2012; MoEFCC 2015). Therefore, a key challenge for land use planning in India is to enhance food production and simultaneously minimize environmental degradation from land-use and land-cover change (LULCC). Land in India is also closely tied to livelihood security as over half of India's population is employed in agriculture and forestry (Census of India 2011). India being one of the ten most forest-rich nations of the world, has received increasing attention under the REDD+ (Reducing Emissions from Deforestation and Forest Degradation) mechanism to protect its forests to help mitigate climate change, preserve its rich biodiversity, and support ecosystem services (Agrawal et al. 2011; Ravindranath et al. 2012; MoEFCC 2015). For similar reasons, India's national forest policy aims to increase its forest cover from the existing ~21% of its total geographical area to a minimum of 33% (MoEF 1988; Joshi et al. 2011). Better monitoring and understanding of the determinants and drivers of LULCC at national scale is crucial to: (1) better understand their environmental and socioeconomic impacts and (2) provide valuable guidance for land use policies toward addressing the future challenges for LULCC in India.

There are three aspects to our study. *First*, we quantified land cover conversions (complete replacement of one land cover by another) at national scale using a wall-to-wall analysis of high-resolution (~30 m) Landsat MSS/TM imageries at decadal time intervals (1985–1995 and 1995–2005). Importantly, our study period (1985–2005) includes the period of economic liberalization in India (1991 onwards) following which the pressure on land resources intensified. We report LULCC estimates at national (Tables S2-S4) and state level (Table S5; Dataset S1), and by agro-ecological zones (AEZs) (Table S6; Dataset S2) considering their policy relevance to forest and agriculture (see Text S1 for rationale). AEZs are regions delineated by similar climatic and soil conditions (Velayutham et al. 1999; Gajbhiye and Mandal 2000). In Indian context, AEZs are the optimal units for macro-level land use planning and efficient transfer of technology, as India's economy is highly dependent on agriculture and forestry (Velayutham et al. 1999; Gajbhiye and Mandal 2000).

Second, we investigated the spatial determinants (defined following Meyfroidt 2015) of three broad LULCC that are central to land use planning in India (Saxena 2006; Maji et al. 2010; DoLR 2013; MoEFCC 2014, 2015): cropland–fallow land conversions, forest area losses, and forest area gains. Our forest definition is consistent with IGBP land classification scheme (Belward 1996) and excludes non-forest tree categories such as commercial plantations of coconut, cashew, coffee and rubber, and fruit orchards (see Table S7 for land class definitions). Cropland area refers to area under crops in any of the three prominent cropping seasons of India (summer monsoon, winter, and summer). We only account for net cropped area, i.e., multiple cropping is counted once. Fallow land refers to land taken up for cultivation, but temporarily allowed to rest, un-cropped across all three cropping seasons. Fallow is typically unproductive agricultural land, but may provide important services, e.g., nutrient replenishment, use by livestock and wildlife, and groundwater recharge. As per capita land is low in India, understanding cropland–fallow land conversions is crucial to plan and evaluate agricultural development efforts to improve food security (Saxena 2006; Maji et al. 2010). We do not classify cropland and fallow land into further sub-categories based on seasons (e.g., rabi, kharif, zaid).

Third, we evaluate and reinforce our modeled results on spatial determinants through collective evidence from synthesis of 102 case studies (see Table S8-S11 for study-wise summary; Text S1 for methods) that incorporate field knowledge of the causes of LULCC mainly through social surveys and local expertise. While ground studies (social surveys, local expertise) offer crucial qualitative insights, data collection is typically expensive and therefore covers small regions. It is hard to generalize and quantify the causal relations of LULCC by studying few villages in a country of over 600,000 villages with diverse agro-ecological and sociocultural environment. Our synthesis helps to identify accumulated effects that are statistically stronger than any individual case study due to increased sample size and greater diversity. It is important to note that the case studies often relate to the triggers of the change (see Meyfroidt 2015) as opposed to the location factors (spatial determinants) identified through our modeling analysis (second aspect). Therefore, while both our modeled results and synthesis of case studies are complimentary and inform each other, the characteristic of information provided by them are different.

Our study differs from existing satellite-based national assessments of LULCC in India on two aspects. *First*, our land cover conversion estimates rely on Landsat analysis that covers longer time period, uses uniform classification scheme, maps patch to patch land dynamics, and is validated using ground data (Roy et al. 2015). Earlier high-resolution land cover mapping activities at national scale were one-time effort (see review by Roy et al. 2015) hence unavailable for monitoring at regular time intervals; their project-specific classification scheme and varying data quality make compilation of consistent time series images difficult. Tracking patch-level dynamics is crucial because the environmental impacts vary depending on the preceding and replaced land cover class (Don et al. 2011; Mahmood et al. 2014). Notably, India monitors forest cover including trees outside forest biannually (FSI 2015), but not patch to patch land dynamics. Our land cover maps have been extensively validated with over 12,600 stratified random samples (ground-verified GPS points) distributed uniformly in different land cover classes following Congalton and Green (1999). Our data have an overall mapping accuracy of 95% (across eleven land classes defined in Table S7), thus providing accurate and reliable information on LULCC. See Roy et al. (2015) for further details on validation.

Second, this is the first study to use village-level socioeconomic data at national scale to investigate the spatial determinants of LULCC. Villages are the highest level of spatial disaggregation in India (>630,000 administrative units; Fig. S1). Thus far, no geospatial socioeconomic database exists for complete India at village level; our data are a significant improvement in spatial resolution compared to existing national datasets ($\sim$5500 administrative units or coarser; see Fig. S2). Overall, we compiled spatial data on over 200 socioeconomic variables for two consecutive census years (1991 and 2001; for use with respective decadal LULCC analysis) (Text S1). The use of village-level data is crucial for two reasons. *First*, it captures the high granularity in socioeconomics (Fig. S2) that is crucial to explain the spatial variations in high-resolution Landsat data. The granularity gets masked at coarser administrative levels (Fig. S2). *Second*, we use over forty village-specific categorical/qualitative variables (Table S12) that cannot be represented at coarser administrative levels (e.g., village-specific primary occupations that reflect the base of the socioeconomic culture prevalent in rural parts of India). We also include key biophysical factors (Text S1) hypothesized to affect the spatiotemporal patterns of land change in India (Table S12).

Methods

Here, we describe our methods and data briefly. See Text S1 for further details.

Data

Table S13 summarizes key datasets used with references. We highlight socioeconomic and LULUC data, both of which are central to our analysis.

We created the spatial socioeconomic database by combining tabular information from the Indian census (both 1991 and 2001; each household is surveyed and aggregated to village/town level) with seamless village- and town-level administrative boundaries of India corresponding to 2001 census specifically prepared for this study, sourced from Survey of India topographic sheets (analog maps). Both the tabular data and administrative boundaries required substantial amount of organization, data cleaning, and quality checks prior to being linked together.

We have a dedicated article describing the technical details and validation of the LULCC database, with basic land cover area statistics (Roy et al. 2015). In contrast, this study presents detailed land conversion analysis of the LULCC database. What follows is a summary. Our data have $\sim$30 m resolution, with features mapped at 1:50,000 scale. We mapped the entire country using on-screen visual interpretation of satellite data for two decades (1985–1995–2005). Our land types are defined following the IGBP land classification scheme (Belward 1996; see Table S7 for definitions). We projected the multitemporal Landsat MSS/TM data to WGS84 datum (UTM 44N projection) at sub-pixel level. We used satellite images from three seasons, viz. winter (January–March), summer (April–June), and summer monsoon (mid-October to December) to identify cropland and fallow land (we do not capture multiple cropping). Our analysis does not allow harvested areas as we select images of peak crop growth in a cropping season. When cloud-free Landsat images were unavailable, we used IRS 1C–LISS III (1994–1995) and Resourcesat 1 (2004–2005) images by geometrically correcting them with sub-pixel accuracy, relative to Landsat (ortho-rectified). We used first-order polynomial equation with allowable root-mean-square error of less than one pixel for geometric rectification. The minimum number of ground control points we used to georectify the satellite images was 15 for flat terrains and 30 for hilly terrain. Manual interpretation of detailed Landsat/LISS III images is laborious. Therefore, studies with large spatial coverage typically interpret Landsat images on sampling basis, representative of the study region (e.g., Gibbs et al. 2010). In contrast, our analysis is a wall-to-wall mapping effort at national scale.

Quantifying land cover conversions

We first interpreted 2005 Landsat scenes to produce a national map of land cover. To minimize errors in land change detection between 2005 and 1995, we overlaid 1995 Landsat images over 2005 map and traced patches where land change had occurred, leaving unchanged patches unmodified (for greater consistency). We preferred this method for two reasons. *First*, it reduces the effort required to produce 1995 map as only patches that underwent change between 1995 and 2005 are traced. *Second*, as patches that remained unchanged over time were preserved, it minimizes errors in land change detection by eliminating human errors in visual interpretation of unmodified patches that can occur if 1995 map were interpreted independent of 2005 map and if land change were inferred by differencing the two maps. We followed similar approach to detect land change between 1985 and 1995, using 1995 map as reference.

Modeling the determinants of LULCC

We quantify the (spatial) determinants by estimating spatial logistic regressions (Text S1) between land cover conversion estimates (dependent variable) and hypothesized socioeconomic and biophysical factors (or their proxies) grounded through local case studies (Table S12). We estimate regression models (Table S14) specific to land cover conversion and decadal time period, at both national scale and for sub-national hot spots identified by AEZs (Table S6). Our regression analysis is carried out at 1 km $\times$ 1 km resolution (see Text S1 for data preprocessing). The 1-km resolution was mainly a tradeoff between the 30-m LULCC data and relatively coarser socioeconomic data ($\sim$2 km $\times$ 2 km per village on average). To minimize loss of information, while aggregating the 30-m LULUC data, we calculated the fraction of 1-km grid cell undergoing various land cover conversions, as opposed to approximating the entire grid cell area to undergo one (dominant) land cover conversion.

Our statistical modeling technique draws on our recent work (Meiyappan et al., 2014) and is common to land change modeling studies. We model the relationship between dependent and independent variables as a "fractional" binomial logit model (Text S1). The model allows for fractional outcomes in dependent variables, consistent with our LULCC data aggregation technique. As our independent variables have different units and scale, we standardized all continuous variables using z-score prior to estimation. We use a state-of-the-art method, the elastic net penalty for variable selection (account for multicollinearity across independent variables). We used bootstrap resampling with 500 replicates, where we resampled the observations (grid cells) and we fitted a new model to the data. The bootstrap, in addition to providing confidence intervals, also accounts for spatial autocorrelation typical to gridded LULCC datasets.

Synthesis of case studies

Our synthesis provides a bottom-up analysis on the causes of LULCC in India. Furthermore, we used the synthesis literature to ground our hypothesized socioeconomic and biophysical factors for statistical estimation (Table S12). We performed a systematic literature search on ISI Web of Science and Google Scholar for studies on LULCC covering India and our study period. We additionally included key (sub-) national reports, not indexed in either literature database. In total, we reviewed 643 articles, of which we discarded 177 as irrelevant (38 of which discussed causes of LULCC processes not a focus of our study). Of the remaining 466 articles, over three-fourth focused only on land change detection, highlighting the relatively less attention on understanding the causes of change. The 102 articles in our synthesis provide information on the causes of land change typically by combining one or more of: household surveys, field transects, and regional/local expertise of authors. Often, studies also included remote sensing component. The studies are summarized in Tables S8-S11, and the study locations are visualized in Fig. S3. To quantify the results of our synthesis, we analyzed the frequency of causes across case studies. We grouped the studies by LULCC processes and into broad clusters of causes (see Dataset S3 for study-wise grouping details and Text S1 for detailed methods); the clusters being specific to LULCC process.

Results

We present the LULCC conversion estimates and spatial determinants in the first three subsections. LULCC conversion estimates are based on analysis of satellite data. All our estimates pertain to the sum of urban, peri-urban, and rural areas within the region of quantification (national level or AEZs as identified). Our results on spatial determinants are based on regression analysis of satellite data with hypothesized biophysical and village socioeconomic variables. We present the results of synthesis from 102 case studies in the fourth subsection.

Conversions between cropland and fallow land

We find major shifts between cropland and fallow land during the period of study (Fig. 1). About 35% (1985–1995) and 46% (1995–2005) of all areas that underwent land cover conversion in India resulted from changes between cropland and fallow land. Furthermore, data suggests that ~10% of existing wastelands (sparsely vegetated land with signs of erosion and land deformation; see Table S7) are consistently reclaimed to cropland during each decade. These development efforts are, however, countered by the much larger amount of cropland being fallowed concurrently. A spatial disaggregation (Fig. 2; Dataset S2) indicates that over 70% of shifts from cropland to fallow land and vice versa are confined to five agro-ecological zones (AEZs): the Western Plain, Kachchh, and part of Kathiawar peninsula (AEZ2), and the semiarid zones (AEZ4, 5, 6, and 8). These five zones also enclose over 90% of wasteland reclaimed to cropland during each decade (Fig. 2; Dataset S2). This indicates that within the same AEZ, wasteland reclamation adds to cropland area on the one hand, and on the other, cropland is being fallowed concomitantly representing a net negative outcome for wasteland reclamation efforts.

Land can be kept under fallow temporarily to restore and maintain soil fertility in multiple cropping systems. However, as our maps are decadal, we cannot identify whether the cropland–fallow conversions observed are a part of land restoration process or not. Therefore, for further insights, we complied annual (1984–2012) district-level ground statistics data on fallow land from the Government of India (Dataset S4). The statistic indicates that in both AEZ2 and

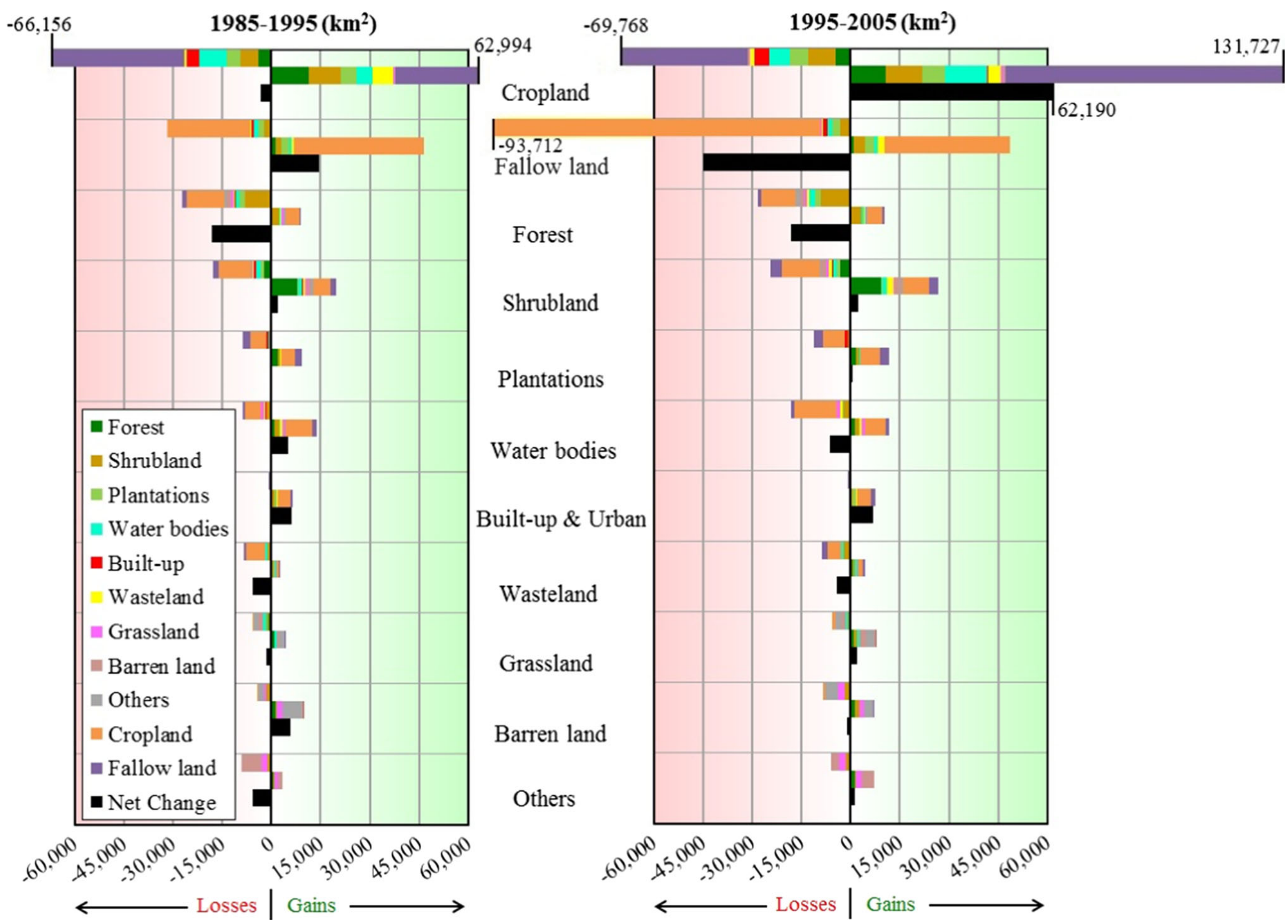

Fig. 1 Gross *gains*, gross *losses*, and net changes in land use and land cover areas at aggregate national scale for the two decades (km^2/decade): 1985–1995 and 1995–2005. Aqua culture and permanent wetlands is included within "Water bodies." "Others" category include Salt Pan, Snow and Ice. Data from this figure are provided in Table S2-S4 (color figure online)

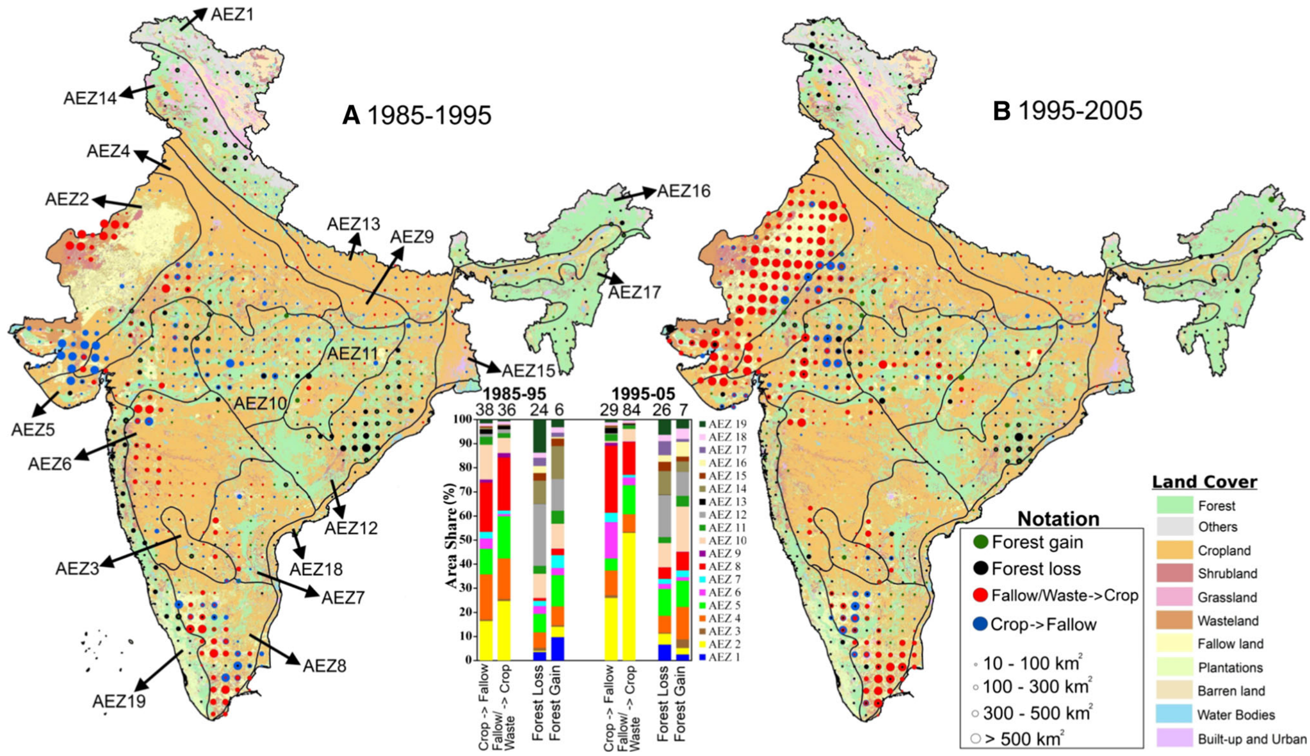

Fig. 2 Spatial breakdown of major land cover conversions: forest loss, forest gain, conversions from cropland and fallow land, and reclamation of fallow land and wasteland to cropland. The size of circles is proportional to the magnitude of change. The *inset bar plot* shows the percent contribution by region to the national total (shown besides bar; units in $\times 1000$ km^2/decade and rounded to nearest integer). The regions are based on agro-ecological zones (AEZs) of India (Table S6). The *background colors* in the map correspond to the type of land cover present at before conversion (see "legends" for color coding). See Fig. S4 for a more detailed breakdown by AEZ (color figure online)

AEZ8 (top two regional hot spots of cropland–fallow conversions) the area of long fallows (land not cultivated for 1–5 years) exceeds that of temporary fallows (<1 year). Furthermore, 3.5% of India's land area was consistently under long fallows over the past decade (Dataset S4).

Our regression analysis at national scale (Fig. 3a, S5a) indicates higher monsoon and post-monsoon precipitation is negatively associated with conversion from cropland to fallow land, echoing previous studies (e.g., Krishna Kumar et al. 2004; Lobell et al. 2008; Auffhammer et al. 2012) (see Table S15 for a description of all biophysical and socioeconomic variables). Post-liberalization period, we observe widespread spatial changes in main male agricultural (wage) laborers and male marginal cultivators (main + marginal) (Fig. S6), primarily driven by urbanization and better income opportunities (relatively less strenuous and more stable non-agricultural jobs) (Mitra and Murayama 2009; Srivastava 2011). During 1995–2005, we find areas converted from cropland to fallow land had substantially lower male main agricultural labor (AEZ2) and total (main + marginal) male marginal cultivators (semiarid hot spots) compared to counterfactual buffer villages (Fig. S7b). These results imply that availability of labor is an emerging factor in determining fallow land. We also find positive association between fallow land and proportion of main female cultivators, indicating gender-biased labor markets (Shiferaw et al. 2006; Gupta and Sharma 2010; Shah 2010; Singh et al. 2011).

Factors prominent in explaining conversion from cropland to fallow land (Fig. 3a, S5a, S7-S10) often were also prominent in explaining vice versa conversion (i.e., reclamation of fallow land to cropland), but with opposite sign (Fig. 3b, S5b, S11-S13). At national scale, the following factors show prominent positive association with reducing fallow land (in decreasing order of importance based on Fig. 3b, S5b): availability of tube well and well irrigation with electricity; higher monsoon and post-monsoonal rainfall; increased market frequency; availability of power supply for agriculture; density of community workers (proxy for technical assistance and incentives for agriculture); availability of communication facility (e.g., bus, trains; proxy for connectivity to markets); and availability of agricultural credit institutions, and higher average income per capita (both indicating access to capital and ability to invest).

In AEZ2, 6, and 8 (Figs. S11-S13), knowledge to reclaim land is an important factor to reduce fallow land

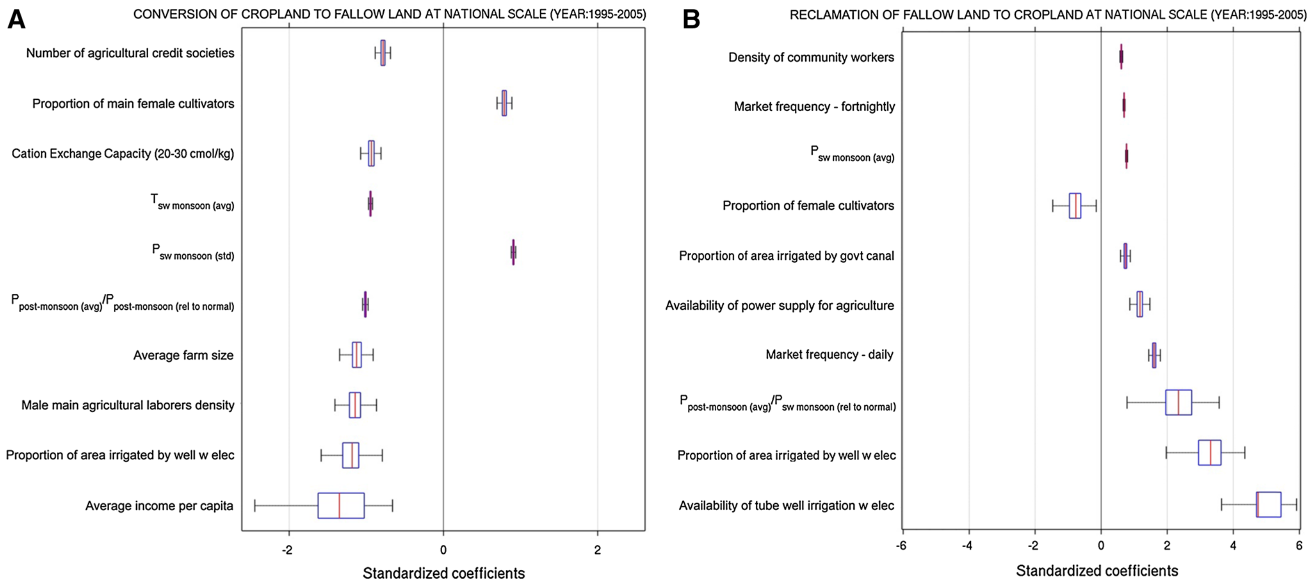

Fig. 3 Factors most prominent in explaining: **a** conversion of cropland to fallow land at national scale (1995–2005), and **b** vice versa conversion, i.e., conversion of fallow land to cropland at national scale (1995–2005). The plots show the standardized regression coefficients of the ten most important variables (largest absolute mean estimates across coefficients) estimated using the spatial logistic regression model (see "Methods" section). Standardized coefficients refer to how many standard deviations a dependent variable will change, per standard deviation increase in the independent variable. Standardized coefficients allow comparisons of the relative effects of independent variables measured on different scales. Results from bootstrap resampling with 500 replicates: *central red line* shows mean estimate; *error boxes* (*blue*) show 25–75% confidence interval; *whiskers* show 5–95% confidence interval. See Fig. S5 for national-scale estimates corresponding to 1985–1995. See Table S15 for description of factors (color figure online)

(proxies: proportion of literate population, access to information such as magazine and newspapers). We find contrasting relationships between farm size (average size within each grid cell) and fallow land across sub-national hot spots. Cropland to fallow land conversion is positively associated with larger farm size in AEZ2 (Fig. S7), and positively with smaller farm size in semiarid hot spots (AEZ4, 5, and 8) (Figs. S8-S10). In AEZ2, resources are a limiting factor to fuller land utilization, as also indicated by negative relationship between fallow land and availability of labor, capital, and irrigation (Fig. S7). The massive reclamation of fallow land to cropland in AEZ2 during 1995–2005 (Fig. 2) is primarily from extension of tube well and well irrigation facilities (Figs. S13, S14). In semiarid hot spots, we find smaller farms are prone to soil erosion (Table S16), as small farms are uneconomical to mechanize (Yadav 1996; Reddy 2003; Singh 2013).

Gross forest area loss

During 1985–1995, India lost ~3.1% (~23,800 km^2 of gross forest loss, i.e., sum of all forest area loss) of the forest area that existed in 1985 (~764,100 km^2), and the rate increased to ~3.5% during 1995–2005 (~25,780 km^2 gross loss of ~745,100 km^2 forest in 1995) (Fig. 1). Overall, India experienced a net forest loss (gross loss minus gross gain) of ~18,000 km^2 consistently during both decades (see Text S2 for extended discussion). Cropland was the major source of forest conversion during both decades, contributing to ~39% of gross forest loss in 1985–1995, and ~35% during 1995–2005. The relative area of gross forest loss to shrubland increased from ~31% in 1985–1995 to ~32% in 1995–2005. Expansion of commercial plantations into forests accounted for ~7% of gross forest loss during both decades. These trends are in stark contrast with the 1988 National Forest Policy that regards forest as a national asset and imposed strict rules to protect them (Agrawal et al. 2011; Ravindranath et al. 2012).

A regional breakdown indicates that gross forest loss is widespread across India, and forest loss hot spots change over time (Fig. 2; Dataset S2). For example, in AEZ19 that enclose the Western Ghats (biodiversity hot spot), 6.8% of the regions forest area in 1985 was converted to other land use (gross forest loss of 3080 km^2) by 1995 (35% each to shrubland and plantation, and 23% to cropland). In 1995–2005, the region's gross forest area loss declined to 1630 km^2. In AEZ5, 4.9% of the regions forest area in 1985 was converted to other land use by 1995, and the rate increased to 7.9% in subsequent decade. Nonetheless, Eastern Plateau and Eastern Ghats (AEZ12), Central Highlands (AEZ10), and Western Himalayas (AEZ14) emerged as persistent hot spots for both decades. AEZ5, 10, 12, and 17 collectively accounted for ~59%

(1985–1995) and ∼56% (1995–2005) of the national total of gross forest area lost to cropland. AEZ4, 5, 10, 12, and 19 collectively accounted for ∼84% (1985–1995) and ∼80% (1995–2005) of the national total of forest area converted to shrubland. AEZ12 alone accounted for 40% (1985–1995) and 35% (1995–2005) of the national total of gross forest area lost to shrubland.

National-scale analysis of spatial determinants (Fig. 4a, S15) show strong negative association between proportion of cropland irrigated and gross forest area loss indicating that improvements in irrigation infrastructure can help to reduce the pressure on adjoining forests. We also find strong spatial association between forest area loss and village primary occupations (Fig. 4a, S15). Villages with following activities were prominently related to forest loss, compared to counterfactual buffer villages (in decreasing order of importance from Fig. 4a): wooden furnitures/timber products; cattle/dairy/leather products (due to overgrazing); mining/quarrying activities; and industrial development (proxy: industrial and construction worker density). Colder and wetter conditions and lack of electricity were also positively associated with forest loss (Fig. 4a, S15) suggesting over-extraction for fuel wood and construction materials.

We find prominent negative association of gross forest area loss with steep slope (difficult to access), and protected areas (Fig. 4a, S15). While land protection reduces forest loss, 9% (1985–1995) and 7.6% (1995–2005) of total gross forest loss have still occurred within protected areas, and 11.2% (1985–1995) and 8.7% (1995–2005) within 5 km buffer from the perimeter of protected areas (critical to maintain the functionality of protected landscapes) (Fig. S16), indicating level of protection is important and has improved over time.

Across AEZ hot spots, the following agriculture-related variables show prominent negative association with gross forest area loss: proportion of irrigated areas (Figs. S17-S19), higher fertility of agricultural soils (proxy: cation exchange capacity; Figs. S17a, S18-S20), average farm size (proxy for economic feasibility to mechanize; Figs. S17a, S18-S20), availability of power supply for agriculture (Figs. S17a, S20), proportion of main (=1-marginal) agricultural laborers (lower income dependence on forests; Fig. S17a), and proximity to agricultural credit institutions (proxy for access to capital; Fig. S20). These relationships broadly indicate that higher agricultural productivity tends to reduce the pressure on adjoining forests. Most diversion of forest to cropland is encroachment, because national forest policy does not favor diversion of forest to non-forest, which requires prior approval from central government (MoEF 1988; Joshi et al., 2011). Furthermore, we find the forest area diverted to cropland have not declined with time (Fig. 1), indicating weak implementation of national forest policy.

A regional analysis indicates that in AEZ19 that encloses the Western Ghats, mining activities, manufacturing of wooden agricultural implements, and villages dependent on coconut and coffee plantations (encroachment) show positive association with forest loss (Fig. S19). Across all hot spots in central India (AEZ5, 10, and 12), mining/quarrying activities, industrial development, and factors associated with low agricultural productivity (e.g.,

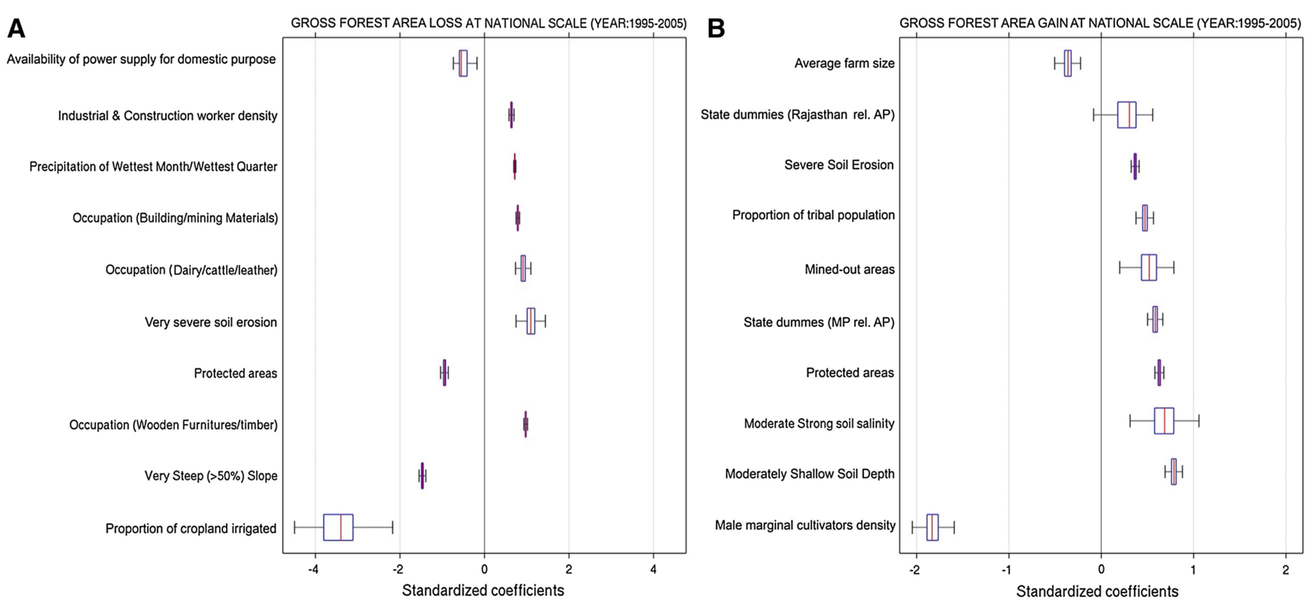

Fig. 4 Similar to Fig. 3, but for: **a** forest area loss at national scale (1995–2005), and **b** forest area gain at national scale (1995–2005). See Figs. S15 and S22 for national-scale estimates corresponding to 1985–1995 (color figure online)

high erosion) show positive association with forest loss (Figs. S20, S17, S18). Other factors prominently associated with forest loss are wooden furniture/timber extraction and cattle overgrazing (AEZ5; Fig. S20); villages making bamboo products (AEZ12; Fig. S18); villages making forest products (e.g., tendu leaves/*beedi*, leaf plates, baskets, brooms, match sticks, paper pulp) (AEZ10; Fig. S17); colder temperatures (over-extraction of firewood and construction materials), wooden furniture/timber, and making of woolen blankets (indicating sheep over-browsing) (AEZ14; Fig. S21).

Gross forest area gain

India recorded a positive trend in gross forest area gain over time (Fig. 1). The gross forest area gain in 1995–2005 was 24% higher than the preceding decade, compensating for the increased gross forest area loss during 1995–2005. Reversion of cropland and shrubland together explain 65% (1985–1995) and 78% (1995–2005) of gross forest area gain. AEZ5, 10, and 12 were persistent hot spots of gross forest area gain in both decades (Fig. 2; Dataset S2); however, the magnitude was much smaller compared to the gross forest area loss in the respective zones. During 1995–2005, substantial area of shrubland recovered to forest in AEZ4, 5 and 12 (Fig. 2).

Both nationally (Fig. 4b, S22) and across sub-national hot spots (Figs. S23-S26), we find prominent positive association between gross forest area gain and following agriculture-related variables (in decreasing order of importance based on Fig. 4b, S22): lower male marginal cultivators; higher levels of soil degradation (characterized by one or more of: shallow depth, salinization, and erosion); and smaller average farm size. These relationships indicate abandonment of marginally productive cropland, followed by either regrowth of forest tree species or conversion to forest plantations. We also find positive association between gross forest area gain and protected areas (Fig. 4b, S22-S26), proportion of tribal population (Fig. 4b, S22-S24), and area of sacred groves (Figs. S22, S24-S26). Tribes are culturally linked to forests, and they are typically motivated by state forest department to jointly manage forest through protection, restoration of degraded forest, and enrichment plantations (World Bank 2005; Government of India 2007; Macura et al. 2011) (notable exception of North-East India where tribes practice shifting cultivation). Sacred groves are typically protected by local community due to cultural/religious beliefs (Ormsby and Bhagwat 2010; Bhagwat et al. 2014).

Across the three sub-national hot spots (AEZ5, 10 and 12), gross forest area gains were positively associated with state administrative divisions, mined-out areas, density of forestry workers, and density of community workers (Figs. S23, S26, S24). The identified state administrative divisions typically have larger amount of forest inundated to water bodies (irrigation projects), and forest diverted to built-up land (e.g., roads, industries) (Fig. S27; Dataset S1). Both state administrative divisions and greening of mined-out areas indicate compensatory afforestation by respective state governments to partly compensate for forest loss. The forestry workers are employed by forest department and are a proxy for level of protection and control. These workers are typically involved in forest maintenance, wildlife protection, fire observations, and interface with tourism, among others. Community workers help with restoration efforts (e.g., greening firewood and fodder) by involving forest department and local communities.

Comparison of modeled results with 102 ground studies

Our synthesis indicates that the three LULCC (cropland–fallow land conversions; forest area losses; and forest area gains) are driven by different combinations of factors. Nonetheless, the accumulated effects (Fig. 5; based on data summarized in Dataset S3) broadly concur with results of our regression analysis at national scale. Our synthesis indicates that fallow land is mainly associated with (based on 37 studies, i.e., $N = 37$) labor shortage/migration driven by new income opportunities ($N = 14$), lack of infrastructure (irrigation and electricity; $N = 8$), lack of access to capital ($N = 7$), and cropland fragmentation (smaller average farm size; $N = 6$). Reclamation of fallow land depends mainly on (based on 16 studies) critical support services (e.g., access to markets and capital; $N = 10$), level of education (knowledge to reclaim land; $N = 7$), and village infrastructure (mainly irrigation; $N = 6$). Illegal forest encroachment (for cropland expansion due to low productivity; $N = 26$), wood extraction for subsistence ($N = 23$), expansion of man-made structures ($N = 21$), industrial exploitation ($N = 15$), and cattle overgrazing ($N = 12$) are common causes of forest loss. Unlike cropland fragmentation that drives fallow land, no case studies ($N = 42$) suggested that forest fragmentation drives forest loss. Regarding forest area gains, only three case studies (D6, D7, and D10 in Table S11) were designed to consider passive forces (regrowth following land abandonment), with other studies focusing on factors that influence the effectiveness of participatory forest management programs (e.g., Joint Forest Management). Our study finds passive forces to be a major factor for forest area increase. The prominent socioeconomic factors of forest area gain identified from our regression analysis are echoed in our synthesis (involvement of local community, education/awareness, and effective forest protection).

Causal factors uncommon at national scale can be most important regionally. For example, both our study and the

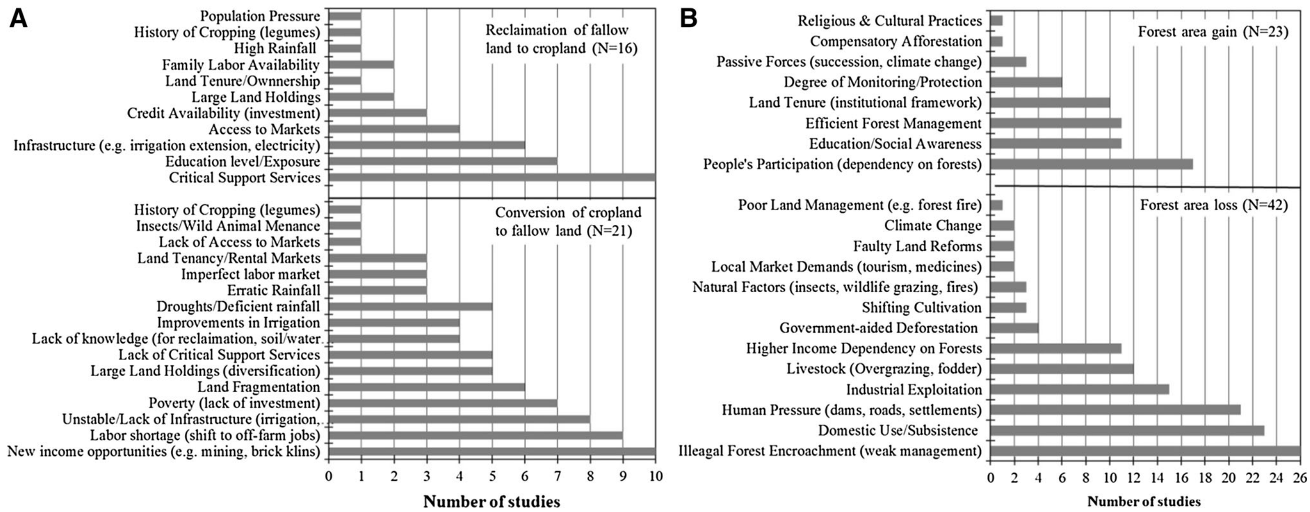

Fig. 5 Frequency distribution of the causal factors identified from the synthesis of 102 case studies. **a** Conversions from cropland to fallow land and vice versa, and **b** forest area losses and gains

synthesis literature (Table S10) report wood extraction for construction materials as a main determinant of forest loss in AEZ14. Some factors can also behave differently in individual cases. For example, different case studies (Tables S8, S9) stemming from same AEZ show opposing effects on how education affects fallow land. Education (proxies: literate population, availability of educational facilities) causes a shift to off-farm jobs, thus increasing fallow land. In contrast, with education farmers perceive higher returns to investment on land, invest more on resource conservation, and have better access to information leading to fuller land utilization. Such heterogeneity is concurrent and important to recognize; in such cases, our statistical analysis covering the entire region helps identify the dominant effect.

Discussion

Our analysis provides a comprehensive spatial coverage of the dynamics and spatial determinants of LULCC in India by integrating remote sensing data with rich and uniform socioeconomic data collected from each village and town at national scale. The analysis is important because a general understanding of the spatiotemporal dynamics and determinants of LULCC over larger regions of India is limited, hindering effective national-level planning and policy making.

Our analysis of spatial determinants is useful because it adds a quantitative component to our study. Determinants help identify biophysical and socioeconomic variables that contribute to the statistical explanation of (the location of) observed LULCC. However, determinants do not necessarily imply causality; they only provide some empirical support for causal relations. On the other hand, local case studies often identify causality. Our synthesis of case studies (Tables S8-S11) helps to identify causes that are common across case studies (Fig. 5). The synthesis is useful because it provides a more generalized understanding of the causes of LULCC in India. However, the study design varied widely across the 102 cases we examined. Therefore, we relied on frequency analysis to identify common causes across case studies, as opposed to a more formal quantitative assessment. Nonetheless, the generalized understanding from our synthesis reinforces the findings of our spatial determinants and can inform national-level policies and governance options.

Caveats

Three caveats are in order. *First*, as we estimated LULCC from decadal satellite images, they capture only the decadal changes in LULCC, and can mask within-decade variations including intermediary land uses. Especially, inter-annual climate variability causes fluctuations in fallow land (Dataset S4). However, the conversions between cropland and fallow inferred between decadal end points reflect only the climate effect of end point. Our decadal data also cannot identify land fallowed as a part of multiple cropping systems to restore and maintain soil fertility. Except cropland–fallow systems, other land cover conversions (e.g., forest to cropland) tend to be unidirectional at decadal timescale due to high cost of land reversion (Gibbs et al. 2010; Pandey and Seto 2015).

Second, both forest degradation and regrowth are gradual and cause subtle modifications to land cover. However, our Landsat analysis detects changes only when the magnitude of modification is large enough to cause shift from one land cover category to another (e.g., forest to shrubland for forest degradation). The resulting bias is likely minimal because: (1) persistent modification of forest would likely manifest as a change in land cover within a decade, and (2) our statistical estimation weighs each observation (grid cell) by the magnitude of land change; thus, small changes have less influence in our model.

Third, our analysis does not extend beyond 2005 due to data limitations. Wall-to-wall analysis of Landsat scenes is laborious, and efforts are underway to extend our decadal land cover conversion estimates to 2015. Furthermore, while India has conducted the 2011 socioeconomic census, tabular data on village profiles is on hold, pending consistency and quality checks. Nonetheless, our analysis already covers two decades and offers key insights on the non-stationary of factors associated with LULCC in India.

Implications for land use planning

Our results highlight the dichotomy where on the one hand, large amounts of India's cropland area are converted fallow, thereby not contributing to agricultural production. On the other, forest area is being encroached for agriculture. We show that both land conversions occur in areas of low agricultural productivity as broadly indicated by factors related to deficits in infrastructure (irrigation and markets), knowledge and critical support services. Our results imply that strategies to improve agricultural productivity can have a positive effect by enhancing food production and simultaneously help reduce the pressure on forest (our analysis, however, excludes indirect impacts that may offset the effectiveness). This is crucial for sustainable land use planning in India because India is among the world's fastest growing economy and population, with constant land area. Henceforth, we discuss specific implications of our results for land use planning in India.

Our results indicate that labor shortage; land fragmentation; and deficits in infrastructure, knowledge, and access to capital are key factors associated with crop to fallow conversions. There are threefold implications of our results. First, with the National Rural Employment Guarantee Scheme (NREGS; Ministry of Rural Development 2005), rural wages have increased through alternative job opportunities in rural areas and new job opportunities in the fast-growing urban centers (note that NREGS was introduced in 2005 which is beyond our study period; however, watershed development programs (Gray and Srinidhi 2013) were a precursor to NREGS). With higher wages, the incentive to produce agricultural crops reduces, thereby pulling people to off-farm jobs (Mitra and Murayama 2009; Srivastava 2011), causing more fallow land. This implies that despite labor shortage, keeping the prices of food and agricultural produce cheap would require encouraging mechanization and better market access to farmers to protect their rights (reduce middlemen exploitation). Cheaper food is important in the short-run because one-third of India's population lives below the poverty line (Gulati et al. 2012). Furthermore, our analysis indicates that livestock overgrazing is a key factor associated with forest loss. Protecting existing forest from overgrazing would require confined feeding which implies higher cost for farmers (except for milch animals in certain areas). Therefore, encouraging mechanization would not only help improve agricultural viability, but also help reduce the pressure on forests.

Second, small farms have low technical efficiency and have increased risk of soil degradation (see Table S16 for AEZ-wise correlation statistics). Importantly, our reported process of fallowing small, less productive farms combined with job opportunities from an industrializing economy show striking similarity to the path outlined in forest transition theory (Rudel et al. 2005; Mather 2007; Meyfroidt and Lambin 2011). The problem of cropland fragmentation is likely compounded in the future with increasing population and further subdivision of households. Effective strategies to prevent further land fragmentation and consolidation of farmers fragmented land holdings can help to improve the economic viability of agriculture in some cases (Jha et al. 2005; Niroula and Thapa 2005; Kumar et al. 2015).

Third, our results underscore the critical need to extension and better management of irrigation infrastructure and other common-pool resources to help reduce fallow land. Improving irrigation infrastructure requires both efficient management of surface irrigation and equitable use of ground water resources. Our analysis suggests that wastelands have already been consistently reclaimed to cropland (primarily AEZ2, 5, and 8), with support from both public and private initiatives, e.g., through building Indira Gandhi Canal in AEZ2 and Integrated Wasteland Development Programs (Rao and Pant 2001; Saxena 2006; Ghosh 2010; Maji et al. 2010). Concurrently, farmers have fallowed much larger areas of existing cropland, representing an undesired trade-off of wasteland reclamation. Numerable social surveys have shown that Indian farmers invest more on protecting fertile cropland (Maikhuri et al. 1997; Shiferaw et al. 2006; Kuppannan and Devarajulu 2009; Wani et al. 2011; Nüsser et al. 2012) than restoring degraded soils. Therefore, better orientation of investment portfolios with farmer's attitude can help reduce fallow land.

Finally, our results show prominent positive association between forest loss and the economic dependence of village communities on forests across many regions. Currently, ~173,000 villages in India depend on forest for subsistence due to lack of alternative economic opportunities (Nayak et al. 2012). The ongoing and future planned privatization of afforestation programs in India tends to maximize corporate profits, with little space for community involvement (Planning Commission 1998; Bramhane et al. 2000; Saxena 2015). Our analysis underscores the critical need for forest policies to widely adopt a bottom-up approach by involving local communities and village councils to effectively implement afforestation programs, e.g., by creating minor forest resources outside of forest area that benefit the local community. There already exist best practices on forest management tested at community level in India (Lise 2000; Prasad and Kant 2003; Nagendra 2009; Bhattacharya et al. 2010; Dilip Kumar 2015). However, forest protection would benefit if these models are upscaled, ingrained as policy, and integrated with implementation system through capacity building and technology upgrades.

Data access

Our satellite LULC data for three decades can be downloaded for free from http://dx.doi.org/10.3334/ORNLDAAC/1336. We are sharing the data at 100 m spatial resolution to conform to the map dissemination guidelines imposed by India's 2005 National Map Policy (Survey of India). Our geospatial village-level socioeconomic database (covering 1991 and 2001) will be made available for download for free from NASA Socioeconomic Data and Applications Center (SEDAC; http://sedac.ciesin.columbia.edu/). Contact the first author for more information.

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Dynamics and determinants of land change in India: integrating satellite data with village socioeconomics

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Text S1. Extended methods and data

Study area. Our study area conforms to the official national boundary published by the Survey of India (http://www.surveyofindia.gov.in/) and includes Indian territories currently disputed with China and Pakistan. Our LULCC estimates and analysis of spatial determinants cover mainland India. We did not map/estimate LULCC for two union territories that together account for ~0.25% of India's land area: Andaman and Nicobar Island (mostly comprised of protected forests), and Lakshadweep (mostly plantations).

Data. A summary of key input datasets used in this study is provided in Table S13. LULCC data is fully described in the methods section of the main paper and references cited therein. Here, we expand on rationale and processing of biophysical and socioeconomic variables used in our analysis of spatial determinants. See Table S12 for hypothesized biophysical and socioeconomic variables. Our hypothesis of explanatory variables was grounded based on synthesis of case studies (detailed in subsequent sub-section).

Biophysical data. Given the significant impacts of climate change on Indian agriculture (Singh et al. 2002; O'Brien et al. 2004; Kumar et al. 2004; Mall et al. 2006; Lobell et al. 2008; Aggarwal 2008; Guiteras 2009; Auffhammer 2012; Lobell et al. 2012; Mondal et al. 2014; Mondal et al. 2015), we included seasonal mean temperature and precipitation as potential explanatory variables in simulations aimed at understating conversions between cropland and fallow land. We defined seasons following Kumar et al. 2004: winter, summer, southeast monsoon, and autumn/post-monsoon season.

We derived seasonal precipitation from the daily gridded product of Indian Meteorological Department (Table S13). The data is the most comprehensive gridded product for India, as it integrates most number of rain gauge stations (N>7000). We derived seasonal temperature from the APHRODITE daily temperature product for Monsoon Asia (Table S13). Both precipitation and temperature products were at 0.25°x0.25° lat/long which is relatively coarser in spatial resolution compared to our LULCC dataset; however, there are no gridded time-varying climate dataset at higher spatial resolution covering our study period (1985-2005). Available higher spatial resolution climate products are either static (Hijmans et al. 2005), or cover shorter periods (2000-present) for temperature only (Huete et al. 2002). We addressed the issue of difference in spatial resolution among LULCC, biophysical datasets, and socioeconomic datasets by bringing all datasets to a common spatial resolution of 1kmx1km lat/long for our analysis of spatial determinants as detailed in “data processing” sub-section.

According to agronomic studies, crop growth is partly a non-linear function of weather conditions, especially temperature (Schlenker and Roberts 2006; Schlenker and Roberts 2008; Schlenker and Roberts 2009; Lobell et al. 2011). To account for non-linearity, we included squared terms for seasonal temperature and precipitation variables as potential explanatory variables in our analysis. Additionally, to test for interactive effects, we included the within season interactions between precipitation and temperature as potential explanatory variables.

For simulations aimed at understanding changes in forest area, we used bioclimatic variables (Hijmans et al. 2005) available at higher spatial resolution (1km x 1km lat/long), and static representative of contemporary climatic conditions. We chose the static data over coarser resolution (but transient) data products as higher spatial resolution was a priority over transient information, to study forest area change at decadal time scale.

To test for the effects of soil conditions on land-cover conversions, we included a wide range of soil parameters across all simulations: depth, reaction (pH), drainage, slope, erosion, salinity, sodicity, cation exchange capacity (measure of soil fertility and nutrient exchange capacity), flooding, and organic carbon content. All soil parameters were ordinal variables, and the data was sourced from the National Bureau of Soil Survey and Land Use Planning, India (Table S13).

Socioeconomic data. Our geospatial socioeconomic database covers over 200 variables at the highest level of spatial disaggregation in India: ~630,000 administrative units at village/town level (Fig. S1). We collected tabular data for two consecutive census years (1991 and 2001) from “Primary Census Abstract” and “Village Directory” data series of the Indian census. We used a sub-set of these variables for our analysis of spatial determinants; the sub-set being specific to land-cover conversion studied (Table S12). We derived some hypothesized socioeconomic variables by combining two or more census variables, for example, we derived average heads per household by dividing “total village population” with “total village households”.

Our village level spatial database has two key advantages. First, these variables show high granularity (Fig. S2) that is important to explain the spatial variation in high-resolution land-cover conversion estimates (i.e. Landsat data). The granularity will get masked even at taluka level, thus making them less suitable for our analysis (Fig. S2). Second, several key explanatory variables are village-specific categorical variables (e.g. infrastructure such as market availability, availability of power supply for agriculture, primary village occupation) that becomes irrelevant at coarser administrative levels (unlike population that can be aggregated).

We started by collecting tabular data for each village/town for both 1991 and 2001 census from the online digital database of the Census of India (http://censusindia.gov.in/). We undertook extensive data cleaning to ensure the data are quality-controlled, and standardized. Our next step was to convert the village/town tabular data into geospatial data. This required administrative boundaries at village/town level at national scale corresponding to census years. Official Geographic Information System (GIS) information on the administrative boundaries of India are made accessible (restricted) only at (sub-) district level (note the broad administrative hierarchy in India: state>district>sub-district>village/town). Therefore, we created a national level GIS file for 2001 with village/town boundaries by digitizing boundaries from the official cadastral maps published by the Survey of India. We also capitalized on village/town level GIS files for several states that were already available to us from earlier projects. We designed algorithms to link both the 2001 and 1991 tabular data to 2001 GIS boundary file, accounting for region-specific data limitations described next.

It should be noted that in some regions, data quality may be poor due to misreporting, human-errors in computerization, quality of village/town boundaries, or data missing due to political strife (e.g. parts of Jammu and Kashmir). We excluded villages/towns from our analysis for which data for all variables were missing. For villages/town where some variables were missing, we did multiple imputations following Baraldi and Enders (2010). We replaced each missing value with a set of plausible values that represent the uncertainty about the right value to impute. We then analyzed the multiple imputed data sets using standard procedures (Baraldi and Enders 2010) for complete data and combine the results (point estimates and standard errors) from these analyses. In general, we found 1991 census data to be more error-prone, likely because it was the first census when officials were trained to digitize village level information. While our algorithm corrected for many erroneous outliers that were apparent, in some cases, it was hard to detect if the outliers were real, or erroneous. In such cases, our statistical estimation may have been influenced by these errors, but unlikely to have influenced our conclusions. Furthermore, we reduced the impacts of such errors on our final results through bootstrap resampling (wrapped around data imputation), where we resampled the observations 500 times, and each time we fit a new model to the data (described in "statistical estimation" sub-section).

Data processing for statistical estimation. Following earlier land change modeling studies (e.g. Serneels and Lambin 2001; Verburg et al. 2006; Sohl et al. 2012), we brought all data to a common spatial resolution for statistical estimation. By experimentation, we chose 1km x 1km lat/long resolution as the best tradeoff between the fine-resolution (30m) LULCC data, and relatively coarse resolution transient climate data (~27km), and socioeconomic datasets (~2.2km on an average calculated by dividing India's geographical area by the number of administrative units in our village/town GIS file). In aggregating the land-cover conversion estimates from 30m to 1km grid cells, we calculated fractional values of each land-cover conversion within each 1km grid cell, so as to retain maximum information. This is unlike discrete spatial aggregation, where the entire area within 1km grid cell is approximated to either undergo one (dominant) type of land conversion, or remain unchanged. Our statistical estimation methods are specifically designed to handle fractional LULCC outcomes, consistent with our data aggregation method.

We used standard bilinear interpolation to downscale the coarser-resolution (transient) temperature and precipitation data to 1km x 1km lat/long resolution. For socioeconomic datasets, we assumed all grid cells falling within a village/town to have the same values as that village/town (note that all continuous variables were normalized by village/town area before gridding to 1km). For grid cells that fall on multiple village/town, we followed two approaches depending on the nature of variable. For continuous variables (e.g. population density), we calculated area weighed averages. For categorical variables (e.g. availability of irrigation facility), we took the value of village/town that has maximum area falling within the grid cell.

The independent variables used in our analysis have different units and scales (order of magnitude). Therefore, the statistical estimates cannot be interpreted directly to make standardized comparisons across explanatory variables. We addressed this issue by standardizing the explanatory variables across observations prior to statistical analysis. We apply standardization only to continuous variables. For categorical (and ordinal) variables, we dummy coded and used them in the model without applying any transformation. The dummy coding converts a categorical variable with 'k' levels into a set of 'k' binary variables. We dropped one variable from each set of dummy variables representing a categorical variable in the model. This is because, in the presence of an intercept (constant) term in the model, inclusion of all dummies from a categorical variable will result in perfect multicollinearity, a scenario known as "dummy variable trap".

We standardized each continuous variable using standardized z-score, with a modification. For each continuous variable, we calculated two statistics from the set of observations: the mean and standard deviation. We computed the z-score standardized value in each grid cell by subtracting the mean from the actual value, and then dividing by standard deviation. The subtracting by mean centers the data to have mean zero, but is strictly not necessary for variable standardization; centering is typically helpful to interpret the main effects in the presence of interactions. The division by standard deviation scales the data to have one standard deviation. This is the typical z-score standardization. However, in the presence of binary variables that are roughly symmetric (with equal probabilities of 0 and 1; hence, with a mean and standard deviation of 0.5), the model estimated coefficients for binary variables correspond to a comparison of two standard deviations, and hence cannot be compared directly with z-score standardized continuous variables that correspond to one standard deviation. Therefore, to put both categorical and continuous variables on same scale, we further divided the z-score standardized continuous variables by 2 following Gelman (2008).

Notably, to derive the standardized squared seasonal climate variables (Table S12), we first standardized the seasonal climate variables, and then squared the standardized variables. We do not standardize the squared seasonal climate variables itself. In other words, we standardized the continuous input variables, not the explanatory variables (predictors) themselves. Similarly, we multiplied the standardized seasonal precipitation and temperature terms to derive the standardized interaction terms.

Rationale for inclusion of state-fixed effects as potential explanatory variables (Table S12). Natural resource management in the Indian constitution falls under three categories: national, state, and concurrent. Forest is concurrent listed; forest policies are made at national level, and state implements them. State also manages its forest (including compensatory afforestation); however, clearing forest for other land use requires prior approval from the central government.

Agricultural land in India is under private holdings. State deals with market creation, national food secure procurement, minimum price fixation, and provides necessary infrastructure to support agriculture. Further, every state has its own agriculture universities which support farmers with extension work. National government is involved in funding projects such as irrigation, and soil conservation. Therefore, state plays a key role in both agriculture and forestry.

Our statistical estimation for analysis of spatial determinants is done either at national level or for regional hotspots (identified by AEZs; see "analysis" sub-section for rationale), meaning the set of observations can belong to different states. Across all simulations, we tested for state-fixed effects (e.g. agriculture and forest policies) that may not be captured by variations in biophysical and socioeconomic variables. We accounted for state-fixed effects by inclusion of state-specific dummies as explanatory variables in our statistical model (one column made as reference category). Our state boundaries are based on Survey of India (censusindia.gov.in). We used 1991 and 2001 state boundaries corresponding to simulations covering 1985-1995 and 1995-2005 decades respectively.

Analysis.

Rationale for analysis of spatial determinants by AEZ, and by epoch. We break down our national-scale analysis into 19 sub-regions based on Agro-Ecological Zones (AEZs) specifically developed for India (Table S6; Gajbhiye and Mandal 2000). There are two reasons for identifying regional hotspots for our analysis of spatial determinants by AEZ. First, in Indian context, AEZs are the optimal units for macro-level land use planning and efficient transfer of technology as India's economy is highly dependent on agriculture and allied sectors including forestry (Alagh 1996; Velayutham et al. 1999; Mandal et al. 2014). Second, for statistical modeling, it is desirable to delineate regions by similar characteristics to avoid heteroscedasticity (occurs when sub-populations have different variability from others). AEZs by definition are regions delineated by similar soil and climatic conditions, and exhibit homogeneity in LULCC processes (Alagh 1996; Velayutham et al. 1999; Gajbhiye and Mandal 2000; Mandal et al. 2014). Typically, AEZs are also used as optimal units for modeling LULCC in global-scale economic models that simulate the interactions among socioeconomics, LULCC, and climate change, for e.g. GTAP-AEZ (Lee et al. 2009) and GCAM (Kyle 2011). Earlier studies (NRC 2014; Agarwal et al. 2002; Verburg et al. 2004; Briassoulis 2000; Parker et al. 2003; Irwin and Geoghegan 2001) have shown that the set of factors and their importance to determining LULCC (e.g. conversion of cropland to fallow land) vary with time. To account for temporal variations we estimated statistical models separately for the two decades (1985-1995 and 1995-2005).

Time considerations for linking decadal LULCC data to concomitant explanatory factors. As our LULCC estimates are assessed from decadal Landsat imageries, they capture only the decadal trends in LULCC, and therefore can mask the within-decade variations in LULCC (e.g. year-to-year conversions between cropland and fallow mainly driven by inter-annual variations in rainfall).

Common to all simulations (Table S14), we assumed the decadal LULCC reflects the net result of time-varying socioeconomic forces (typically change gradually with time) that acted within the respective decade. The census in India is conducted once in 10-years, and we assumed 1991 socioeconomics to reflect the time-averaged conditions between 1985 and 1995, and 2001 socioeconomics to reflect the time-averaged conditions between 1995 and 2005. Accordingly, we used 1991 socioeconomics to relate with LULCC in 1985-1995, and 2001 socioeconomics to relate with LULCC in 1995-2005.

Earlier studies have shown that cropland area in India is sensitive to inter-annual variations in climate, especially rainfall (Tables S8, S9). The decadal changes between cropland and fallow land inferred from Landsat will reflect only the climate effect of end year of the respective decade.

Therefore, for simulations aimed at understanding conversions between cropland and fallow land, we related 1994-95 averaged climate variables to LULCC between 1985 and 1995, and related 2004-05 averaged climate variables with LULCC between 1995 and 2005.

Statistical estimation.

Overview. Our methodology for relating the spatial (at 1km x 1km lat/long) patterns of land-cover conversion (dependent or response variable) to concomitant biophysical and socioeconomic factors (or their proxies; the independent or explanatory variables) originates from our recent work (Meiyappan et al. 2014). Our method is broadly consistent with land change modeling literature (NRC 2014; Agarwal et al. 2002; Verburg et al. 2004; Briassoulis 2000; Parker et al. 2003; Irwin and Geoghegan 2001; Lesschen et al. 2005). Each simulation listed in Table S14 is subject to the statistical analysis detailed below.

The overall approach can be broken down into four steps. First, we select observations (i.e. grid cells within the study area e.g. AEZ hotspot) based on which we estimate the model. Second, we explain the "fractional" binomial logistic regression that we use to model the relationship between the dependent and independent variables. The model allows for fractional outcomes in dependent variables, consistent with our Landsat-based LULCC data aggregation technique. Third, we detail the algorithm to account for multicollinearity across independent variables. As a safety check (prior to step 3), we ensured that no highly collinear variables (Pearson's $r > 0.9$) were present in the model. Finally, we explain the how we estimate and interpret the regression coefficient.

Selecting observations. For ease of understanding, we explain this section with an example of Simulation 1 (i.e. conversion between cropland to fallow land at national scale between 1985 and 1995; Table S14). The approach however is similar across all simulations.

As we are interested in conversions between cropland and fallow land, we masked out grid cells within the study region (i.e. national for Simulation 1) where both cropland and fallow land (fallow land + wasteland) area in initial year (1985) was zero. In the masked grids, both cropland to fallow land conversion or the reverse conversion cannot occur between the two time points. For statistical estimation, we included all grids where non-zero cropland area in 1985 was converted to fallow land by 1995 (i.e. the conversion of interest). We further included buffer grids around zones of cropland to fallow land conversion. In buffer grids, all cropland either remained unchanged between 1985 and 1995, or had seen reverse conversion (i.e. fallow land to cropland). We selected the buffer size such that summed across observations, the area of cropland converted to fallow land (1985-1995) roughly equaled the counter-factual (sum of area of cropland that remained unchanged between 1985 and 1995 or have undergone reverse conversion). The buffer size is simulation specific (Table S14), and depends on the spatial confirmation of the land change patterns typically varying between 1.5 and 7 km.

The two response variables in our “fractional” binomial logistic regression are (Simulation 1): (1) the cropland area in each grid cell (during 1985) that was converted to fallow land by 1995 $('l'=1)$, and (2) the counter-factual which is the sum of cropland land area in each grid cell that remained unchanged between 1985 and 1995, and fallow land area that was converted to cropland between 1985 and 1995 (i.e. reverse conversion) $('l'=2)$. We normalized the response variables in each grid cell by the sum of cropland and fallow land area during 1985 in that grid cell, so that sum of responses adds to 1.0 in each grid cell, and each response takes a value from 0 to 1. We weigh each grid cell (observation) in the regression by the sum of cropland and fallow land area fraction in 1985, so that larger area changes are assigned greater weights in our regression. We standardized each explanatory variable (based on statistics computed from the observations) prior to model estimation as described in an earlier sub-section titled “data processing for statistical estimation”.

Regularized logistic regression. We represent $'F_{lg}'$ to be the fractional area (dependent variable) of the two land fractions $(1 \le 'l' \le 2)$ as explained above in grid cell $'g'$. The grid cell constraints can be mathematically expressed as:

$$0 \le F_{lg} \le 1, \ \sum_{l=1}^{2} F_{lg} = 1 \tag{1}$$

We assume $'F_{lg}'$ to be a function of a matrix $'X_g'$ with dimension $'p'$ of explanatory variables (Table S12; specific to simulation). We model the relationship between the dependent and explanatory variables as a “fractional” binomial logistic (FBNL) model proposed by Papke and Wooldridge (Papke and Wooldridge 1996; Papke and Wooldridge 2008). The FBNL regression allows for fractional outcomes of each dependent variable, thus being able to account for fractional land areas within each 1km grid cell, consistent with our LULCC data spatial aggregation technique. Therefore, FBNL allows for spatial heterogeneity within grid cells.

The logistic regression model (Eqs. 2, 3) represents the class-conditional probabilities through a linear function of the explanatory variables.

$$F_{1g} = \frac{1}{1+e^{-\left(\beta_0 + X_g^T \beta\right)}} \tag{2}$$

$$F_{2g} = \frac{1}{1+e^{\left(\beta_0 + X_g^T \beta\right)}} = 1 - F_{1g} \tag{3}$$

In Eqs. (2, 3), the superscript ^{T} indicates the vector transpose. β_0 is a constant coefficient and β is a vector of coefficients with a component for each explanatory variable. β_0 and β are unknowns that need to be estimated.

Alternatively Eqs. (2, 3) implies that

$$\log\left(\frac{F_{1g}}{F_{2g}}\right) = \beta_0 + X_g^T \beta \tag{4}$$

We fit this model by regularized maximum binomial likelihood. We derive the objective function by maximizing the penalized log-likelihood:

$$\max_{(\beta_0,\beta)\in {}^{p+1}} \left[\frac{1}{N}\sum_{g=1}^{N}\left(F_{1g}\left(\beta_0 + X_g^T\beta\right) - \log\left(1+e^{\left(\beta_0 + X_g^T\beta\right)}\right)\right)\right] - \lambda P_\alpha\left(\beta\right) \tag{5}$$

where $'N'$ is the number of observations in the study region. In Eq. (5), the first term is the log-likelihood part, a concave function of the parameters. The second term $\lambda P_\alpha\left(\beta\right)$ is the penalization applied. The penalization is included to prevent over fit due to multicollinearity of the covariates as explained in the next section. $\lambda \geq 0$ is the shrinkage parameter, and P_α is the elastic-net regularization term (40). The penalization term shrinks the coefficients towards 0, relative to the log-likelihood estimates.

Variable selection: Multicollinearity is a common problem in land change modeling where one or more explanatory variables are dependent on each other. High degree of multicollinearity results in high standard errors and spurious coefficient (β_l) estimates. We use elastic-net penalty (Zou and Hastie 2005) to account for multicollinearity. Elastic-net linearly combines lasso (L1) and ridge (L2) penalties respectively. Ridge method capitalizes on the strengths of correlated variables, by shrinking the value of their coefficients towards each other. In other words, when highly correlated predictors are present, ridge has a grouping effect on the variables, thereby avoiding omitted variable bias that is typical of other traditional methods used in land change modeling (e.g. Pearson correlation, forward selection, backward elimination). However, ridge cannot do variable selection, and keeps all predictors in the model. In contrast, lasso can do variable selection where many coefficients are expected to be close to zero, and a small subset to be larger and non-zero. However, the method is extremely variable because in the presence of highly correlated predictors, lasso will randomly pick one and ignore the rest. The elastic-net creates a useful compromise between ridge and lasso; it does variable selection like lasso, but also has a grouping effect as ridge, where strongly correlated explanatory variables are retained in the model.

The elastic-net penalty term in Eq. (5) can be explicitly written as:

$$P_\alpha(\beta)=\left[\frac{(1-\alpha)}{2}\ \beta\ _2^2+\alpha\ \ \beta\ \ _1\right] \tag{6}$$

In our model, the elastic-net penalty is controlled by mixing parameter α . When $\alpha = 1$, the first term in Eq. (6) becomes zero, and only the second term remains, which is the lasso penalty (L1 indicated by subscript 1). Conversely, when $\alpha = 0$ the second term in vanishes, and only the first term remains, which is the ridge penalty (indicated by subscript 2). A value of α between 0 and 1 is a mix of lasso and ridge penalty. For each simulation, we chose the α parameter using k-fold cross-validation (with k=10), where we randomly partitioned the observations within the study region into 10 equal size subsamples. Of the 10 subsamples, we trained a single subsample as the validation data for testing the model, and we used the remaining 9 subsamples as training data. We repeated the cross-validation process 10 times (the *folds*), with each of the 10 subsamples used exactly once as the validation data. We then averaged (combined) the 10 results from the folds to produce a single estimation. Overall, we fitted a sequence of model for 9 different values of α equally spaced between 0 and 1 (0.1, 0.2..., 0.9), each over a grid of λ values (Fig. S28 for an example). The variables we selected (variables with non-zero coefficients) for the final estimation corresponds to the 'best model', defined as the model (α and λ parameter) with minimum binomial deviance. See Table S14 for α and λ parameters corresponding to the 'best model' for each simulation.

We use the cylindrical coordinate descent method (Friedman et al. 2007; Friedman at al. 2010) for fitting the elastic-net regularization path for FBNL. The cylindrical coordinate method optimizes each parameter, while keeping other parameters fixed, and repeats the cycling until convergence. The individual grid weights are accounted within coordinate descent takes solves a penalized weighed least-square problem. While the FBNL procedure is based on regularized maximum multinomial likelihood (penalized log-likelihood), the elastic-net is based on penalized least squares. The coordinate descent algorithm fuses FBNL and elastic-net through a three step procedure: 1. simple least squares coefficients are computed on the partial residual, 2. soft-thresholding is applied to account for lasso, and, 3. proportional shrinkage is applied to take care of ridge penalty. Further technical details are spelled out in refs. (Friedman et al. 2007; Van der Kooij 2007). The coordinate descent method takes advantage of sparsity in the data and is extremely efficient for fitting large datasets as used here.

Bootstrap resampling for confidence interval. We use the penalized regression only for variable selection, because the regression coefficients (β_0 and β) estimated by penalization typically has a downward bias. Therefore, for unbiased coefficient estimates, we refit a standard logistic regression with only the variables selected from the elastic-net (i.e. from the 'best model'). For standard logistic regression, we fit Eq. (5), but by setting λ to zero (thus eliminating the penalty term). As we have standardized all explanatory variables prior to model fitting, the fitted β coefficients can be compared to infer the relative importance of different explanatory variables. The standardized β coefficients refer to how many standard deviations a dependent variable will change, per standard deviation increase in the independent variable. We obtained estimates of the mean (in figures: central mark on the box), 5th to 95th percentile confidence interval (ends of whiskers), and 25th to 75th percentile confidence interval (boxes) by bootstrap resampling, where we resampled the observations and we fitted a new model to the data. For each simulation, we used 500 bootstrap samples, so that e.g. the 25th percentile corresponds to the 125th lowest value. The bootstrap serves three purposes. First, the percentile range provides an uncertainty estimate on the impact of each explanatory variable. Second, the procedure minimizes the effect of any erroneous socioeconomic data that we were unable to identify through the data cleaning process. Third, resampling procedure accounts for spatial autocorrelation that is typical of spatial LULCC datasets. If we disregard spatial autocorrelation in LULCC data, we violate a key statistical assumption that residuals are independent and identically distributed. For brevity, across all simulations we present the 10 variables with largest absolute mean estimates (i.e. 10 most important). The elastic-net parameters and the binomial deviance of the fitted model corresponding to each simulation are presented in Table S14.

Synthesis of case studies. There were two reasons for synthesizing existing ground-based studies on the causes of LULCC in India. First, we used the synthesis to hypothesize the initial set of variables to test over larger spatial regions through our statistical analysis (Table S12). This was important given that we have a large number of socioeconomic variables (N>200), and testing for all of them is resource intensive, considering the high spatial resolution of analysis. Second, from synthesis we could identify common effects (and variations) across studies that are statistically stronger than any individual study due to larger sample size and greater diversity (Fig. 5; Dataset S3). The synthesis therefore provides a second line of evidence (from ground) to complement and evaluate our modeled results.

We reviewed the English language literature for LULCC studies covering India published between 1980 and May 2015. We relied on two scientific indexing services: Web of Science and Google Scholar because many relevant studies were published in national journals that were indexed only in one of the two databases. For initial screening, we searched the literature broadly to include all LULCC processes using the following key word search in Web of Science (similar keywords used for Google Scholar): TI=(Drivers OR determinants OR causes OR dynamics) AND TS=(India AND land*) AND TS=(crop* OR fallow* OR *forest* OR agricul* OR shrub* OR defor* OR wasteland* OR degrade*). The broad literature search for India was meant to get an understanding of the weightage (i.e. number of studies) assigned to studying different LULCC processes, and the type of analysis involved (e.g. land change quantification only, or includes analysis of spatial determinants, and methods of data collection). Overall, the literature review resulted in more than

630 articles that we studied in detail. In order to be included in our analysis, the study had to meet the following four criteria:

1. Study must have dealt LULCC processes that are a focus of our study i.e. conversions between cropland and fallow land, or forest area conversions (both gains and losses). The study region should be within India.
2. Study must discuss the causes of LULCC based on field data (e.g. household surveys, field transects), and/or local/regional expertise of the authors.
3. Study must have covered at least a part of our 20-year study period (1985-2005).
4. Study must not repeat the results presented in another paper.

Among the 630+ articles, we filtered those that met criteria 1, which resulted in 453 articles. In other words, about 72% of all articles focused on LULCC processes that are a focus of our study, highlighting their importance in Indian context. We further narrowed the set of articles to those that meet criteria 2, which yielded 103 articles. In exception, we retained about five studies (counted in 103 studies) that did not meet criteria 2 as they yielded significant insight through modeling, but supported through ground evidence from other published studies. Stage 2 elimination indicates that over three-fourth of the articles focused only on quantifying the magnitude of change (typically from remote-sensing at sub-national scale), indicating less attention has been given to identifying their causes. Applying criteria 3 and 4 resulted in 98 articles. In addition to this set of peer-reviewed articles, we reviewed and included five reports (PhD thesis; reports from government or external agencies such as World Wildlife Fund) that were similar in method and scientific rigor, and were not indexed in either literature database. In total, our synthesis includes 102 studies covering 64 journals.

We have summarized all the 102 studies in Tables S8-S11. See Fig. S3 for a visualization of the study locations. The number of studies by LULCC processes was: conversions between cropland and fallow land (N=37), forest area loss (N=42), and forest area gain (N=23). We included studies that examined the causes of failure to effectively implement forest protection mechanisms (thus causing continued forest loss) under “forest area gain”. The studies vary in sample size, spatial extent and location, time period, and method of data collection and interpretation. Following earlier land change synthesis studies (e.g. van Vliet et al. 2016; Magliocca et al. 2015; Geist and Lambin 2002; van Asselen et al. 2013), we analyzed the frequency of causes across studies (*meta-study*). We grouped the studies by LULCC processes and into broad clusters of causes (see Dataset S3 for study-wise grouping details); the clusters being specific to LULCC process. The results from frequency analysis are shown in Fig. 5.

Text S2. Forest transition in India

According to Forestry Survey of India (FSI), India experienced forest transition from net-deforestation in 1985-1995 (-8600 km^2) to net-reforestation in 1995-2005 (~57500 km^2) (see FSI 2013) and earlier reports cited therein). In contrast, our analysis shows that India experienced a net-deforestation of over 18000 km^2 during both decades (Fig. 1). The discrepancy in the sign and magnitude of change in forest area between the two studies is attributable to the difference in definition of 'forest cover'. Unlike the IGBP definition we followed (see Table S7), the FSI counts all the land with more than one hectare with a tree canopy density of more than 10% as the 'forest cover' which encompass many non-forest (land use) tree categories such as commercial plantations, orchids, tea and coffee gardens. In particular, the FSI definition of 'forest cover' has been questioned for including the green patch of 'open area' (trees outside demarcated forest areas, where most of the increase took place) because green cover accounting cannot be generalized by assessing a small patch of land, in particular 'open forest' area as 'forest cover' (Gilbert 2012; Ravindranath et al. 2014; Puyravaud et al. 2010; Pandit et al. 2007). Our study underscores the need to have a consistent definition of forest across countries, especially if carbon credits are attached to help protect tropical forests (Agrawal et al. 2011; Ravindranath et al. 2012).

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Supplementary Tables

Table S1. Extension to Table 1.

Environmental Problem	**Remarks**
Human land use	Estimated as the sum of four categories from the data of Ellis et al. 2010. The four categories are: 1. Dense settlements, 2. Villages, 3. Croplands and 4. Rangelands. The data corresponds to year 2000.
Climate change	Estimates averaged over the period 2001-2010. Greenhouse gas (GHG) emissions from LULUC for India and World were based on FAOSTAT database (FAO 2013). The estimates include emissions from agricultural activities, net forest conversion, biomass burning, peat fires, cultivation of histosols, and histosols under grassland. They do not include forest sinks. Total anthropogenic GHG emissions for India and world (totals needed to compute %) for 2001-2010 were based on EDGARv4.2FT2012 (2014).
Biodiversity loss	Net biodiversity change before year 2005 as estimated by Newbold et al. 2015
Land degradation	Range for global estimates as reviewed by Gibbs and Salmon (2015). We excluded two conservative estimates that were limited to cropland degradation only (both estimates lower than the lower bound presented in table 1). For India, we relied on the official estimate reported by the Government of India (Government of India 2014). While differences in the definition of land degradation may exist, the comparison indicates that the land degradation estimated for India is greater than the upper bound estimate for the global case. As per the national report, the major causes of land degradation in India include: loss of vegetation due to deforestation, cutting beyond permissible limits, unsustainable fuel wood and fodder extraction, shifting cultivation, overgrazing, encroachment into forest lands, forest fires, overgrazing, inadequate soil conservation measures, improper crop rotation, indiscriminate use of agro-chemicals, improper management of irrigation systems and excessive extraction of ground water, urbanization, poverty, inequitable sharing of resources.
Water use for agriculture	Circa (2010); Based on FAO (2015) for both India and the world; Numbers indicate the % of total freshwater withdrawal that was used for agriculture.
Nutrient excess in crops (Water pollution)	Circa (2000); Data from West et al. (2014); The numbers indicate the applied nutrient that is in excess i.e. not harvested in the plant. The numbers are based on analysis of 17 major crops that account for 73% of nitrogen and 68% of phosphorous applied globally.

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Table S2. Gross area losses, gross area gains, and net area changes in land use and land cover areas for 1985-1995 and 1995-2005. All values have been rounded up to nearest integers. For reference, the total geographical area (TGA) of India is 3,287,590 km^2.

Land use and land cover class	**1985-1995 (km^2)**			**1995-2005 (km^2)**		
	Losses	**Gains**	**Net Change**	**Losses**	**Gains**	**Net Change**
Built-up & Urban	-531	6724	6193	-651	7667	7016
Cropland	-66156	62994	-3162	-69768	131727	61959
Fallow land	-31837	46520	14683	-93712	48958	-44754
Forest	-27169	8905	-18264	-28352	10278	-18074
Plantations	-8788	9247	463	-11131	11767	636
Shrub land	-17682	19733	2051	-24341	26709	2369
Grassland	-5646	4172	-1474	-5833	7676	1793
Barren land	-4082	9848	5766	-8723	7378	-1345
Waste land	-8349	2584	-5765	-8804	4540	-4264
Water bodies[1]	-8802	13831	5029	-18190	11938	-6252
Others[2]	-8978	3462	-5516	-6395	7312	917
Total	**-188020**	**188020**	**0**	**-275900**	**275900**	**0**

1 Includes Aqua Culture, Water bodies, and Permanent Wetlands.
2 Includes Salt Pan, Snow and Ice.

Table S3. Land-use and land-cover change (LULCC) transition matrix for 1985-1995 in km^2. Marginal transitions (<1% of total gains and losses) have been termed as not significant (n.s.).

To 1995 → / From 1985 ↓	Built-up & Urban	Cropland	Fallow land	Forest	Plantations	shrub land	Grassland	Barren land	Waste land	Water bodies[1]	Others[2]
Built-up & Urban		291	26	48	26	78	n.s.	n.s.	36	22	n.s.
Cropland	3811		39551	4065	4336	5221	91	182	712	8187	n.s.
Fallow land	946	25356		319	1861	1708	131	89	135	1291	n.s.
Forest	298	11470	1418		1839	8059	838	1245	251	1102	649
Plantations	585	4728	2530	176		341	n.s.	n.s.	85	327	n.s.
Shrubland	736	9670	1618	2250	887		123	339	534	1341	183
Grassland	n.s.	457	n.s.	638	n.s.	736		1650	n.s.	1013	1079
Barren land	n.s.	231	n.s.	371	n.s.	1079	701	62205	49	89	1458
Waste land	139	5946	563	247	132	830	n.s.	n.s.		438	n.s.
Water bodies[1]	177	4845	714	400	120	1044	813	n.s.	526		n.s.
Others[2]	n.s.	n.s.	n.s.	390	n.s.	636	1460	6216	249	n.s.	

1 Includes Aqua Culture, Water bodies, and Permanent Wetlands.
2 Includes Salt Pan, Snow and Ice.

Table S4. Land-use and land-cover change (LULCC) transition matrix for 1995-2005 in km^2. Marginal transitions (<1% of total gains and losses) have been termed as not significant (n.s.).

From 1995↓ / To 2005 →	Built-up & Urban	Cropland	Fallow land	Forest	Plantations	Shrubland	Grassland	Barren land	Waste land	Water bodies[1]	Others[2]
Built-up & Urban		390	74	35	37	57	n.s.	n.s.	14	34	n.s.
Cropland	4394		38392	4669	5776	8192	295	315	1619	6116	n.s.
Fallow land	1308	84521		482	2680	2632	77	199	641	1172	n.s.
Forest	271	10602	1023		1795	9167	961	1305	473	1451	1305
Plantations	812	6776	2588	272		364	n.s.	n.s.	67	234	n.s.
Shrubland	512	11285	3571	3264	913		959	1552	774	1088	422
Grassland	n.s.	908	n.s.	79	n.s.	543		1375	n.s.	928	1817
Barren land	n.s.	543	n.s.	109	n.s.	1545	2190		225	n.s.	3723
Waste land	164	3828	1928	189	99	1862	n.s.	n.s.		710	n.s.
Water bodies[1]	145	12874	1075	594	335	1563	846	n.s.	674		n.s.
Others[2]	n.s.	n.s.	n.s.	584	n.s.	783	2230	2481	n.s.	n.s.	

1 Includes Aqua Culture, Water bodies, and Permanent Wetlands.
2 Includes Salt Pan, Snow and Ice.

Table S5. State-wise summary of key land-cover conversions based on our decadal analysis of Landsat data (the state-wise results pertain to the sum of urban, peri-urban, and rural areas). See Dataset S1 for supporting analysis. The state boundaries are based on 2001 census. In this table, the term "forest degradation" refers to "forest to shrub land conversion".

STATE	KEY CHANGES
NORTH INDIA Summary: Alarming loss in forest area: loss of 3.4% of region's forest area in 1985-1995, to 4.7% in 1995-2005. Region with maximum conversion of cropland to built-up areas in both decades.	
CHANDIGARH	Planned city with no expansion in the interior areas. Increase in built-up area at the expense of cropland in the periphery due to new planned residential estate (Panchkula Urban Estate) and increasing urban sprawl due to nearness of Chandigarh city and good network of roads.
DELHI (capital region of India)	Increasing rates of conversion of cropland to built-up.
HARYANA	Increasing rates of conversion of cropland to built-up. During 1995-2005 decade, significant amount of fallow land was brought under cultivation, and water bodies were lost to expansion of cropland and forest.
HIMACHAL PRADESH	Overall net loss in forest cover during both decades, but the rates of forest loss has reduced with time. Significant conversions among three categories: others (snow cover), grassland and barren land.
JAMMU & KASHMIR	Significant interactions between barren land and grassland/snow cover. The loss in forest cover has more than doubled from 1985-1995 to 1995-2005 resulting in more barren land, snow cover, shrub land, & grassland due to degradation and clear felling.
PUNJAB	State with highest cropland to built-up conversion in 1995-2005.
RAJASTHAN	The net increase in cropland area nearly tripled from 1985-1995 to 1995-2005 due to recovery of fallow land, wasteland, and shrub land. Increasing rates of forest degradation (Forest → Shrubland) and cropland degradation/abandonment (Cropland → Shrubland). State with second highest area of forest recovery between 1985 and 2005. State with maximum recovery of wasteland area in both decades.
UTTAR PRADESH	State with second highest decrease in surface water spread between 1985 and 2005 due to cropland expansion. Significant conversions between cropland and fallow land. Overall, cropland, fallow land, and water bodies area has decreased whereas built-up and shrub land area has increased.
UTTARAKHAND	Transition from net decrease to net increase in snow cover between 1985-1995 and 1995-2005, and vice-versa for barren land, shrub land, and grassland.
WEST INDIA Summary: Region with high dynamism in conversions between cropland and fallow land in both decades	
DADRA & NAGAR HAVELI	No major/significant change.
DAMAN & DIU	No major/significant change.

GOA	Loss of forest to shrub land (degradation) and cropland. Increase in built-up area.
GUJARAT	Huge areas of cropland were converted fallow in 1985-1995, and vice-versa in 1995-2005. Increasing loss in forest cover to cropland (some of which was subsequently converted fallow). Increasing reclamation of wasteland mainly to cropland, shrub and, forests, and water bodies. Decrease in expansion of built-up areas with time.
MAHARASHTRA	Increasing loss of surface water spread, with increasing proportions from to cropland expansion (90% loss in water bodies is for cropland in 1995-2005). Increase in built-up area at the expense of cropland. Consistent recovery of fallows to cropland. Decrease in forest and shrub land area, for expansion of cropland and built-up area. Some forests are converted to shrub land, and subsequently to cropland.
SOUTH INDIA **Summary: Region with most dynamism in transition between cropland and plantations/fallow land/water bodies.**	
ANDHRA PRADESH	State with most decrease in surface water spread between 1985 and 2005. The loss of water bodies more than doubled between the two decades, with increasing proportions converted to cropland (~85% in 1995-2005). Also, the state with highest cropland to water body conversion (24-27% of national total). Transition from net decrease to net increase in cropland area between 1985-1995 and 1995-2005. Significant conversion between cropland and fallow land, and cropland and water bodies during both decades. Net decrease in forest cover by ~780 km^2 during both decades, due to conversion to cropland and shrub land (degradation). Increasing rate of conversion of cropland and fallow land to built-up area. Net decrease in shrub land during both the decades for conversions to cropland, plantations, forest, and built-up areas.
KARNATAKA	Net increase in built-up, fallow land, plantation and water bodies and corresponding decrease in cropland, forest, and shrub land. Plantations show accelerated increase due to conversion of cropland, fallow land, and forests.
KERALA	Net increase in built-up and plantations area, and net loss of forest area. Plantations are the main source of built-up land, and forests and cropland are the main sources of plantations.
PUDUCHERRY	No major/significant change.
TAMILNADU	State with maximum dynamism among cropland, fallow land, and plantations during both decades. Increasing rates of conversion of plantations, fallow land, shrub land, and wasteland to cropland. Net increase in built-up area sourced mainly from cropland. Increased rates of conversion of forest to plantations. Overall, net increase in cropland area and net decrease in fallow land, wasteland, shrub land, plantations, and forests.
EAST INDIA **Summary: Region with highest loss in forest area: loss of 6.5% of region's forest area in 1985-1995, and 5.1% in 1995-2005. Highest rates of forest degradation in both decades.**	
BIHAR	No major land changes during both decades relative to the state's area, indicating lack of development. Land conversions are mainly among cropland, water bodies, fallows, and shrub land. Increasing rates of conversion of cropland to built-up areas.
JHARKHAND	Net decrease in cropland, and corresponding increase in fallow land. Net decrease in forest area due to cropland

	expansion.
ODISHA	State with highest rate of forest loss in both decades (10.8% and 8.8% of forest cover was lost in decades 1985-1995 and 1995-2005 respectively) due to conversion to shrub land (degradation) and cropland. State with maximum forest degradation in both decades, and maximum deforestation in 1985-1995. The proportion of deforestation for shrub land has increased from 51% to 68% between the two decades. The shrub land are subsequently converted to cropland.
WEST BENGAL	No major land changes, relative to state's area. The major conversions are conversion of cropland to water bodies, and vice-versa and reclamation of fallow land to cropland.
CENTRAL INDIA Summary: Region with maximum forest regrowth from cropland abandonment during both decades.	
CHHATTISGARH	Net increase in cropland mainly sourced from fallow, forest, and shrub land. Overall, net decrease in forest, shrub land, and fallow land during both decades.
MADHYA PRADESH	State with highest deforested area in 1995-2005, and second highest in 1985-1995 due to conversion to cropland and shrub land (degradation). State with maximum area of forest recovery during both decades. Transition from net decrease to net increase in cropland from 1985-1995 to 1995-2005, and corresponding vice-versa change in fallow land.
NORTH-EAST INDIA Summary: Roughly 80% of forest loss in the region in both decades is for cropland expansion (shifting cultivation) indicating the region is not headed towards settled cultivation.	
ARUNACHAL PRADESH	Deforestation for cropland expansion during both the decades.
ASSAM	Increasing rates of deforestation for cropland expansion. Water bodies, grassland and plantations are the other sources of cropland expansion. Net increase in water bodies due to conversion of cropland and grassland. Water bodies interact with all natural and man-mad classes, due to occasional water flooding.
MANIPUR	Increasing rates of deforestation for cropland expansion.
MEGHALAYA	Deforestation for cropland expansion and forest degradation (forest → shrub land).
MIZORAM	Increasing rates of deforestation for cropland expansion.
NAGALAND	Increasing rates of deforestation for cropland expansion.
SIKKIM	Transition from net decrease in snow cover to net increase in snow cover from 1985-1995 and 1995-2005, and corresponding vice-versa change in barren land.
TRIPURA	Increasing loss of forest cover for expansion of cropland and built-up area.

Table S6. Classification of India into twenty Agro-Ecological Zones (AEZs) following National Bureau of Soil Survey and Land Use Planning, India (Gajbhiye and Mandal 2000). See Text S1 for rationale.

Ecosystem type	AEZ	Physiography	Climate	Soils	Growing period
Arid ecosystem	AEZ1	Western Himalayas	Cold arid	Shallow skeletal soil	<90 days
	AEZ2	Western Plain, Kachchh and part of Kathiawar Peninsula	Hot arid	Desert and saline soil	<90 days
	AEZ3	Karnataka Plateau (Rayalseema as inclusion)	Hot arid	Red and black soils	<90 days
Semiarid ecosystem	AEZ4	Northern Plain and Central Highlands including Aravallis	Hot semi-arid	Alluvium-derived soils	90-150 days
	AEZ5	Central Highlands (Malwa), Gujarat plain and Kathiawar Peninsula	Hot semi-arid	Medium and deep black soils	90-150 days
	AEZ6	Deccan Plateau	Hot semi-arid	Shallow and medium black soils	90-150 days
	AEZ7	Deccan plateau (Telangana) and Eastern Ghats	Hot semi-arid	Red and black soils	90-150 days
	AEZ8	Eastern Ghats and Tamil Nadu Uplands and Deccan (Karnataka) Plateau	Hot semi-arid	Red loamy soils	90-150 days
Subhumid ecosystem	AEZ9	Northern Plain	Hot subhumid (dry)	Alluvium-derived soils	150-180 days
	AEZ10	Central Highlands (Malwa and Bundelkhand)	Hot subhumid	Red and black soils	150-210 days
	AEZ11	Moderately to gently sloping Chattisgarh/Mahanadi Basin	Hot subhumid	Red and yellow soils	150-180 days
	AEZ12	Eastern Plateau (Chhotanagpur) and Eastern Ghats	Hot subhumid	Red and lateritic soils	150-210 days
	AEZ13	Eastern Plain	Hot subhumid (moist)	Alluvium-derived soils	180-210 days

	AEZ14	Western Himalaya	Warm subhumid to humid (with inclusion of perhumid)	Brown forest and Podzolic soils	180-210+ days
Humid-Perhumid ecosystem	AEZ15	Assam and Bengal Plain	Hot subhumid (moist) to humid (inclusion of perhumid)	Alluvium-derived soils	210+ days
	AEZ16	Eastern Himalayas	Warm perhumid	Brown and red hill soils	270+ days
	AEZ17	North-Eastern Hills (Purvachal)	Warm perhumid	Red and lateritic soils	270+ days
Coastal ecosystem	AEZ18	Eastern Coastal Plain	Hot subhumid to semi-arid	Coastal and Deltaic alluvium-derived soils	90-210+ days
	AEZ19	Western Ghats and Coastal Plain	Hot humid-perhumid	Red, lateritic and coastal alluvium-derived soils	210+ days
Island ecosystem	AEZ20	Islands of Andaman-Nicobar and Lakshadweep	Hot humid to perhumid island	Red loamy and sandy soils	240+ days

Gajbhiye KS, Mandal C (2000) Agro-ecological zones, their soil resource and cropping systems. Status paper, In: Status of Farm Mechanization in India. Indian agricultural statistical institute, New Delhi, pp 1-32.

Table S7. Definition of the 11 land-use and land cover classes used in our study, consistent with the IGBP land classification scheme (Belward 1996).

No.	Land-use/cover classes	Definition
1	Cropland	Temporarily cropped area followed by harvest and a bare soil period (e.g. single and multiple cropping systems). Note that perennial woody crops will be classified as either forest or shrubland, whichever is appropriate. Includes orchards. We do not differentiate between different types of cropland based on seasons (e.g. kharif, rabi, zaid).
2	Fallow land	Land taken up for cultivation, but are temporarily allowed to rest, un-cropped for one or more seasons. We do not differentiate between different seasonal cropland types e.g. kharif, rabi, zaid) being fallowed.
3	Forest	Land with woody vegetation with greater than 60% cover and height exceeding 2 m. Also includes savannas (both woody and non-woody) defined as herbaceous and other understory systems, with forest canopy cover of 10-60%, and height exceeding 2m. “Forest” here was obtained by combining six forest classes from IGBP Level II classification: Deciduous broadleaf forest, Deciduous needle leaf forest, Evergreen broadleaf forest, Evergreen needle leaf forest, mixed forests, and savannas (woody + non-woody). Note that IGBP definition of forest is different from that of Forestry Survey of India (FSI 2015. FSI defines forest cover as all lands more than 1 ha in area, with a tree canopy density of more than 10% as forest, irrespective of ownership and legal status. FSI reported forest area includes areas of trees outside forest (forest plantation, and agriculture plantations). In our study, forest plantations are a separate category (“Plantations” category), and agricultural plantations are included within “Cropland” category.
4	Shrubland (open & closed)	Land with woody vegetation less than 2 m in height and with greater than 10% shrub canopy cover. The shrub foliage can be either evergreen or deciduous.
5	Plantations	Commercial horticulture plantations and tree cash crops.
6	Water bodies	Areas with surface water, either impounded in the form of ponds, lakes, reservoirs, aquaculture, permanent wetlands or flowing as streams, rivers, etc. Permanent wetland is defined as a land with a permanent mosaic of water and herbaceous or woody vegetation. The vegetation can be present in either salt, brackish, or fresh water.
7	Built-up &Urban	Land covered by buildings and other man-made structures.

8	Wasteland	Sparsely vegetated land with signs of erosion and land deformation that could be attributed to lack of appropriate water and soil management, or natural causes. These are land identified as currently underutilized and could be reclaimed to productive uses with reasonable effort. Degraded forest (<10% tree cover) with signs of erosion is classified under wasteland.
9	Grassland	Land with herbaceous land cover. Tree and shrub cover is less than 10%.
10	Barren land	Exposed soil, sand, or rocks and has less than 10% vegetation cover throughout the year.
11	Others	Includes land user snow/ice cover for most of the year. Also includes Salt Pan (land covered with salt and minerals).

Belward AS (1996) The IGBP-DIS Global 1km Land Cover Data Set 'DISCOVER': proposal and implementation plans. Report WP No. 13, IGBP-DIS, Stockholm, Sweden.

FSI (2015) India State of Forest Report. Forestry Survey of India (Ministry of Environment and Forest). Dehradun, India.

Table S8. Summary of studies (N=21) on conversion of cropland to fallow land. Keywords in the third column are highlighted in bold for skimming.

Study #	LULCC	Key results	Study details	Methods	Ref
A1	Cropland → Fallow → Grassland	• **Out-migration** to urban areas for better jobs • **Labor shortage** • **Water scarcity**	**Location**: 11 villages in South India covering three states (Andhra Pradesh, Karnataka & Tamil Nadu) **Study period**: 1981-2006 **Focus**: Cropland abandonment	Land investigations Household survey (sample size unknown) Participatory rural appraisal	Tiwari et al. 2010
A2	Cropland → Fallow	• **Inter-annual fluctuations in rainfall**: over half the cultivated areas in Tamil Nadu are rain fed • **Continuous failure** & **delayed onset of monsoon** • Dry & drought-prone regions with mostly tank irrigation (**unstable water source**), & little well irrigation (relatively stable) • **Improvements in irrigation facilities**: leads to diversification to water-intensive cash crops in small areas, converting some lands fallow. Crop selection depends on its price behavior in markets/demands • **Labor scarcity** & **increase in urban wage rates** (fallow conversions in regions with high rainfall): with labor scarcity, wages increase which increases the cost of cultivation keeping the land fallow • **Inadequate capital** & **non-**	**Location**: Six regions in the state of Tamil Nadu, with differing agro-ecological zones, irrigation system & farming practices **Study period**: 1960-2000	Survey of 900 farms Secondary data on district level land use statistics	Ramasamy et al. 2005; Nadkarni and Deshpande (1979)

		availability of credit facilities: especially in tank irrigated areas which is unstable with more rice-based system & have no access to ground water • **Higher non-agricultural income**: shortage of family labor because off-farm jobs are less strenuous, & generate higher & stable income • **Larger size of land holdings**: Credits, labor, & water becomes limiting factor to expansion			
A3	Cropland ↔ Fallow	• **Large size of land holdings** • **Land tenancy**: higher leased-in area/land owned fraction results in less fallow land • **Better irrigational facilities**: focused efforts on small areas, leaving other areas fallow • **Land rental markets**/Formal land tenancy: increases land access & provides stable livelihoods to poor reducing fallows	**Location**: National level **Study period**: 1992-2005 **Note**: The study has no primary data component, but we included in our analysis as the study provides key insights on cropland-fallow land dynamics in India.	Statistical analysis of state level panel data on land utilization from Indian government combined with census statistics	Bardhan and Tewari (2010)
A4	Cropland → Fallow	• **Drought-prone regions** • **High capital requirements for adopting modern outputs** viz. irrigation (especially well irrigation), tractors & commercialization: reason applies to regions with high rainfall; in drought-prone regions technology diffusion is poor.	**Location**: Andhra Pradesh (comparison across districts within the state & by size class) **Study period**: 1955-1987	Primary data collected at farm level (sample size & distribution unclear) Secondary data on land use statistics	Reddy (1991)
A5	Cropland → Fallow	• **Introduction of irrigation facilities**: leads to diversification to water-intensive cash crops (e.g. cotton,	**Location**: Command area of Tawa irrigation project, Hoshangabad district, Madhya Pradesh	Regional/local expertise	Shrivastva et al. 1991

		oilseeds) in small areas, converting some lands fallow. Crop selection depends on its price behavior in markets/demands	**Study period**: 1970-1980	Secondary data on land use statistics	
A6	Cropland → Fallow/Wasteland/Barren	• **Division of land** • **Higher land holding size** • **Number of fragments of operational holdings** • **Poor irrigational facilities** • **Decrease in family labor** (out-migration for non-farm jobs): less incentive to invest in soil conservation • **Higher dependency on farm income**: More fertilizer inputs leading to more degradation • **Higher education** has two effects: ➢ More awareness → less degradation ➢ More off-farm jobs → more degradation • Wild animal menace • Weeds infestation	**Location**: Himachal Pradesh **Study period**: 1995-2005 **Focus**: Land degradation in farms	Survey of 200 farm HH in 20 villages Secondary data on land use statistics	Gupta and Sharma (2010)
A7	Cropland → Fallow → Grassland	• **Out-migration** to urban areas due to **unemployment** (less demand for labor) • **Low labor wage rates** for farming • **Small land holdings** • **Risk in agriculture**	**Location**: Majhgawan block, Satna district, Madhya Pradesh **Survey period**: Circa 2000 **Note**: See Rajendran (1993) for an associated discussion on labor use in Thanjavur district, Tamil Nadu. See Oberai & Ahmed (1981) for labor use behavior in agriculture based on household survey of 26 villages in Ludhiana district, Punjab.	Survey of 140 HH: half from agriculturally modernized & half from un-modernized villages	Lenka et al. 2002

A8	Cropland → Fallow/Wasteland/Barren	• **Access to stored rainwater** e.g. proximity to pond/micro-level spatial organization of cropland • **Diversification to cash-oriented crop**s • **Inability of small farmers (correlated to caste) to cope with agricultural crisis**, due to inability to compete with big farmers for control of natural & human resources • **More profits & risk free nature of non-agricultural jobs**: need for money to sustain HH • **Labor shortage**: out-migration for better jobs in urban areas (rural employment diversification) • **Small size of land holdings** make mechanization uneconomical (lack of labor & oxen) • **Lack of medical facilities** (high oxen mortality) • **Weak institutional arrangements**: feudal culture & faulty land reforms • **Droughts** • Road constructions created **new rural jobs** (e.g. dairy industry & fisheries)	**Location**: Magadha area, Gaya district of South Bihar. **Study period**: 1960-present **Focus**: Case of marginalization of agricultural land by forced tenancy when off-farm jobs become more profitable & risk-free than earnings from small farms	Data collected through participation-observation Regional/local expertise	Singh S (2013)

A9	Cropland → Fallow/Wasteland/Barren	• **Droughts**, **water scarcity**, & **soil degradation** • Low economic returns to investments: related to **soil quality/productivity** & **structure of markets** • Other variables that determine conversions: ➢ **Access to credit**, **labor scarcity**, **scarcity of land**, **caste**, **social capital** & distance from home (supervision problem, high transaction cost) • **Imperfect labor markets**: male workforce are better in resource conservation management • **Size of farm**: ➢ Large land holdings → less incentive to invest ➢ Scarce land (land/person) → more investment • **More off-farm income** → less incentive for investment in soil-water conservation, seeds & irrigation • Availability of water for irrigation in post-rainy season (rabi crops) • High rainfall in rainy/kharif seasons (difficult working conditions) • **History of cropping & fallowing**: Fewer fallows where legumes (nitrogen-fixing) were grown in previous year (crop rotation system)	**Location**: Six villages in Rangareddy district, Andhra Pradesh **Survey period**: 2001-2002 **Focus**: Causes of agricultural land degradation & conservation through natural conservation management **Context**: The six villages are semi-arid regions prone to droughts, water scarcity & soil degradation. One village is under community water shed management program, & other five adjoining villages are not.	Survey of 60 HH within each village Detailed plot- & crop-wise input & output data collected from all operational holdings of surveyed HH (n=568)	Shiferaw et al. 2006a; Shiferaw et al. 2006b
A10	Cropland → Fallow/Wasteland/Barren	• New income opportunities: in booming tourism sector, government, & army • Brick production for houses in	**Location**: Upper Indus Basin of Central Ladakh (high altitude desert region), Northern India (Trans-Himalayan environment)	Remote sensing of land cover Qualitative	Nüsser (2012)

		fallows • Labor scarcity • Increased monetary income	**Study period**: 1969-2006 **Survey period**: 2007-2009 **Focus**: Case of subsistence-based agriculture, where primary income is from non-farm sector. The authors present two local case studies at the village level (Stok & Indus valley) & an overview of the complete Central Ladakh Basin, Leh.	interviews with experts from both government & non-governmental organization Regional/local expertise	
A11	Cropland → Fallow → Grassland	• **Labor scarcity** due to male out-migration: most are landless or small landholders who work as wage laborers during cropping season • **Higher education** among family labor: young literates prefer off-farm jobs • **Imperfect labor markets**: Women, elderly, & children take care of farming & their decisions about resource-use efficiency is poor compared to non-migrant farmers • **Small land holdings** per capita • **Less family income** other than remittances • **Proportion of lower caste**: proxy for available input capital & land availability • **Lack of critical support services →** drives migration	**Location**: Kathihar & Samastipur district, Bihar; Varanasi & Azamgarh district, Uttar Pradesh **Study period**: 1990s **Focus**: Migration induced agriculture land abandonment. Both the states account for ~40% of total out-migrants in India from rural places (especially male), & the rate of out-migration is increasing rapidly. Out-migration is mainly from Bihar to Delhi & Punjab; Uttar Pradesh to Maharashtra & Delhi.	Structured interviews of randomly selected 200 out-migrant families & 200 non-migrant families with land holdings less than 2 ha from each state Secondary data from National Sample Survey & from statistical abstract published by the Government of India	Singh et al. 2011
A12	Cropland → Fallow/Wast	• **Higher land-man ratio**: more degradation where agricultural	**Location**: National extent; Study broken down at regional level (by	Expert knowledge on the dynamics	Reddy (2003);

	eland/Barren	pressure is less i.e. low population agriculturally backward regions are more prone to degradation than developed intensively practiced regions • **Size of land holdings**: Small land areas are put to more intense use, than bigger land holdings where some land is irrigated & rest is allowed to remain fallow • **Irrigation increases** salt affected & water logged **degradation when managed poorly** • Poverty, population, institutional credits, & rainfall (hypothesized natural factor) not sufficiently related to degradation	agro-ecological zones, districts, & states) **Study period**: Various (1980s) **Focus**: Farmland degradation	on soil degradation in India Statistical modeling combining remote sensing of land cover with socio-economic, demographic, technological, institutional & biophysical factors	Yadav (1996)
A13	Cropland → Fallow/Barren/Wasteland	• **Distress out-migration**: positive feedback as leads to sub-optimal land use & further degradation of land due to shortage of labor or able bodied persons of the HH • **Lack of irrigation**: perception that people think if land is irrigated it is not degraded, even if the land is saline or eroded • **Risk aversion attitude**: Leasing out lands as risk aversion strategy or using them for short & more remunerative crops	**Location:** Three dryland, drought-prone regions (Surendranagar, Amreli, & Jamnagar) of Surashtra, Gujarat **Survey period**: circa 2005 **Focus**: Migration induced land degradation. In dry regions water, rather than land is the limiting factor.	Survey of 1227 HH in six villages	Shah (2010)
A14	Cropland → Fallow	• **Irrigation facilities**: also a proxy for mechanization, because it is associated with intensive farming • **Lack of access to institutional credit**: larger farms have more access	**Location**: 2 sub-divisions in Burdwan district, West Bengal **Survey period**: 2005-2006	Survey of 185 farmers from 5 villages	Ghosh (2010)

		to more agricultural implements as their asset base is stronger • **Size of land holdings**: Uneconomical to use modern costly agricultural implements & machinery • **Lack of support services** through government extension agencies for providing knowledge & information on modern agriculture	**Focus**: Small & marginal farmers who have difficulties exploiting agricultural implements. Farm mechanization is related to higher productivity & incomes.		
A15	Cropland → Bareland	• **Growth of mining industry & thermal power plants**: Extension of mining areas, infrastructure & residential complexes of mining industry due to increased job availability	**Location**: Singaruli district, Madhya Pradesh **Study period**: 1978-2010	Regional/local expertise Historical literature Satellite mapping of land cover	Areendran et al. 2013; Singh et al. 1991; Singh et al. 1997; Khan and Javed (2012)
A16	Cropland → Wasteland/ Barren	• For **production of brick kilns** due to urbanization: ➢ Demands for bricks have increased rapidly, its rate stimulated by the centrifugal forces of the city & its influence in the region ➢ Higher profits than agriculture: Land owners make quick money from leasing out their land for soil quarrying ➢ Requires less labor efforts ➢ Brick kiln owners earn higher wages from: employment in brick kilns, transportation of bricks from the quarrying site to the kilns for being baked, & from kilns to the demand site (city)	**Location**: Peripheral areas of Aligarh City, North India **Survey period**: 2001-2002 **Background**: Brick making is mostly confined to rural & peri-urban areas. India is the second largest producer of bricks in the world. The Gangetic plain of North India accounts for about 65% of the total brick production due to availability of good fertile alluvial soils (Punjab, Haryana, Uttar Pradesh, Bihar, & West Bengal); Peninsular & coastal India accounts for rest 35% production (Gujarat, Orissa, Madhya Pradesh, Maharashtra & Tamil Nadu).	20 field survey in each of the 59 surrounding villages (10 village HH & 10 brick kiln workers HH) Remote sensing of land cover Secondary data from village land use records	Singh and Asgher (2005)
A17	Cropland →	• Cropland → Fallow (1980-90):	**Location**: Sadiyagad micro	Field	Rao and

	Fallow	**Restricting access to government forest** under conservation forestry **provided less manure** (lack of leaf litter) making agricultural land unproductive • Fallow → Cropland (1990-95): **Government intervention on watershed development** (through World Bank) by providing agricultural assistance (irrigation, pesticide & fertilizer) • Cropland → Fallow (1990-): **Lack of appropriate follow-up/monitoring** after the development program ended: aid driven development syndrome where capital accrues immediately after withdrawal of project	watershed, in mid-elevation zone of Central Himalaya **Study period**: 1980-1996 **Focus**: Forest policy effects on cropland	investigations Regional/local expertise Remote sensing of land cover, topographical maps combined with socioeconomic data collected from conducting series of workshops & interviews with local population	Pant (2001)
A18	Cropland → Wasteland/Barren land	• **Unsustainable land use practices**, different from traditional tribal cultivation (e.g. farming deep-rooted oil crops that caused soil erosion)	**Location**: Two villages in Attappady block, Palakkad district, Kerala **Study period**: 1930s-present **Survey period**: circa 1995 **Focus**: Land use & crop selection of aboriginals & in-migrants	Survey of 367 farm HH (6% of total farm HH) in two villages Secondary data on settlements & land use patterns	Velluva and Velluva (2006)
A19	Cropland → Barren/Waste land	• **Transforming into suburbs, residential, & commercial land uses** e.g. farm houses, godowns, mills & brick kilns especially in areas: ➢ that have good water supply & growing water levels ➢ close to urban center which gives much higher returns compared to agriculture	**Location**: Two development blocks in the metropolitan periphery of Delhi (Alipur & Najafgarh) **Study period**: 1990s **Survey period**: 1998 **Note**: See ref. 26 for similar study in Delhi based on survey of 896 farming	Interview of 300 persons based on pre-structured questionnaire	Singh and Mohan (2001)

			HH.		
A20	Cropland → Wasteland	• Single factor causation: **Advancement of mining and industrial activity**.	**Location**: Talcher-Angul region, Orissa. **Study period**: 1973-2011 **Focus**: Focused on land degradation.	Remote sensing Topographical maps Ground validation using Google imageries.	Panwar et al. 2011
A21	Cropland → Fallow/Wasteland/Shrubland	• Inadequate supply & erratic **availability of electricity**: Hindering use of modern agricultural equipment such as cold storage & food processing industries • Lack of **marketing & storage facilities** • Lack or poor quality **agriculture extension facilities** • Poor **diagnostic/medical labs** for both crops & livestock • **Unprofessional attitude of authorities**	**Location**: National scale: Comparison of Eastern & North-Eastern India (has lower diversification that rest of India) with rest of India **Survey year**: 2003 **Focus**: Improving cropland stability through agricultural diversification: enhances profits & stability of farm incomes, generates employment opportunities, alleviate poverty & improve the sustainability of agricultural systems.	Statistical analysis of farm level information from 2003 National Sample Survey, based on information collected from over 178000 HH plots	Kumar and Singh (2012); Kumar (2009)

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Table S9. Summary of studies (N=16) on reclamation of fallow land to cropland. Keywords in the third column are highlighted in bold for skimming.

Study #	LULCC	Key results	Study details	Methods	Ref
B1	Cropland stability (preventing fallow conversion)	• **Adoption of new technology** among tribal community, determined by: ➢ **Income from crops** ➢ **Credit orientation of farmers** ➢ **Attitude towards high yielding varieties** ➢ **Risk orientation** ➢ **Age of farmers**: young farmers adopt more ➢ **Size of land holding**: big farm size/less fragmentation → more adoption indicating easy orientation; small farm size → less adoption indicated by more labor workers	**Location**: Hazaribagh & Ranchi districts, Chotanagpur region of South Bihar **Study period**: 1988-89 **Focus**: Cropland productivity/stability among tribal farms	Survey of 160 tribal farm holdings	Chandra and Singh (1992)
B2	Cropland stability (preventing fallow conversion)	• Social factors: farmers **caste**, availability of **family labor**, **land ownership**, **legumes in cropping sequence** • Infrastructural factors: **Irrigation facilities**, **seed type**, optimal plant population, **labor & capital investment** & use of organic manure	**Location**: Two distinct agro-ecological zones in Eastern India (Bankura & Malda district, West Bengal) **Focus**: Focused on smallholder farmers, especially on maize yields	180 farm-level surveys in four villages	Banerjee et al. 2014
B3	Fallow → Cropland	• Availability of **private well irrigation** • **High rainfall & industrially less progressive** regions • **Expansion of irrigation facilities** • Availability to **road facilities** (market access)	**Location**: Six regions in the state of Tamil Nadu, with differing agro-ecological zones, irrigation system & farming practices **Study period**: 1960-2000	Survey of 900 farms Secondary data on district level land use statistics	Ramasamy et al. 2005; Nadkarni and Deshpande (1979)

B4	Fallow → Cropland	• **Access to weather information** (through television, newspaper, etc.)/ perceived changes in temperature • **Availability of capital**: wealthier farmers more likely to take risks • Participation in social institutions relating to **agriculture/natural resource management** : better adaptation to erratic & variable/delayed monsoon rainfall	**Location**: 7 villages in Bihar **Survey period**: Various (1990s & 2000s) **Focus**: Changes in land management practices e.g. increased cropping & irrigation.	981 HH surveys	Wood et al. 2014
B5	Fallow/Wasteland/Shrubland → Cropland	• **Level of urbanization/infrastructure**: capital investment capacity of the HH, use of new technology & knowledge, cost advantage (markets & roads) of transportation of high value crops, their quick sales, & increased demand • **Availability of capital**: ability to acquire assets & equipment's necessary to cultivate high value crops & other such allied activities • **Educational level** of HH head (exposure) • Soil quality • **Size of land holdings** • Status of land possession/**land tenure** • Equitable provision of economic security in terms of **credit supply, subsidies**, etc. to all religious & social (caste) classes. e.g. to scheduled caste/tribe farmers for more settled cultivation to augment agricultural diversification	**Location**: National scale: Comparison of Eastern & North-Eastern India (has lower diversification that rest of India) with rest of India **Survey year**: 2003 **Focus**: Improving cropland stability through agricultural diversification: enhances profits & stability of farm incomes, generates employment opportunities, alleviate poverty & improve the sustainability of agricultural systems.	Statistical analysis of farm level information from 2003 National Sample Survey, based on information collected from over 178000 HH plots	Kumar and Singh (2012); Kumar (2009)
B6	Fallow → Cropland	• **Community-based watershed management** through customary governance institutions • **Government program incentives**:	**Location**: Kuchgad micro watershed, Almora District, Central Himalayas	Discussion interviews with officials of management	Wakeel et al. 2005

		Building of roads & vegetable storage facility sustained agriculture for urban exports & access to products outside the region	**Study period**: 1967-1997 **Survey period**: 1997-2000 **Note**: See Dhyani et al. (2006) who conducted studies in Khootgad & Mohnagad watershed in Central Himalayas where fodder production expanded to uncultivated rainfed land.	institutions (e.g. forest department, *vanpanchayats*, & local inhabitants in village meeting) Regional/local expertise Interpretation of satellite data, information on legal & policy changes	
B7	Fallow/Wasteland/Barren → Cropland	• **Development interventions** by government: New structures to prevent flash flooding, sedimentation & to divert water to higher parts • **External influences**: Non-governmental organization support in watershed management programs, resource management efficiency, expansion & improvement of irrigation infrastructure, & agrarian innovations	**Location**: Upper Indus Basin of Central Ladakh (high altitude desert region), Northern India (Trans-Himalayan environment) **Study period**: 1969-2006 **Survey period**: 2007-2009 **Focus**: Change in irrigated agriculture in mountainous environment with artificial irrigation fed by melt water from glaciers & snow cover, controlled entirely by gravity. The authors present two local case studies at the village level (Stok & Indus valley) & an overview of the complete	Remote sensing of land cover Qualitative interviews with experts from both government & non-governmental organization Regional/local expertise	Nüsser et al. 2012

			Central Ladakh Basin, Leh.		
B8	Fallow/Wasteland → Cropland	• Investment in **irrigation, wells & agricultural development**: Resulted in spread of dry-season cropping & year-around monoculture due to faster rotations under irrigation	**Location**: Godwar, Rajasthan **Study period**: 1986-1999	Remote sensing of land cover; Historical data; HH production information; Discourse of planners & state experts	Robbins (2001)
B9	Fallow → Cropland	• During 1990-95: **Government intervention on watershed development** (through World Bank) by providing agricultural assistance (irrigation, pesticide & fertilizer)	**Location**: Sadiyagad micro watershed, in mid-elevation zone of Central Himalaya **Study period**: 1980-1996 **Focus**: Forest policy effects on cropland	Field investigations Regional/local expertise Remote sensing of land cover, topographical maps combined with socioeconomic data collected from conducting series of workshops & interviews with local population	Rao and Pant (2001)
B10	Barren/Waste land → Cropland	• **People's participation**: Depends on people's perceptions , priorities & involving them in decision-making process • Using traditional knowledge based agroforestry systems, with **water management** (irrigation capacity) as an integral component	**Location**: Banswara village, Chamoli district, Uttarakhand **Study period**: 1990-1995 (period of model implementation) **Focus**: Restoration of degraded community	Survey of 219 HH (>85% of HH in village)	Maikhuri et al. 1997

			lands/abandoned agricultural lands with various degrees of degradation		
B11	Fallow/Grass land/Barren/ Wasteland → Cropland	• **Soil & water conservation** through watershed development increased ground water recharge for irrigation • **Diversification** to short-term **water-efficient cash crops** from perennial (traditional) crops that boost income of farmers	**Location**: Rajasamadhiyala (Gujarat) & Shekta (Maharashtra) watershed located in semi-arid regions **Study period**: 1998-2005 **Focus**: Restoration of degraded land	Interview of 20% of farmers in each watershed selected through stratified random sampling	Wani et al. 2011
B12	Barren/Shrub land → Cropland	• **Increasing population pressure** • **Altitude & land availability for clearing**: most cropland expansion in middle zone; higher zone unfit for cultivation; no land available in lower zone • Out-migration in lower zone villages due to better access to road, educational facilities & increased willingness to buy property outside the region reduces some pressure on land, which partly compensates for increasing population pressure	**Location**: High altitude, cold desert of Lahaul-Spiti district, Himachal Pradesh **Study period**: not mentioned	300 HH surveys collected across 10 villages lying across three altitudinal zone (>4500 m; 3000-4500 m; <3000 m) Secondary data on land cover, census, & topography	Warpa and Singh (2014)
B13	Barren/Shrub land/Wastela nd → Cropland	• **Higher education** (exposure) • **Attitude** towards Jatropha/perception of risk • More **income dependency of agriculture** • **Availability of support services**: technical help from non-governmental organization & agricultural department • Higher **minimum expected income** has negative effect: with higher minimum	**Location**: North East India. The authors use Assam & Arunachal Pradesh as sample to represent altitude & topography of other states in the region **Survey period**: 2011-2012 **Focus**: Reclamation of wasteland for biofuel	144 key informant interviews in 23 villages in the two states	Choudhury and Goswami (2013)

		expected income, the possibility of getting that income goes down, which leads to non-fulfillment of the expectations of farmers, which discourages them to expand • Insignificant factors (but were expected to be important): age of HH head, primary occupation, distance to nearest market, availability of unemployed family member, shortage of labor for agriculture, non-farm employment opportunity, expected price of jatropha seed, labor cost of jatropha, access to bank credit, & extension services	production (Jatropha) **Note**: In this study, wasteland includes: land with/without scrub, land under shifting cultivation, degraded forestland. In North-East India, 46% of wasteland is in shrub, 17% in shifting cultivation, & 8% in degraded forest (scrub dominated).		
B14	Barren/Waste land → Cropland	• **Community-based watershed management** through customary governance institutions, local user groups & non-governmental organizations: ➢ improved the water table ➢ increased perenniality of water wells ➢ increased the availability of water for livestock & domestic use	**Location**: Tamil Nadu **Study period**: 1990-present **Focus**: An assessment of overall performance of watershed development programs on restoring degraded lands (non-forest wasteland)	Synthesis of published case studies	Kuppannan and Devarajulu (2009)
B15	Barren/Waste land → Cropland	• **Community-based watershed management**: ➢ improved ground water recharge & availability in both upstream & downstream villages ➢ better economic returns (more crop yields) & stable livelihood for farmers	**Location**: Rajasamadhiyala micro-watershed, Rajkot district, Gujarat **Study period**: 1995-2003 **Focus**: Impact assessment of a watershed that was created in 1983	Focused group discussion & stratified detailed HH surveys of 20% of farm HH/farmers in study site (on-site) & two villages downstream (off-site assessment)	Sreedevi et al. 2006
B16	Fallow/Wast	• **Farmers attitude**: willingness to invest	**Location**: Six villages in	Survey of 60 HH	Shiferaw et

	eland/Barren → Cropland	in maintaining current fertility levels than restoring degraded lands • **Access to new production & resource management technology** through watershed management program ➢ Better recharging of ground water ➢ Shift towards paddy & irrigated crops (vegetables) that cannot be sustained in water-scarcity • **Higher education** (exposure): ➢ More investment in soil-water conservation ➢ More access to information • Higher perceived returns to investments on land	Rangareddy district, Andhra Pradesh **Survey period**: 2001-2002 **Focus**: Restoring degraded agricultural land through natural conservation management **Context**: The six villages are semi-arid regions prone to droughts, water scarcity & soil degradation. One village is under community water shed management program, & other five adjoining villages are not.	within each village Detailed plot- & crop-wise input & output data collected from all operational holdings of surveyed HH (n=568)	al. 2006a; Shiferaw et al. 2006b

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Table S10. Summary of studies (N=42) on forest area loss. Keywords in the third column are highlighted in bold for skimming.

Study #	LULCC	Key results	Study details	Methods	Ref
C1	Forest → Shrub/Barren	• **Illegal forest encroachment** & clear felling • **Wood extraction for subsistence** by local village communities for house construction/repair, fuel wood, & manufacturing agricultural equipment's • Illegal **cattle grazing** by villagers that inhibit regeneration of forests • Conversions higher near forest edges (proximity to roads & settlements)	**Location**: Bhanupratappur forest division, Kanker district, Chhattisgarh **Study period**: 1990-2000 **Focus**: Deforestation & forest degradation	Field investigations Regional/local expertise Statistical modeling (Landsat + secondary data on explanatory factors)	Kumar et al. 2014
C2	Forest → Shrub/Barren	• **Industrial development** due to availability of large coal reserves, & construction of Gobind Ballabh Pant Sagar reservoir • **Land exploitation** for surface water, ground water, coal, building material, industrial waste disposal, quarrying for limestone, establishment of thermal power stations, cement factory, & construction of reservoirs	**Location**: Singaruli district, Madhya Pradesh **Study period**: 1978-2010 **Focus**: Deforestation & forest degradation	Regional/local expertise Historical literature Land cover/change detection using satellite imagery & GIS mapping	Areendran et al. 2013; Singh et al. 1991; Singh et al. 1997; Khan and Javed (2012)
C3	Forest → Shrub/Barr	• **Poor land management** & forest fire • **Wood extraction for subsistence**	**Location**: Dabka watershed, Kosi Basin in Lesser	Regional/local expertise	Rawat et al. 2012

	en	• **Overgrazing** • **Soil erosion** & accelerated runoff from substandard construction of roads & buildings • **Social/population pressure**	Himalayas, Nainital district **Study period**: 1990-2010 **Focus**: Oak & Pine forests	Field investigations Land cover/change detection using satellite imagery & GIS mapping	
C4	Forest → Shrub/Barren	• **Industrial development** (large-scale hydro-electric project)	**Location**: Sainj Valley, fragile mountain ecosystems of the Western Himalayas **Study period**: 2005-2010 **Focus**: Deforestation & forest degradation	Land cover/change detection using satellite imagery & GIS mapping	Jolli (2012)
C5	Forest → Barren/Wasteland	• **Over-extraction of fodder for livestock** on common land	**Location:** Three dryland, drought-prone regions (Surendranagar, Amreli, & Jamnagar) of Surashtra, Gujarat **Survey period**: circa 2005 **Focus**: Degradation on common pool resources	Survey of 1227 HH in six villages	Shah (2010)
C6	Forest → Shrub/Barren	• Timber harvesting at large scale/**unregulated management actions** • **Wood extraction for subsistence** (fuel wood) • **Shifting cultivation**, illegal encroachments (for agriculture) & unsustainable land use practices on land deforested for agriculture • **Road constructions** • **Overgrazing**	**Location**: Malkangiri district, Orissa **Study period**: 1973-2004 **Focus**: Deforestation & forest degradation	Regional/local expertise Field investigations Land cover/change detection using satellite imagery & analysis of historical maps	Pattanaik et al. 2011

		• **Social/population pressure**			
C7	Forest → Shrub/Barren	• **Wood extraction for subsistence** (fuel wood) • Livestock **grazing** & fodder • **Illegal clear felling** & timber collection for household & agricultural purposes • **Natural factors** (e.g. fire, mortality by insects, diseases)	**Location**: Eastern Ghats of Tamil Nadu **Study period**: 1990-2003 **Focus**: Deforestation & forest degradation	Satellite mapping of land cover Field investigations Interviewing local people during the investigations	Jayakumar et al. 2009 and references cited therein
C8	Forest → Shrub/Barren	• Free **cattle grazing** by large land owners, in response to emerging milk markets • **Wood extraction for subsistence** (fuel wood for cooking & heating water, sold to small-scale businesses & food stalls) • Cut-&-carry **fodder** collection • **Encroachment for agriculture** by farmers with large land holding • **Illegal felling** & lopping in reserve & village commons • **Population/social pressure** • **Weak/inefficient institutional framework** for protection & monitoring (corruption, misunderstanding, alienation, & mistrust between forest department & villagers) • **Increased dependence of poor on forest** due to low farm productivity (low technology) • Small stone mines, & small timber collection	**Location**: Protected areas of Sariska Tiger Reserve, Eastern Rajasthan **Study period**: 1980-2000 **Focus**: Deforestation & forest degradation **Focus**: A case of inefficient forest protection by Joint Forest Management, where villagers & forest department jointly manage state forests & share forest revenues.	Group surveys in 37 villages 180 HH surveys in a subset of 4 randomly sampled villages	Heltberg (2001)
C9	Forest → Shrub/Barren	• **Wood extraction for subsistence** (fuel wood mainly for water heating in high rainfall region) • **Fodder** collection for livestock	**Location**: Five protected areas of Eastern & Western Ghats of Peninsular India	Survey of 1245 HH from villages across the study sites	Davidar et al. 2010

		• Collection of green leaves for producing green manure sold to local plantation industries • **Income dependence on forests** (inversely related to proportion of agricultural households). • Proportions of wage labor households indicating more dependence on forests • **Local markets based on tourism** (e.g. tea shops that use wood for energy)	**Survey period**: Various (in 1990s & 2000s depending on the study site) **Focus**: Forest degradation		
C10	Forest → Shrub/Barren	• **Wood extraction for subsistence** (fuel wood, fodder & other products) • **Illicit felling** by local people • **Encroachment** (land clearing) of land **for agriculture**	**Location**: Pulianjolai Reserved Forests, Kolli hills of the Eastern Ghats of Tamil Nadu **Study period**: 1990-1999 **Focus**: Forest degradation	Regional/local expertise Satellite mapping	Jayakumar et al. 2002
C11	Forest → Cropland, Shrub/Barren	• Most deforestation is for **agriculture** • **Increasing population pressure** (human & animal) • **Wood extraction for subsistence** (food, fuel, fodder, manure, & non-timber forest products) • **Overgrazing** by the livestock (removes regenerating seedlings through browsing, trampling, reduces natural regeneration) • **Clear-felling for industrial wood material extraction** (1963-80) due to lack of forest policy • Government intervention for integrated land use & natural resource management (1980-95) reduced deforestation & clear felling:	**Location**: Sadiyagad micro watershed, in mid-elevation zone of Central Himalaya **Study period**: 1962-1996 **Focus**: Deforestation & forest degradation	Field investigations Regional/local expertise Satellite mapping & topographical maps combined with socioeconomic data collected from conducting series of workshops & interviews with local population	Rao and Pant (2001)

		Intervention through technology transfer & efficient agricultural services (e.g. irrigation, access to credits & local markets, subsidized agricultural inputs liker fertilizers, soil & water conservation programs, & promotion of agroforestry).			
C12	Forest → Cropland, Shrub/Barren	• **Deforestation for agriculture** in people managed forests • **Wood extraction for subsistence** in government reserved forests (lopping of broad leaved trees) • Strong **institutional framework** protected cropland expansion in reserved forests • Oak forest degradation (promotes pine forest growth) by locals in government forests, because **oak forests generate no revenue to forest department**.	**Location**: Kuchgad micro watershed, Almora District, Central Himalayas **Study period**: 1967-1997 **Survey period**: 1997-2000 **Focus**: Deforestation & forest degradation **Related Study**: See Dhyani et al. (2006) who conducted studies in Khootgad & Mohnagad watershed in Central Himalayas where fodder production expanded to community land (due to emerging milk markets).	Discussion interviews with officials of management institutions (e.g. forest department, *vanpanchayats*, & local inhabitants in village meeting) Regional/local expertise Interpretation of satellite data, information on legal & policy changes	Wakeel et al. 2005
C13	Forest → Shrub/Barren	• Demand for **non-timber forest products**: growing market demand for medicinal plants • **Population/social pressure** & increased consumption • **Weak institutional framework** • Need for cash within tribal society • Joint Forest Management & private farm forestry reduced the pressure on forests	**Location**: Madhya Pradesh state **Study period**: 1990s & early 2000s **Survey period**: 2005-2006 **Focus**: Forest degradation & forest protection in protected	Interview with 34 forest officers of different rank, policy-makers, representatives of local forest user organizations, & forest/livelihood experts from civil society & academia	Véron and, Fehr (2011)

		• Less **income dependence on forests** by locals reduced the pressure on forests	areas	Qualitative data from 4 forest-dependent villages, & 7 villages where forests was not a focus	
C14	Forest → Cropland & Plantations, Shrub/Barren	• **Unplanned in-migration** from surrounding regions: ➢ Uncontrolled deforestation ➢ **Overgrazing** by cattle ➢ **Wood extraction** (fire wood) • Emergence of plantations (e.g. rubber, tea) by in-migrants from land alienation/appropriation of tribe's land & government sponsored programs • Degradation from **shifting cultivation**, cattle grazing by tribes as their land holdings decreased • Implementation of **land reform** measures: Feudal landlords deforested private forests quickly to timber traders at throw away prices (circa 1960)	**Location**: Two villages in Attappady, Palakkad district, Kerala **Study period**: Trends applicable after 1930s to present **Survey period**: circa 1995 **Focus**: Compare & contrast the land use & crop selection patterns of aboriginals & settlers	Survey of 367 farm HH (6% sample) in two villages Secondary data on settlements & land use patterns	Velluva and Velluva (2006)
C15	Forest → Cropland, Shrubland/ Barren	• **Encroachment for agriculture** • Severe **infections** • Urbanization/**population pressure** • **Climate change** (shifts in vegetation due to low moisture)	**Location:** 11 study sites in Dehradun forest division **Study period**: 1976-1999 **Focus**: Sal forest deforestation & degradation	Regional/local expertise Satellite mapping & aerial photographs	Chauhan et al. 2003
C16	Forest → Shrubland	• **Availability of land for clearing** • **Topography & Altitude**: forests are relatively stable in complex terrains & higher altitudes (proxy of accessibility) • **Accessibility**: Proximity to roads & settlements	**Location:** Balkhila sub-watershed, Garhwal Himalayas **Study period**: 1991-2001 **Focus**: Forest degradation	Regional/local expertise Field investigations Satellite mapping & topographic sheets	Joshi and Gairola (2004)

			(Oak to Pine forests) & fragmentation		
C17	Forest → Cropland, Shrubland, Bareland	• **Promotion of** tea **plantations** by government to economically mitigate the risk of agriculture • Large-scale deforestation by **plywood industry** (prior 1996 until ban was imposed) • **Population pressure** (resident & immigrant) driven by economic & political factors • Urbanization & **industrialization** • Inability of industrial sector to combat **unemployment** that shifted pressure on forests • Natural calamities (earthquakes) lead to **proliferation of landless people**, opening up forest land for settlements • **Low level of protection & monitoring** due to civil/society unrest (insurgency), & interstate conflicts along state borders	**Location:** Upper Brahmaputra Valley, Assam **Study period**: 1947-present **Focus**: Deforestation & forest degradation	Regional/local expertise References supporting arguments	Sharma et al. 2012
C18	Forest to Cropland, Shrubland, Bareland	• Increasing **population pressure** • Increasing need for **timber** • **Wood extraction** for firewood	**Location**: Doodhganga watershed in Kashmir Himalayas **Study period**: 1991-2005	Regional/local expertise Statistical model linking satellite derived land cover maps with ground data on population & stream discharge	Showqi et al. 2014
C19	Forest → Shrubland, Bareland	• **Wood extraction for subsistence** (fuel wood, fodder & auxiliary non-timber forest products) • **High income dependence on forest** by poor people with small land holdings	**Location**: Nainital district, Kumaoan Himalayas, Uttar Pradesh **Survey period**: 1996	Survey of 233 HH based on stratified random sampling in 12 villages within the district	Reddy and Chakravarty (1999)

		• **Weak institutional framework** for common property rights/participatory resource management (involving local communities & public agencies)	**Focus**: Forest degradation; Impacts of restricting access to common property (forest products) on poverty		
C20	Forest → Cropland, Shrubland, Bareland	• **Encroachment for agriculture** • **Wood extraction for subsistence** (fuel wood, fodder, & small timber collection) • **Overgrazing** • **Accessibility** to reserve forest & forest stocks (collection time/kg; family labor inputs) • Large land owners substitute private fuels from farms (private trees) over forest fuel wood i.e. fragmentation of **land holdings** increase pressure on forests • **Poor housing construction**: economically poor people (scheduled caste/tribes) use more wood for better heating in winter • **Weak institutions** for natural resource management/forest protection	**Location**: Villages in the vicinity of Saariska Tiger Reserve, Alwar District, Rajasthan **Survey period**: 1996-1997 **Focus**: Forest degradation; How people adapt to forest degradation to meet energy requirements	Survey of 180 HH in 4 villages (25% stratified random sampling) located at varying distance from the reserve	Heltberg et al. 2000
C21	Forest → Shrub/Barren	• **Coal mining:** major force of forest degradation in the study region.	**Location**: Part of Jaintia hills district, Meghalaya **Study period**: 1975-2001 **Focus**: Forest degradation Similar study of the same region was done by Prakash & Gupta (1998).	Field work & Regional knowledge Remote sensing	Sarma (2005) Also see Prakash and Gupta (1998)
C22	Forest →	• **Population pressure:** Increased	**Location**: Six micro-	Intensive field	Tiwari

	Shrub/Barren	demand for natural resources in the region. • **Excessive grazing.**	watershed in Lesser Himalayan Ranges & Siwalik Hills, Nainital district, Kumaon. **Study period**: 1975-2005 **Focus**: General changes in land dynamics	surveys, observations, monitoring, and socioeconomic surveys. Remote sensing and topographical maps	(2008)
C23	Forest → Shrubland, Bareland	• **Intentional forest-fires** by forest dwellers: ➢ To ensure current vegetation forms on stand & at landscape level remain consistent as they produce flow of specific ecosystem services (e.g. pasture, bodha grass used for roof thatching) ➢ **Fuel-wood** for domestic requirements (becomes available when trees are fully/partially burnt) ➢ To remove grass & reduce thickness of shrubs to enable **accessibility** for fuel wood collection	**Location**: Sadhukonda reserve forest, Chittoor district, Andhra Pradesh **Survey period**: Late 2000s **Focus**: Forest degradation through forest fires, or maintaining forests at degraded levels	Interview of 557 HH in 14 villages around the reserve forest	Schmerbeck et al. 2015
C24	Forest → Shrubland, Bareland	• **Intentional forest-fires** by forest dwellers: ➢ **Fuel wood** utilization ➢ Fire driven **fodder** for livestock	**Location**: Kadava-kurichi Reserved Forest & neighboring villages, Dindigul district, Tamil Nadu **Survey period**: 1998-2000 **Focus**: Degraded dry forests	Survey of 473 HH from 19 villages that included both users & non-forest users from reserve forests	Schmerbeck (2003); Schmerbeck and Seeland (2007); Schmerbeck (2011)
C25	Forest → Shrubland, Bareland	• **Intentional forest-fires** by forest dwellers: ➢ Practice **shifting cultivation** by local tribes	**Location**: Biligiri Rangaswamy Temple Wildlife sanctuary, Karnataka	21 interviews in 5 villages with individuals knowledgeable in the	Roveta RJ (2008)

		➢ Litter fire in dry season to **prepare cultivation land** (e.g. to fertilize land, clean understory vegetation for security & mobility, control pests & diseases, improve food & fodder production) ➢ Collection of **non-timber forest products** after ban on shifting cultivation	**Survey period**: Circa 2005 **Focus**: Forest degradation **Note**: See Saigal (1990) and Semwal et al. 2003 for similar case studies on fire-driven ecosystem services in Central India (fires to produce/collect tendu leaves used in cigarettes), & North-central India (fires to produce/collect a particular flower used in liquor).	use of fire in the area	
C26	Forest → Cropland, Plantations	• **Availability of land** for clearing (aspect) • **Topography & Altitude**: forests are relatively stable in complex terrains & higher altitudes (proxy of accessibility) • **Industrialization & economic growth** • **Level of protection**	**Location:** Cauvery river basin, Karnataka **Study period**: 2001-2006	Regional/local expertise Statistical modeling of satellite land cover with explanatory factors	Lele et al. 2010
C27	Deforestation & Forest Degradation	• Due to "**scientific management**" during 1977-1989. • **Grazing cattle**'s from surrounding villages. • Hydro-electric **dam construction** • **Uncontrolled forest resource extraction** by villagers for minor forest products.	**Location**: Pench Tiger Reserve (PTR), Nagpur District, Maharashtra. **Study period**: 1977-2007 **Focus**: Effects of parks on forestry	Field investigations Remote Sensing	Mondal and Southworth (2010)
C28	Deforestation/Forest degradation	• **Selective logging** • **Clear felling for commercial plantations** (coffee, tea, and cardamom) • **Forest fire** • **Wildlife grazing** • **Illegal invasion** after clearance	**Location**: Kalakad-Mundanthurai Tiger Reserve, South Western Ghats **Study period**: 1973-2004	Detailed remote sensing analysis Regional knowledge for interpretation of change	Giriraj et al. 2008

		• **Soil erosion** from human pressure	**Focus**: Forest cover change in biodiversity rich region		
C29	Forest → Shrub/Barren	• **Flouted mining regulations**	**Location**: Part of Bokaro district, Jharkhand **Study period**: 1972-2006 **Focus**: Forest degradation	Detailed remote sensing analysis of changes in mining areas. No ground work.	Malaviya et al. 2010
C30	Forest → Shrub/Barren/Wasteland	• **Mining** • Increasing employment in mining: **Fire wood extraction** for cooking purpose • Wood for sharpening of the tools of mining.	**Location**: Bijola mining area, Rajasthan. **Study period**: 1971-1991 **Focus**: Impacts of mining on human ecosystem	Remote sensing Regional expertise	Chauhan (2010)
C31	Deforestation	• **Government policy** that encouraged agricultural production (plantations), and migration from coastal to upland regions. • Major investments in power and irrigation projects for **reservoirs and infrastructures**	**Location**: Kerala. **Study period**: Late 1950s to 2000. **Focus**: Impacts of growing population on land use patterns.	Analysis of several case studies from the region.	Wolman et al. 2001
C32	Forest → Cropland	• **Higher altitudes/favorable climatic conditions** reflecting farmer's attitude to maximize income • **Moderate slopes** where traditional terracing was feasible • Encroachment due to **weak institutional arrangements** of forest protection & lack of monitoring (especially community & protected forests) • **Income dependence of local community on forests** ensures forest	**Location**: Pranmati watershed, Uttar Pradesh, Central Himalayas **Study period**: 1963-1993 **Survey period**: 1994-1995 **Focus**: 60% agricultural expansion from community forest; 35% from protected forests; & 5% from reserved	Integration of data from existing maps, satellite mapping of land cover, participatory survey with villagers, & field measurements	Semwal et al. 2004; Sen et al. 2002

		protection (especially reserved forests)	forest. Locals generate income from reserved forests by pine resin extraction.		
C33	Forest → Cropland	• **Illegal felling** from increased level of insurgency • Force settlement of **immigrant** population from neighboring countries for political reasons	**Location**: Sontipur district, Assam **Study period**: 1994-2001 **Focus**: Deforestation in reserve forests	Regional/local expertise Ground investigations Satellite mapping of land cover	Srivastava et al. 2002
C34	Forest → Cropland	• **Availability of land for clearing**: depends on **slope, altitude & aspect** • **Population pressure**: presence of settlements & proximity to roads	**Location:** Balkhila sub-watershed, Garhwal Himalayas **Study period**: 1991-2001 **Focus**: Conversion of scrub & low-density pine forest to agriculture	Regional/local expertise Field investigations Remote sensing of land cover & topographic sheets	Joshi and Gairola (2004)
C35	Forest → Built-up, Cropland, Plantations	• Literacy (proxy) explains over 50% of deforestation in the region because literacy rate is population centric & leads to **development pressure** in neighboring forests	**Location**: Kerala state **Study period**: 1961-1988 **Focus**: Deforestation trends	Regional/local expertise Statistical modeling using panel data on district level statistics on land use & socioeconomic factors	Sivaram (2003)
C36	Forest → Built-up	• **Industrial development** of large-scale hydro-electric project	**Location**: Sainj Valley in fragile mountain ecosystems of the Western Himalayas **Study period**: 2005-2010	Regional/local expertise Satellite mapping of land cover	Jolli (2012)
C37	Mangrove Forest degradation	• **Social/population pressure** • **Agricultural reclamation** • **Wood extraction for subsistence** (fuel wood & construction materials)	**Location**: Bhitarkanika Conservation Area, Orissa (East coast of India)	Land cover/change detection using satellite imagery & GIS mapping	Ambastha et al. 2010

		• **Industrial development** (construction of jetties, roads, defense structures, missile testing site, inshore fisheries by mechanized vessels) • Lack of other alternative resources/**accessibility** to roads, waterways, & markets • **Level of protection**	**Survey period**: Circa 2006 **Focus**: Mangrove forest degradation. **Significance**: The study area has second largest mangrove forests in India.	Survey of 324 HH (10% sample) in 35 inhabited villages representing all community & economic groups	
C38	Forest → Water bodies	• Inundation from **dam construction** (Balimela dam & Upper Sileru dam)	**Location**: Malkangiri district, Orissa **Study period**: 1973-2004	Regional/local expertise Field investigations Satellite mapping of land cover & analysis of historical maps	Pattanaik et al. 2011
C39	Forest → Water bodies	• Construction of **large-scale dams** over rivers to divert water for irrigation	**Location**: 234 villages that will be submerged by Sardar Sarovar Project in Narmada valley covering Gujarat, Maharashtra, & Madhya Pradesh **Study period**: 2000s **Focus**: Study explored the potential impacts of a government dam construction project underway. The dam was opened in 2006	Survey of 5% of total HH in 6 tribal villages upstream of dam area & located at the border of Gujarat & Maharashtra Secondary data on socioeconomics	Singh and Mathur (2001)
C40	Forest → Water bodies	• Conversion to **aquaculture farms** for production of export-quality shrimps • **Increased demand for prawns**: conversion increased by setback of Thailand aquaculture industry due to	**Location**: Eight administrative units of Sundarban, the coastal zone of Bay of Bengal	Expertise on mangrove ecosystems/aquacultur e in India	Kumar (2012)

		prawn disease outbreak • **Population/social pressure**: encroachment into fragile areas • **Net relative land productivity**: differentials in returns on forest relative to other land use • **Un-accounting of ecological services**: mangroves are reported to have insignificant returns in official statistics, because only economic returns are accounted	**Study period:** 1986-2004 **Focus**: Conversion of mangrove forests to hatcheries	Statistical modeling of satellite land cover & economic data	
C41	Forest → Water bodies	• Single factor causation: **Dam construction**	**Location**: Three major river basins in the Indian Himalayas along which 292 dams are under-construction or proposed. **Study period**: 2000s **Focus**: Impacts of hydropower development on biological diversity	Remote sensing Topographical Maps Regional Expertise The study also provides future projections based on modeling.	Pandit and Grumbine (2012); Grumbine and Pandit (2013)
C42	Forest → Wasteland	• Single factor causation: **Advancement of mining and industrial activity**. • Population pressure due to employment opportunities cause **wood extraction for subsistence**.	**Location**: Talcher-Angul region, Orissa. **Study period**: 1973-2011 **Focus**: Focused on land degradation.	Remote sensing Topographical maps Ground validation using Google imageries.	Panwar et al. 2011

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Table S11. Summary of studies (N=23) on forest area gain. Keywords in the third column are highlighted in bold for skimming.

Study #	LULCC	Key results	Study details	Methods	Ref
D1	Forest protection/regrowth	• **Legitimacy of ownership** increases protection • **Degree of monitoring** (preventing illegal harvesting, over harvesting & over grazing) • **Forest/population users ratio**: very high values imply ineffective forest management; very low values implies difficulties in coordination between users; nominal ratio is ideal • **Flexibility to adapt management practices** in response to changing local social & ecological needs. State/National level plans is not the best for all cases	**Location**: Study sites spread throughout India & Nepal. Exact locations not provided. **Study period**: 1990s & 2000s	Synthesis of published local case studies at forest/community level (from International Forestry Resources & Institutions) Satellite mapping analysis at landscape level (few square km in each case study area)	Nagendra (2009)
D2	Forest protection/regrowth	• **Better institutional framework** through below points: ➢ **Clear specification of property rights** reducing distress out-migration, being a part of labor force allocation decisions. ➢ Property rights depend on levels of asset ownership (cattle, participating in common property rights). • **Dependence on common land** • Level of **education** (exposure)	**Location**: Udaipur district, Rajasthan **Survey period**: 1994 **Focus**: Reduction of deforestation & forest degradation followed by forest area gains	Survey of 32-35 randomly sampled HH each in 6 villages	Chopra and Gulati (1998)

D3	Forest protection/regrowth	• Conflicts due to **non-transparency in allocation of resources & benefits** with involved communities • **Lack of/inefficient conflict resolution mechanism** • **Weak institutional arrangements** • **Inadequate peoples participation** due to the autonomy of state forest department • **Poor collaboration** between state forest department & people • **Centralization of adaption management practices** that did not suit the changing local social & ecological needs.	**Location:** Forest tracts of Central & Central-Eastern parts of India, covering the states of Madhya Pradesh, Chhattisgarh, Jharkhand, Orissa, & West Bengal **Study period**: 1990-2000 **Focus**: An example of ineffective forest protection/regrowth through Joint Forest Management	Focused group discussions with 25 Joint Forest Management committees Survey of 10% stratified HH with predominately agriculture-based livelihood with forest-based earning & wage incomes from non-timber forest products	Bhattacharya et al. 2010; Rishi (2007)
D4	Afforestation of degraded forest	• **Compensatory afforestation** by government for forest lost due to dam construction • Afforestation by replanting of uprooted trees, or sub-standardized plantations (lack the originality & gene pool of originally deforested forest)	**Location**: 234 villages that will be submerged by Sardar Sarovar Project in Narmada valley covering Gujarat, Maharashtra, & Madhya Pradesh **Study period**: 2000s **Focus**: Study explored the potential impacts of a government dam construction project underway. The dam was opened in 2006	Survey of 5% of total HH in 6 tribal villages upstream of dam area & located at the border of Gujarat & Maharashtra Secondary data on socioeconomics	Singh and Mathur (2001)
D5	Forest protection/regrowth	• **Empowering people** to involve in Joint Forest Management • **Institution building** at the community level • **Voluntary people participation**, depends on:	**Location:** Haryana, Uttar Pradesh, & Bihar **Survey period**: 1995-1996 **Focus**: Cases of successful joint	Survey of 13 HH in each of the 10 villages, in three states with different institutional setting	Lise (2000)

		➢ Social: Attitude towards & benefit from village meetings ➢ Economic: dependence on forest, forest quality • Peoples participation increases with **education** (exposure), & **women involvement**	forest management. Locals depend on forest for subsistence, hence their cooperation with state government is essential to forest management		
D6	Grassland/ Shrubland → Forest	• Passive force: **Natural regeneration** following land abandonment • Active forces: **Conscious community effort** to restore forests due to religious & cultural practices (e.g. nature worship) • **Formalization of land boundarie**s: Transition from shifting cultivation to settled agriculture • **Social awareness** of forest loss & importance of natural resource management	**Location**: Anthropogenic tropical forest-agricultural landscapes in two forest groves sites in Kodagu district of Western Ghats **Study period**: This study focus on century scale trends **Focus**: Reforestation in forest groves (grass-dominated open landscapes to forests). Groves are small fragments of tropical forests that have received community protection , whereas in buffer zones of groves, forest decreases from land-use change	Field investigations Ecological surveys & historical literature	Bhagwat et al. 2014
D7	Grassland/ Fallow → Shrubland → Forest	• **Localized succession** & **disturbance dynamics**: such forests are being dominated by invasive species that can mature within 8-10 years	**Location**: Godwar, Rajasthan **Study period**: 1986-1999	Remote sensing of land cover; Historical data; HH production information; Discourse of planners & state experts	Robbins (2001)
D8	Forest protection/r egrowth	• **Perception of environment favors** peoples participation • **Quality of forest** • **Personal benefits from forest** • Importance & personal **benefit from meetings**	**Location**: Paschim Medinipur district, West Bengal **Survey period**: 2011 **Focus:** Factors that affect	Survey of 150 HH belonging to 31 forest protection committees using stratified random sampling	Jana et al. 2014

		• Size of HH & land holdings (**income dependency on forests** & labor availability) • **Adequate institutional checks** & balances	participation in Joint Forest Management. Study region is a backward district with 34% of population below poverty line.		
D9	Forest protection/regrowth	• **Women's involvement** improves forest protection/management because: ➢ They are more dependent on forests for income (greater family income, who otherwise would be unemployed) ➢ More sensitive to the economically sustainable goals under participatory forestry	**Location**: Bankura district, Bengal **Survey period**: 2005-2006 **Focus**: Example of the role of female forest protection committee on forest conservation projects	Survey of 431 HH in 8 villages both involved & not involved in Joint Forest Management	Das (2011)
D10	Forest expansion	• **Warming climate** causes an upslope shifting of existing forest species	**Location**: Dabka watershed, Kosi Basin in Lesser Himalayas, Nainital district, Uttarakhand **Study period**: 1990-2010 **Focus**: Expansion of mixed forests	Regional/local expertise Field investigations Satellite mapping of land cover	Rawat et al. 2012
D11	Forest protection/regrowth	• **Cessation of commercial logging** by park management caused forest regrowth • **Reduction in the intensity of land use** (in tea estates) • Forest stability in complex **topography & low population** areas • **Deforestation** towards less- or unprotected peripheral areas due to **illegal timber & furniture markets** by transportation networks (road & rail)	**Location**: Landscape surrounding the Mahananda Wildlife Sanctuary in Northern part of West Bengal **Study period**: 1990-2000	Regional/local expertise Discussions with local forest officials Satellite mapping of land cover	Nagendra et al. 2009

D12	Forest protection/r egrowth	• Declared as **protected area**. • **National-level conservation policy** in 1998 that banned felling of forests in national parks.	**Location**: Pench Tiger Reserve (PTR), Nagpur District, Maharashtra. **Study period**: 1977-2007 **Focus**: Effects of parks on forestry	Field investigations Remote Sensing & GIS	Mondal and Southwor th (2010)
D13	Forest Regrowth (Wasteland → Forests)	• **Promotion of secondary & tertiary sectors of economic activities** in the region, rather than focusing on traditional primary resource development practices. • Effective implementation of **Joint Forest Management** (JFM). • Creation of **village level participatory institutions** for management of village forests. • **Joint Restoration efforts** by forest department and NGOs in collaboration with local community.	**Location**: Six micro-watershed in Lesser Himalayan Ranges & Siwalik Hills, Nainital district, Kumaon. **Study period**: 1975-2005 **Focus**: General changes in land dynamics	Intensive field surveys, observations, monitoring, and socioeconomic surveys. Remote sensing and topographical maps	Tiwari (2008)
D14	Forest protection/r egrowth	• **Involvement of women and young people** – they support forest conservation. • **Attitude**: **Dependence on forest products** reduces their willingness to support state forest department with conserving forests. • Forest conservation was **independent of wealth**. All people depended on forests.	**Location**: Kalakad–Mundanthurai Tiger Reserve, Southern Western Ghats, India. **Study period**: Circa 2000 **Focus**: Attitudinal evaluation of conservation of the local villagers after implementation of a World Bank funded eco-development project.	Twelve villages located within 3 km from the reserve boundary 2–3% of the total households surveyed totaling to 677 surveys	Arjunan et al. 2006
D15	Forest protection/r egrowth	• **Collaboration of village community with government forest agencies** (Joint forestry management) with nested	**Location**: Study of three villages in the Aravalli Hills, South Haryana.	Perspective article by regional expert from the Forest department, Government of India.	Kumar (2013) Also see Bhattach

		levels of authority is crucial to forest conservation. • Ethnic homogeneity, small to medium size, autonomy in decision-making and high dependence on forests is not always the main factors to forest conservation. • Attention to both short-term and long-term interests makes forest conservation more resilient.	**Study period**: Not mentioned (roughly 2000s) **Focus**: Contrasting three villages that have full title over the common lands and forest, and have taken three radically different alternatives to conserve them.		arya et al. 2010; Dilip Kumar (2015); Prasad and Kant (2003)
D16	Forest protection/r egrowth	• **Lack of interest by villagers**: Due to low productivity, long gestation, uncertain incentives, lack of foreseeing long-term benefit. • **Improving institutional conditions of forestry workers** is important for efficient JFM.	**Location**: Tamil Nadu, South India. **Study period**: 1997+ **Focus**: Assessment of forester's perspective on infectiveness in implementing Joint Forest Management (JFM).	Interview with 28 forest officers of varying rank s from 5 forest divisions with largest number of JFM villages and history of implementing them.	Matta et al. 2005
D17	Forest protection/r egrowth	• **Attitude towards conservation**: Depends on exposure, village-type, resident's occupation, caste, source of fuel for cooking, and educational qualifications, and size of land holdings. • Clearly **defining land ownership and rights on forest products** improves villager's participation to forest conservation. • **Regular monitoring** (self) of the impact of right-holders on forests.	**Location**: Sontipur and Golaghat district, Assam, North-East India **Survey period**: 2010 **Focus**: Attitudinal analysis of forest dwellers and encroachers.	Survey of 190 households in four village forests (~10%) and two encroached villages. Combined with secondary data on geographical location and demographic pattern	Mahanta and Das (2013)
D18	Forest protection/r egrowth	**Suggested solutions**: • **Granting forest rights** to rural people, combined with government/external interventions • **Extension of technical facilities**	**Location:** Ranibundh forest range, Bankura district, West Bengal. **Study period:** 2000s	Survey of 50% of inhabitants in each of seven chosen villages within the study area.	Datta and Sarkar (2012)

		• **Alternative rural employment** prospects **Causes of failure until now based on which above solutions were suggested**: • Predominance of private agencies in marketing of non-timber forest productions • Risk of eviction • Loss of customary rights to access forest resources • Low employment prospects • Lack of training about proper management of non-timber forest	**Focus:** Examined the causes of failure to conserve forests by local community despite their income dependence on non-timber forest products		
D19	Forest protection/regrowth	• **Low levels of village participation** • Increased risk of poaching and regional conflicts – due to trading loss of linkages with outside agencies and neighboring villages in favor of close linkage to forest department. • **Politicizing the administration** of forest resource – creates inequality in forest rights among various economic sections of the community.	**Location:** Gadabanikilo village, Ranpur block, Nayagarh district, Orissa. The study block is an unit for the implementation of development activities by government. **Survey period:** 2005 **Focus:** Examines the negative impacts of shift from self-organized community management to joint forestry management (pre- and post-2002).	Extensive knowledge of the village. Examination of government written records. 23 semi-structured interviews at community, NGO, forest federation, and forest department levels. 9 focus group discussions at the community level.	Nayak and Berkes (2008)
D20	Forest protection/regrowth	• **Lack of motivation of villagers** to protect despite timber benefit sharing mechanism because: ➢ **Incentive sharing was not performance-based** ➢ **Limited information** provision	**Location:** West Chhindwara Forest Division, Madhya Pradesh **Survey period:** 2010-11	Interviews with forest officers of varying ranks from five JFM committees (of 321 JFMs).	Ota et al. 2013

		mechanism - forest officers were the way to motivate people. ➢ **Exclusion of committee members from monitoring** of harvested timber (related to forest officers perception and attitudes).	**Focus:** Institutional design of timber benefit sharing mechanism under Joint Forest Management (JFM) and its effectiveness as incentive to forest protection	40 randomly selected household interviews in each of the 5 committees Secondary information e.g. working plan of forest division, micro-plans of management committees.	
D21	Forest protection/regrowth	• **Women participation in JFM enhances forest protection.** Can be achieved through: ➢ Policies that empower women to establish their own management unit ➢ Involving them in policy planning and implementation • **Dependence on forest resources** (physical or monetary or both) enhances involvement in JFM	**Location:** Bankura district, West Bengal. **Survey period:** 2005-06. **Focus:** Crucial role of women participation in Joint Forest Management (JFM).	431 household surveys from eight villages with and without JFM. The sampled villages consisted of three forest divisions of the district.	Das (2011)
D22	Forest protection/regrowth	• Lack of clear **proprietary rights** • Lack of appropriate **conflict resolution** mechanism • Increasing autonomy by revenue and forest department: **Lack of space for people's involvement** • **Poor support system** • **Centralization of working plans** and siviculture decisions does not suit local conditions.	**Location:** Two Van Panchayats in Nainital and Almora district, Uttaranchal. Two forest protection committee's from Midnapore district, West Bengal. **Survey period:** Circa 2000 **Focus:** On the declining effectiveness of institutions in protecting forests.	Discussion with committee members (subset of 35 members) and villagers (~150 randomly sampled households in total).	Ballabh et al. 2002
D23	Forest protection/regrowth	• Lack of appropriate policy to improve the **economic situation of forest fringe dwellers** and to reduce unsustainable	**Location:** Three south-western districts (Purulia, Bankura, and West Midnapore) of West	Combination of primary and secondary data.	Ghosal (2014)

		extraction. • **Ineffectiveness of Joint Forest management** (framed at national level) to work at micro-level. • **Lack of monitoring** at ground-level. • **Lack of involving women** in forest management committees due to social taboos (tribal region). Women have more knowledge of the forest surrounding as they are the prime collectors of non-forestry timber products.	Bengal. **Survey period:** 2008-09 **Focus:** Effect of policies that promote systematic and sustainable harvesting of non-timber forest products on forest conservation.	Primary data included fieldwork in 11 villages (sample size not mentioned as only qualitative discussion was provided). Includes interview with forest officers, and villagers. Secondary data included government reports, newspaper reports, research reports, and journal articles.	

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Table S12. Hypothesized socioeconomic and biophysical factors (or their proxies) included in our analysis. The "Reference" column corresponds to individual case studies in our synthesis (see "Study #" in Tables S8-S11) based on which we grounded our hypothesis. See Table S15 for more detailed description of the variables that appears in the figures (showing standardized regression coefficients) presented in the results section.

Broad clusters	Explanatory factor	Rationale	Reference
Farm Characteristics	Average farm size	Evidence suggests two contrasting effects: Larger farm size is positively related to fallow land as credits, labor, and water become limiting factors to expansion. Small farm size is positively related to fallow land because of low productivity (uneconomical to mechanize). There exist contrasting evidence to show both positive and negative relation between farm size and forest encroachment, when productivity of farms are low.	A2, A3, A6, A7, A8, A9, A11, A12, A14; B1, B5; C1, C6, C7, C8, C10, C11, C12, C14, C15, C19, C20; D8, D17
	Land Tenancy (Percent of leased-in area)	Higher land tenancy is expected to be negatively associated with fallow land, because it increases land access and provides stable livelihood to the poor.	A3, A13; B2, B5; C14
Demographic factors	Total human population density	Higher population pressure is expected to be negatively associated with fallow land due to increased land requirements. Higher population pressure is expected to be positively associated with forest loss due to increased demand for natural resources.	A12; B12; C3, C6, C8, C11, C13, C14, C15, C17, C18, C22, C28, C33, C34, C37, C40, C42; D11
	Average number of heads per household (urban + rural)	Higher family size is expected to be positively associated with forest loss as it increases family labor availability to collect forest produce (e.g. fodder) even from distant locations. Forest loss/degradation would occur only if the forest harvest exceeds the sustainable yield.	C20; D8
	Urban population density	Evidence suggests two contrasting effects:	A16, A19;

	Proportion of urban population	Higher urban pressure is expected to be positively related to fallow land as it can bring new income opportunities, some of which can degrade land over time (e.g. brick kilns). Higher urban pressure is expected to be negatively related to fallow land as it increases farmer's exposure to new technology and knowledge, cost advantage of transportation, adoption of high-yielding varieties, their quick sales and demand. Higher urban pressure is expected to be positively related to forest loss due to increased demand for forest products (e.g. furniture's).	B5; C2, C15, C17, C34
	Female population density Proportion of female population	Evidence suggests that male out-migration (for better income jobs than agriculture) will lead to higher fallow land, because out-migration of males increase the workload of females resulting in less efficient land management due to multi-tasking (on/off field activities) and lack of confidence and opportunity for long outdoor activities. Nonetheless, their participation and contribution to resource conservation has always been predominant throughout the country. Overall, we expect higher proportion of female population to be positively related to fallow land. Higher proportion of female population is expected to be negatively related to forest loss because they are more dependent on forest for income (i.e. it generates greater family income, who otherwise would be unemployed). Dependency of forests generally makes them more sensitive to forest protection.	A9, A11; D5, D9, D14, D21, D23
Labor force	Working population density Proportion of employed population Marginal workers density Proportion of marginal workers	Higher proportion of unemployed population (1 minus proportion of working population) is expected to be positively related to forest loss because it increases the economic dependence on forests and also increased availability/affordability of alternate energy sources including cooking fuel. Higher proportion of marginal workers (<6 months/yr employed) is expected to be positively related to forest loss because they typically depend more on forests for income.	C9, C10, C14, C17, C42; D6, D8, D18

	Total cultivators density Marginal cultivators density Proportion of marginal cultivators Total agricultural laborers density Marginal agricultural laborers density Proportion of marginal agricultural laborers Female cultivators density Proportion of female cultivators Female marginal agricultural laborers density Male marginal cultivators density Proportion of male marginal cultivators Male main agricultural laborers density Proportion of main female cultivators Proportion of main male agricultural laborers Proportion of marginal female agricultural laborers	A cultivator is a person (family worker/single worker/employer) involved in cultivation of land owned or held from government or held from private persons or institutions for payment in money, kind or share of crop. A person who worked in another person's land for wages in cash, kind or share is an agricultural/wage laborer. We expect lower cultivators per unit farm area to be positively associated with fallow land due to family labor shortage (typically due to migration of males to urban areas for off-farm jobs due to risk aversion attitude of farmers). Family labor shortage also provides less incentive to invest in soil-water management, furthering degradation. We expect lower wage laborers per unit farm area to be positively associated with fallow land because labor shortage tends to increase wage rates which increase the cost of cultivation keeping land fallow. We accounted for imperfect labor markets by including gender-wise variables. We also broadly accounted for income differences by splitting the variables as main and marginal workers. Marginal workers are those who had not worked for the major part of the reference period (i.e. less than 6 months). We expected higher proportion of marginal workers and wage laborers will increase the pressure on forests, due to higher economic dependence on forests.	A1, A2, A6, A7, A8, A9, A10, A11, A13; B2, B12
	Density of community workers	Community workers include presence of governmental or non-governmental organization (NGO) that typically provides technical assistance and incentives (e.g. fertilizers) to agriculture. They also help with forest restoration efforts in collaboration with forest department and local communities, among others. We expect higher density of community workers to be negatively associated with fallow land and forest loss, and positively associated with forest gain.	A17; B6, B7, B9, B13, B14; D15, D18

<table>
<tr><td rowspan="3"></td><td>Density of forestry workers</td><td>Forestry workers are people employed by forest department either on contract-basis or full-time employment. They are mainly involved in maintenance of forest, roads, wild life protection/census, wildlife watch, fire observation, manning of forest watch towers, interface with tourism, and extraction of grasses for army or other national use.

We expect forestry workers to be negatively associated with forest area loss and positively to forest area gain as they are a proxy for level of protection.</td><td>D13</td></tr>
<tr><td>Industrial & Construction workers density</td><td>We expect industrial and construction workers density to be positively associated to forest loss due to two reasons. First, the variable is a proxy for the intensity of forest conversion to built-up areas. Second, the worker density is also a proxy for the pressure exerted on forests due to their dependence on forest for domestic purposes.</td><td>C2, C4, C11, C17, C26, C27, C31, C36, C37, C38, C39, C41, C42; D3</td></tr>
<tr><td>Mining/Quarrying worker density</td><td>We expect mining and quarrying worker density to be positively associated with forest loss due to direct forest conversions for the mining/quarrying activity and indirectly due to dependence of the worker community on forests for domestic purposes.</td><td>A15, A16, A20; B3; C2, C8, C21, C29, C30, C42</td></tr>
<tr><td rowspan="5">Level of Education</td><td>Illiterate population density</td><td rowspan="6">Evidence suggests two contrasting effects:

Higher education level and exposure is negatively associated with fallow land because farmers make better investment decision, better adapt to new technology, and soil-water conservation.

Higher education level and exposure is positively associated with fallow land because the literates tend to prefer off-farm jobs that provide higher and more stable income. The off-farm job typically is through urban migration (in which case causes family labor shortage converting land fallow) or by converting the farm land for other high-income purposes (e.g. brick kilns to serve near-by markets).

With higher education levels farmers also perceive higher returns to investment on land. The effect of this perception on fallow land is unclear because. With higher perceived returns famers tend to use</td><td rowspan="5">A6, A11; B1, B4, B5, B10, B13, B16; C35; D2, D5, D8, D9, D14, D16, D17, D18</td></tr>
<tr><td>Proportion of literate population</td></tr>
<tr><td>Female literate population density</td></tr>
<tr><td>Proportion of female population that is literate</td></tr>
<tr><td>Number of educational facilities</td></tr>
<tr><td>Exposure</td><td>Access to information</td><td>A9, A10, A11; B1, B4, B5, B10, B12, B13, B16; D2, D5, D6, D8, D9, D14, D16, D17, D18, D20</td></tr>
</table>

		the land more effectively reducing fallow land. Concurrently, higher perceived returns tend to reduce their chances of meeting the expected returns that can lead to abandoning the land for better income opportunities. Higher education level and exposure is expected to be negatively associated with forest loss (or positively to forest gain) because the population is more aware of the long-term benefits of forest protection. Some studies have contrastingly suggested that higher literacy rates increase the pressure on neighboring forests to meet development needs furthering forest loss.	
Irrigation Infrastructure	Proportion of cropland irrigated Proportion of area irrigated by government canal Proportion of area irrigated by private canal Proportion of area irrigated by well without electricity Proportion of area irrigated by well with electricity Proportion of area irrigated by tube well without electricity Proportion of area irrigated by tube well with electricity Proportion of area irrigated by tanks Proportion of area irrigated by rivers Proportion of area irrigated by lakes Proportion of crop area irrigated by other means Availability of well irrigation with electricity Availability of tube well	We expect extension of irrigation facility to be negatively associated with fallow land in small farms. In Agro-Ecological Zones with large farms with low productivity, we expect irrigation extension to increase fallow land as it typically leads to directing more concentrated efforts on the irrigated area at the expense of other areas (in large). Along the same lines, some studies have also suggested that improvement (shift) in irrigation facility (from less stable to more stable and reliable irrigation source) also can increase fallow land due to concentrated efforts in small areas. We expect extension of irrigation facility to be negatively associated with forest loss, as it reduces the economic dependence of farmers on neighboring forests. At the same time, extension of irrigation infrastructure (e.g. dam construction) often leads to inundation of forest areas that can lead to forest loss. In such cases, we also tested for a cascading effect where government does compensatory afforestation (forest gain) by planting the uprooted trees or forest plantations in neighboring regions.	A1, A2, A3, A4, A5, A6, A9, A13, A14, A17; B2, B3, B5, B6, B7, B8, B9, B10, B11, B14, B15, B16; C8, C11, C12, C20, C38, C39, C41; D3

	irrigation with electricity		
	Availability of irrigation facility		
	Availability of well irrigation without electricity		
	Availability of tube well irrigation without electricity		
	Availability of tank irrigation		
Infrastructure (Electricity)	Availability of power supply for domestic purpose	We expect provision of electricity supply for domestic purpose to be negatively associated with forest loss as it will reduce the dependence on forest for firewood and building materials (especially during cold seasons).	C1, C6, C7, C8, C9, C10, C11, C12, C14, C18, C20, C23, C30, C37
	Availability of power supply for agriculture	We expect provision of electricity supply for domestic purpose to be negatively associated with fallow land as it allows use of modern equipment's for agriculture. The reliability (erratic) of power source is also an important factor that we do not account for due to lack of data.	A21
Poverty Indicators	Average income per capita	We expect lower income per capita to increase fallow land as it reduces the ability to invest in land owing to capital-intensive nature for adoption modern outputs (acquire assets and equipment's), and to cope with agricultural crisis. We included scheduled caste and scheduled tribe populations as they are economically weaker sections of the community. Evidence suggests two contrasting effects: Lower per capita income are positively associated with forest loss as they are dependent on forest for livelihood and subsistence (when extraction exceeds sustainable yields), conditional of lack of other alternatives for livelihood. Lower per capita income is negatively associated with forest loss for two reasons. First, they tend to protect forests because forests are important for their livelihood (attitude). Tribal population (proxy for	A2, A4, A6, A8, A9, A11; B1, B2, B4, B5; C1, C3, C6, C7, C8, C9, C10, C12, C13, C14, C18, C19, C20, C23, C24, C25, C32, C37
	Tribal population density		A9, A11, A12, A18; B1, B2, B5; C14, C20, C23, C4, C24, C25, C32, C37; D17
	Backward caste population (scheduled caste + tribe) density		
	Proportion of tribal population		
	Proportion of backward caste population		

		low income groups) is culturally linked to forests and they are typically motivated by state forest department to jointly manage forest through protection, restoration of degraded forest, and enrichment plantations.	
Accessibility (Navigation & Irrigation source)	Availability of market facility in the village/ Market functioning frequency Distance to nearest town Availability of communication facility (e.g. bus, train) Approach to pucca road Approach to kachcha road Approach to foot path Approach to river Approach to canal Approach to waterways	Evidence suggests two contrasting effects: (rural infrastructure) Improved accessibility is negatively associated with fallow land as it improves the capital investment capacity of the household, exposure to use of new technology and knowledge, provides cost advantage of transportation of high value crops, their quick sales, and increased demand. Improved accessibility is positively associated with fallow land as it creases rural employment diversification due to new income opportunities (e.g. brick production, dairy industry) that can lead to conversion of cropland to fallow land among others. Based on case-study evidence, we expect improved connectivity to be positively associated with forest loss due to increasing demand for forest products, and ease of illegal timber logging and transport.	A8, A9, A10, A15, A16, A19, A21; B3, B5, B6, B12; C1, C6, C9, C15, C16, C34, C37, C40; D11
Critical support services	Number of agricultural credit societies/institutions Distance to nearest agricultural credit society/institution	Overall, we expect access to agricultural credit society to be negatively associated with fallow land as it drives the capital availability to invest in farming. However, the access to capital depends on asset base of the farmer, so may not benefit all farmers equally.	A2, A11, A14, A17, A21; B1, B5; C8;
	Number of veterinary medical facilities	We expect access to veterinary medical facilities to be negatively associated with fallow land as it reduces oxen/livestock mortality rate, an key component of non-mechanized agriculture in India.	A8, A11, A21
Income dependency: Binary variables coded to indicate primary	Building/mining Materials	We expect extraction of building (e.g. mud for bricks) and mining (e.g. coal) materials will be positively associated to forest loss and fallow land due to direct land conversions to conduct the activity.	A15, A19, A20; C2, C17, C21, C29, C30, C42
	Dairy/cattle/leather Wool/Woolen Blankets Poultry	We expect that livestock-based activities will be positively associated with forest loss due to increased chances of overgrazing and fodder collection.	C8, C12

occupations of each village.	Coffee Production	We tested if villages dependent on specific plantations are prone to forest loss due to legal land conversions or illegal land encroachments.	C28, C31
	Tea production		C14, C17, C28
	Coconut Production		C31
	Rubber production		C14
	Forestry-related Products	We tested if villages dependent on forestry products for primary income are prone to forest loss due to over-extraction above sustainable yields. Forestry products includes but not limited to extraction of tendu leafs, making agarbathis/incense sticks, baskets match sticks, brooms, beedi/cigarettes, paper products, and gutka.	C7, C9, C10, C11, C13, C19, C23, C25, C27, C28
	Making of Wooden Furniture's/timber	We expect a positive association between wood furniture/timber making villages and forest loss.	C6, C17, C18
	Manufacturing of wooden agricultural implements	We expect a positive association between villages making wooden agricultural implements and forest loss.	C1
	Prawn harvesting	We tested if forest loss is positively associated to prawn harvesting, specifically due to conversion of mangrove forests to aquaculture farms.	C40
	80+ other binary-coded variables to capture the other common primary occupations in India relevant to the three land-cover conversions investigated in this analysis.	Example: We included several crops (including Arecanut, Cotton, Rice, Wheat, Sugarcane, Bajra, Jowar, Pulse, Maize, Pigeon Peas, and Groundnut) to test if any crop-specific village occupation is prone to more forest encroachment.	-
Climate	Average seasonal temperature; Four variables: $T_{winter\ (avg)}$, $T_{pre-monsoon\ (avg)}$, $T_{sw\ monsoon\ (avg)}$, $T_{post-monsoon\ (avg)}$.	See Table S14 for an explanation of these variables. Both temperature and rainfall are important factors influencing crop cover. Therefore, we tested for key seasonal variables to account for the impacts of climate change and variability on cropland conversion (to and from fallow land). We use squared variables to test for nonlinear effects of climate on cropland conversions. As we estimated LULCC from decadal Landsat imageries, they capture only the decadal changes in LULCC, and can mask within-decade variations in LULCC. Especially, inter-annual climate	A2, A4; B3
	Average seasonal precipitation; Four variables: $P_{winter\ (avg)}$, $P_{pre-monsoon\ (avg)}$, $P_{sw\ monsoon\ (avg)}$, $P_{post-monsoon\ (avg)}$.		
	Squared average seasonal temperature; Four variables: $T^2_{winter\ (avg)}$, $T^2_{pre-monsoon\ (avg)}$, T^2_{sw}		

	$_{\text{monsoon (avg)}}$, $T^2_{\text{post-monsoon (avg)}}$	variability causes fluctuations in fallow land. However, the conversions between cropland and fallow inferred between decadal end points will reflect only the climate-effect of end point. Therefore, we used 1994-1995 climate data to study cropland ↔ fallow conversions during 1985-1995 decade, and 2004-2005 climate data to study cropland ↔ fallow conversions during 1995-2005 decade.	
	Squared average seasonal precipitation; Four variables: $P^2_{\text{winter (avg)}}$, $P^2_{\text{pre-monsoon (avg)}}$, $P^2_{\text{sw monsoon (avg)}}$, $P^2_{\text{post-monsoon (avg)}}$		
	Variation in average seasonal precipitation relative to long-term normal; Four variables: $P_{\text{winter (rel. to normal)}}$, $P_{\text{pre-monsoon (rel. to normal)}}$, $P_{\text{sw monsoon (rel. to normal)}}$, $P_{\text{post-monsoon (rel. to normal)}}$		A2, A4, A7, A8, A9
	Standard deviation in daily seasonal precipitation; Four variables: $P_{\text{winter (std)}}$, $P_{\text{pre-monsoon (std)}}$, $P_{\text{sw monsoon (std)}}$, $P_{\text{post-monsoon (std)}}$		A2, A4, A7, A8, A9
	Annual Mean Temperature	We used key static bioclimatic variables to test for the effects of passive forces (e.g. climate-driven shifts in natural vegetation) on forest area change. We also hypothesized that colder and wetter regions (especially those with low village infrastructure) will be positively associated with forest loss due to increased dependence on forests for fuel wood and building materials.	C3, C7, C9, C14, C15, C18, C19, C20, C23, C24, C32, C37; D7, D10
	Mean Temperature of Wettest Quarter		
	Mean Temperature of Warmest Quarter		
	Mean Temperature of Coldest Quarter		
	Max Temperature of Warmest Month		
	Min Temperature of Coldest Month		
	Annual Precipitation		
	Precipitation of Wettest Quarter		
	Precipitation of Coldest Quarter		
	Precipitation of Driest Quarter		
	Precipitation of Warmest Quarter		
Edaphic Condition	Cation Exchange Capacity (proxy for soil fertility)	These factors determine the soil quality and extent of various forms of soil degradation, both crucial in determining crop and forest	A9, A12; B5, B11, B16; C3,

	Soil erosion Soil depth Soil salinity Slope Soil flooding	productivity. We expect increased level of soil degradation to be positively related to fallow land and forest area loss. The degradation may result from both natural and anthropogenic factors (e.g. sub-standardized construction of roads, overuse of fertilizers).	C8, C14, C15, C20, C23, C28, C32, C34; D7
Elevation	Terrain	We expect positive association between topography and fallow land because cropland management is expected to be more suited to flat terrain or in areas with gentle slopes, also conducive to the construction of houses and infrastructure. We expect negative association between topography and forest loss because rougher terrains are more difficult to access.	B12; C16, C26, C31, C32, C34; D7, D11
Political boundaries	State dummies/State-fixed effects	See detailed explanation provided in Text S1 (sub-section titled "Rationale for inclusion of state-fixed effects").	A8; C6, C8, C11, C12, C13, C17, C19, C20, C31, C33; D1, D2, D3, D5, D6, D8, D13, D15, D16, D17, D18, D19, D20, D22, D23
Other variables	Protected areas	We expect negative association between protected areas and forest loss (and positively associated with forest gain). Protected areas however render no information of the level of protection. We included "density of forestry workers" as a variable proxy for the level of protection and control.	C1, C6, C8, C9, C10, C11, C12, C13, C17, C20, C23, C24, C25, C26, C27, C28, C32, C37, C40; D1, D11, D12
	Mined-out areas	We expect positive association between mined-out areas and forest area gain due to compensatory afforestation efforts by government	

		on mined-out areas to compensate for the forest loss. We expected a weak association because case studies suggest that the forest plantations do not survive over time in many cases, due to high levels of soil degradation caused from mining.	
	Sacred groves	We expect positive association between sacred forest groves and forest area gain as the forests are typically protected by local community due to cultural and religious beliefs (however, not in all cases).	D6
	Cattle density	We expect positive association between cattle density and forest loss because cattle's increases the animal pressure on forest from grazing. Due to data limitations, a static map (circa 2006) was used for land-conversion analysis during both decades. This is a minor concession as we are interested in the spatial variations of independent variables in our spatial regression model, rather than their absolute magnitude (note that we standardized all explanatory variables using *z*-score prior to running the regressions).	C1, C3, C5, C6, C7, C8, C9, C10, C11, C14, C19, C20, C22, C24, C25, C27

Table S13. Summary of various input datasets used in this study. Geographic Information System abbreviated as GIS. All are national database, and brought to 1km x 1km resolution for this analysis.

Data Code	Data	Spatial Resolution	Temporal Resolution/Coverage	Remarks
Survey (Tabular data)				
1	Over 200 socioeconomic variables from 'primary census abstract' and 'village directory'	Village level (~630,000 units)	Two census years (1991, 2001)	Tabular data: http://censusindia.gov.in/ This study ties the tabular data to village-level administrative boundaries.
Remote Sensing (all data included ground surveys for interpretation and validation)				
2	Land cover (Landsat MSS/TM)	30m (1:50k scale)	1985, 1995, 2005	Roy et al. 2015a
3	Sacred groves	23.5m (1:50k scale)	Circa 2005	Roy et al. 2015b; Satellite data interpreted using field maps from each state of India. Sacred groves typically are preserved over many decades.
4	Soil	Resampled to 1km in GIS (1:250k scale)	Static (1980-2001)	National Bureau of Soil Survey and Land Use Planning, India (NBSS&LUP 2002)
5	Mined-out areas	30m (1:50k scale)	1985, 1995, 2005	Roy et al. 2015, a; Variable culled from Level III classification.
6	Terrain	30m	Circa 2000	SRTM (http://glcf.umd.edu/data/srtm/); Gap filled using 10m CARTOSAT data sampled to 90m (Muralikrishnan et al. 2013).
7	Protected areas	Resampled to 1km (1:50k scale)	Two periods (1990s and 2000s)	Combination of data from natural features, GPS points, and inputs from states of India (WII 2012).
Climate data (Gridded from observations)				
8	Rainfall	Resampled to 1km in GIS (0.25°x0.25° lat/long)	Daily (1901-2014)	Pai et al. 2014; Gridded from ~7000 rain gauge stations (most comprehensive for India)
9	Temperature	Resampled to 1km in GIS (0.25°x0.25° lat/long)	Daily 1961-2007	APHRODITE (NCARS 2014)
10	Bioclimatic variables	1km x 1km	Static (contemporary conditions)	19 variables from Hijmans et al. 2005

Ancillary data				
11	Village/town boundaries of India	Resampled to 1km in GIS (1:10k scale or finer)	2001	Hard-copy maps: Survey of India Digital version: This study
12	State boundaries of India (for state dummies)	Resampled to 1km in GIS (1:250k scale)	Two census years (1991 and 2001)	Official data from Survey of India.
13	Agro-Ecological Zones of India	Resampled to 1km in GIS (1:250k scale)	Static (contemporary conditions)	Gajbhiye and Mandal (2000)
14	Cattle population density	1km x 1km	Static (circa 2006)	Robinson et al. 2014

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Table S14. List of model simulations with key model parameters. The 'elastic-net' parameters correspond to the 'best model' i.e. the model from *k*-fold cross-validation with maximum percent of null deviance explained (see Fig. S28 for an example). The hypothesized explanatory variables are provided in Table S12.

Land-cover conversion	Spatial estimation	Time	Buffer area (km)	Elastic-net parameters		Results		Sim #
				α	$Log(\lambda)$	Figure	% (of null) deviance explained	
Cropland → Fallow land	National	1985-1995	6.6	0.8	-8.38	Fig. S5a	0.85	1
		1995-2005	7.3	0.9	-9.72	Fig. 3a	0.90	2
	AEZ2	1985-1995	1.5	0.6	-10.08	Fig. S7a	0.95	3
		1995-2005	7.4	0.8	-4.59	Fig. S7b	0.97	4
	AEZ8	1985-1995	5.2	0.7	-6.80	Fig. S8a	0.86	5
		1995-2005	1.2	0.6	-5.82	Fig. S8b	0.75	6
	AEZ4	1985-1995	2.6	0.7	-9.60	Fig. S9	0.75	7
	AEZ5	1995-2005	4.6	0.6	-7.02	Fig. S10	0.78	8
Fallow land → Cropland	National	1985-1995	7.7	0.8	-10.37	Fig. S5b	0.94	9
		1995-2005	7.7	0.7	-5.27	Fig. 3b	0.78	10
	AEZ8	1985-1995	1.7	0.8	-5.85	Fig. S11a	0.93	11
		1995-2005	7.8	0.6	-5.02	Fig. S11b	0.78	12
	AEZ6	1985-1995	7.7	0.8	-4.95	Fig. S12	0.96	13
	AEZ2	1995-2005	4.1	0.7	-10.09	Fig. S13	0.80	14
Gross forest area loss	National	1985-1995	6.5	0.8	-8.06	Fig. S15	0.76	15
		1995-2005	1.6	0.8	-7.85	Fig. 4a	0.78	16
	AEZ10	1985-1995	3.7	0.8	-5.01	Fig. S17a	0.88	17
		1995-2005	7.4	0.7	-9.97	Fig. S17b	0.84	18
	AEZ12	1985-1995	6.4	0.6	-8.35	Fig. S18a	0.80	19
		1995-2005	7.7	0.7	-6.46	Fig.S18b	0.93	20
	AEZ5	1995-2005	0.8	0.6	-6.81	Fig. S20	0.86	21

	AEZ19	1985-1995	5.4	0.9	-7.59	Fig. S19	0.87	22
	AEZ14	1995-2005	6.9	0.8	-4.53	Fig. S21	0.91	23
Gross forest area gain	National	1985-1995	7.5	0.8	-5.68	Fig. S22	0.79	24
		1995-2005	5.6	0.9	-4.86	Fig. 4b	0.91	25
	AEZ5	1985-1995	6.2	0.6	-5.29	Fig. S23a	0.91	26
		1995-2005	6.1	0.7	-5.68	Fig. S23b	0.81	27
	AEZ12	1985-1995	3.4	0.6	-6.92	Fig. S24	0.86	28
	AEZ14	1985-1995	5.4	0.9	-4.35	0.37 (low explanatory power)		29
	AEZ4	1995-2005	1.8	0.6	-10.32	Fig. S25	0.72	30
	AEZ10	1995-2005	5.8	0.8	-10.61	Fig. S26	0.85	31

Table S15. Description of all variables that features in at least one of the figures in the results section presenting standardized regression coefficients.

Broad category	Explanatory variable name	Description	Variable type	Data source code
Farm Characteristics	Average farm size	The average size of a farm in each 1km grid cell	Continuous	1
Demographic factors	Proportion of female population	Ratio of female population to total (male + female) population	Continuous	1
Labor force	Proportion of marginal agricultural laborers	Ratio of marginal agricultural laborers to total (main + marginal) agricultural laborers. Includes both male and female agricultural laborers. A person who worked in another person's land for wages in cash, kind or share was regarded as an agricultural laborer. Such a person had no risk in cultivation but merely worked in another person's land for wages. An agricultural laborer had no right of lease or contract on land on which he worked.	Continuous	1
	Proportion of female cultivators	Ratio of female cultivators to total (male + female) cultivators. Includes both main (>6 months employment) and marginal (<6 months employment) cultivators. A cultivator if a person engaged either as employer, single worker or family worker in cultivation of land owned or held from government of held from private persons or institutions for payment in money, kind or share of crop. Cultivation included supervision or direction of cultivation. A person who had given out his/her land to another person or persons for cultivation or money, kind or share of crop and who did not even supervise or direct cultivation of land was not treated as cultivator.	Continuous	1
	Proportion of main female cultivators	Ratio of main female cultivators to total (main + marginal) female cultivators. Terminology: Marginal (<6 months employment), and Main (>6 months employment).	Continuous	1

	Male main agricultural laborers density	Density male agricultural laborers in each grid cell who has worked for more than 6 months a year (main worker).	Continuous	1
	Male marginal cultivators density	Density male cultivators in each grid cell who has worked for less than 6 months a year (marginal worker).	Continuous	1
	Density of community workers	Density of community workers in each grid cell. Community workers can include health workers, presence of governmental or non-governmental organization (NGO) that helps with restoration efforts in collaboration with forest department and local communities, among others. They also provide technical assistance in agriculture.	Continuous	1
	Density of forestry workers	Density of forestry workers in each grid cell. People who are employed by forest department either on contract-basis or full-time employment. They are mainly involved in maintenance of forest, roads, wild life protection/census, wildlife watch, fire observation, manning of forest watch towers, interface with tourism, and extraction of grasses for army or other national use. They also collect tendu leafs and other minor forest produce (for government agencies). Lastly, they are also involved in working plan preparation.	Continuous	1
	Industrial & Construction worker density	Density of workers employed in manufacturing and, building and construction industry in each grid cell.	Continuous	1
	Mining/Quarrying worker density	Density of workers employed in mining or quarrying activities in each grid cell.	Continuous	1
Level of Education	Illiterate population density	Density of illiterate population (> 6 years old) in each grid cell. Includes both male and female.	Continuous	1
	Proportion of literate population	Ratio of literate population to total (literate + illiterate) population above 6 years old. Includes both male and female.	Continuous	1
	Access to information	Binary variable indicating access to newspaper, magazines, etc.	Categorical	1

Irrigation Infrastructure	Proportion of cropland irrigated	Ratio of irrigated cropland area to total cropland area. Includes all types of irrigation.	Continuous	1
	Proportion of area irrigated by govt canal	Ratio of cropland area irrigated by government canal to total irrigated area.	Continuous	1
	Proportion of area irrigated by well w/o elec	Ratio of cropland area irrigated by well without electricity to total irrigated area.	Continuous	1
	Proportion of area irrigated by well w elec	Ratio of cropland area irrigated by well with electricity to total irrigated area.	Continuous	1
	Proportion of area irrigated by tube well w/o elec	Ratio of cropland area irrigated by tube well without electricity to total irrigated area.	Continuous	1
	Proportion of area irrigated by tube well w elec	Ratio of cropland area irrigated by tube well with electricity to total irrigated area.	Continuous	1
	Availability of well irrigation w elec	Binary variable indicating the presence or absence of well irrigation with electricity.	Categorical	1
	Availability of tube well irrigation w elec	Binary variable indicating the presence or absence of tube well irrigation with electricity.	Categorical	1
	Availability of irrigation facility	Binary variable indicating the presence or absence of any type of irrigation facility.	Categorical	1
Infrastructure (Electricity)	Availability of power supply for domestic purpose	Binary variable indicating the presence or absence of power supply for domestic use.	Categorical	1
	Availability of power supply for agriculture	Binary variable indicating the presence or absence of power supply for agriculture use.	Categorical	1
Poverty Indicators	Average income per capita	Average income of a person in the village. Includes unemployed population in the person count.	Continuous	1
	Proportion of tribal population	Ratio of scheduled tribe population to total population.	Continuous	1
	Proportion of backward caste population	Ratio of (scheduled tribe + schedule caste) population to total population. Both scheduled caste and tribes are considered lower caste and economically weak.	Continuous	1
Accessibility (Navigation and/or Irrigation source)	Distance to town	Distance to nearest town. There are about 5160 towns in India and ~630,000 villages.	Continuous	1
	Market frequency	Dummy-coded variable indicating the frequency of markets (daily, weekly, fortnightly, no markets). The category “no markets” is used as reference	Ordinal	1

		category.		
	Availability of communication facility	Binary variable indicating availability of bus stand train stations, etc. that connects to nearby towns.	Categorical	1
	Approach to *pucca* road	Binary variable indicating access to *pucca* road in the village. *Pucca* road is a black-topped road (all weather roads).	Categorical	1
	Approach to river	Binary variable indicating access to river in the village.	Categorical	1
	Approach to canal	Binary variable indicating access to government canal in the village.	Categorical	1
Critical support services	Number of agricultural credit societies	Total number of agricultural credit societies present in the village.	Continuous	1
	Distance to nearest agricultural credit society	Distance to the nearest agricultural credit society (the nearest credit society may be in the same village or nearby villages).	Continuous	1
Income dependency (Primary Occupation)	Occupation (Building/mining Materials)	Binary variable indicating if building (includes brick kilns, marble, granite) and/or mining (primarily stone and coal) as one of the top three primary occupations of the village.	Categorical	1
	Occupation (Dairy/cattle/leather)	Binary variable indicating if primary occupation related to raising livestock such as cattle, goat, and sheep and making related products including dairy (milk, ghee), and leather.	Categorical	1
	Occupation (Coffee)	Binary variable indicating if primary occupation is coffee growing.	Categorical	1
	Occupation (Coconut Production)	Binary variable indicating if primary occupation is coconut plantations.	Categorical	1
	Occupation (Forestry Products)	Binary variable indicating if primary occupation is related to forestry products. Forestry products includes but not limited to extraction of tendu leafs, making agarbathis/incense sticks, baskets match sticks, brooms, beedi/cigarettes, paper products, and gutka.	Categorical	1
	Occupation (Wool/Woolen Blankets)	Binary variable indicating if primary occupation is related to sheep shearing or making woolen	Categorical	1

		products.		
	Occupation (Bamboo Products)	Binary variable indicating if primary occupation is related to bamboo production and related products.	Categorical	1
	Occupation (Wooden Furniture/timber)	Binary variable indicating if primary occupation is related to making wooden furnitures (e.g. chair) or timber extraction.	Categorical	1
	Occupation (Wooden Agricultural implements)	Binary variable indicating if primary occupation is related to manufacturing wooden equipment's used for agriculture including axe, carts, and wooden ploughs.	Categorical	1
Climate	$T_{\text{sw monsoon (avg)}}$	Temperature in each grid cell averaged over the southwest monsoon season (June-September; 'Rabi' season).	Continuous	9
	$T_{\text{post-monsoon (avg)}}$	Temperature in each grid cell averaged over the post-monsoon season (October-November).	Continuous	9
	$T^2_{\text{post-monsoon (avg)}}$	Squared temperature in each grid cell averaged over the post-monsoon season. Squared values are used to account for non-linear response of climate to crop cover.	Continuous	9
	$P_{\text{sw monsoon (avg)}}$	Precipitation in each grid cell averaged over the southwest monsoon season (June-September; 'Rabi' season).	Continuous	8
	$P_{\text{post-monsoon (avg)}}$	Precipitation in each grid cell averaged over the post-monsoon season (October-November).	Continuous	8
	$P^2_{\text{sw monsoon (avg)}}$	Squared precipitation in each grid cell averaged over the southwest monsoon season. Squared values are used to account for non-linear response of climate to crop cover.	Continuous	8
	$P_{\text{sw monsoon (rel to normal)}}$	Average southwest monsoon precipitation over a given time period relative (minus) to the long-term (1961-2005) average.	Continuous	8
	$P_{\text{post-monsoon (rel to normal)}}$	Average post monsoon precipitation over a given time period relative (minus) to the long-term (1961-2005) average.	Continuous	8
	$P_{\text{sw monsoon (std)}}$	Standard deviation in daily precipitation amounts in	Continuous	8

		each grid cell during the southwest monsoon season.		
	$P_{post\text{-}monsoon\ (std)}$	Standard deviation in daily precipitation amounts in each grid cell during the post-monsoon monsoon season.	Continuous	8
	Annual Mean Temperature	Variable name is self-explanatory.	Continuous	10
	Mean Temperature of Wettest Quarter	Variable name is self-explanatory.	Continuous	10
	Annual Precipitation	Variable name is self-explanatory.	Continuous	10
	Precipitation of Wettest Month	Variable name is self-explanatory.	Continuous	10
	Precipitation of Wettest Quarter	Variable name is self-explanatory.	Continuous	10
	Precipitation of Coldest Quarter	Variable name is self-explanatory.	Continuous	10
Edaphic Condition	Cation Exchange Capacity	Dummy-coded variable indicating the level of cation exchange capacity (CEE) of soil (<10 cmol/kg, 10-20 cmol/kg, 20-30 cmol/kg, and >30 cmol/kg). The level '<10 cmol/kg' is used as reference category. CEE is an indicator of soil fertility.	Ordinal	4
	Soil erosion	Dummy-coded variable indicating the level of soil erosion (None to very slight, Slight, Moderate, Severe, Very severe). The level 'None to very slight' is used as reference category.	Ordinal	4
	Soil Depth	Dummy-coded variable indicating the level of soil depth (Extremely shallow, Very shallow, Shallow, Moderately Shallow, Moderately Deep, Deep, Very deep). The level 'Extremely shallow' is used as reference category.	Ordinal	4
	Soil salinity	Dummy-coded variable indicating the level of soil salinity (Negligible (1-2 dS/m), Slight (2-4 dS/m), Moderate (4-8 dS/m), Moderate strong (8-15 dS/m), Strong (15-25 dS/m), Severe (25-50 dS/m), Very severe (>50 dS/m)). The level 'Negligible (1-2 dS/m)' is used as reference category.	Ordinal	4
	Slope	Dummy-coded variable indicating the slope level (Level to nearly level (0-1%), Very gentle (1-3%), Gentle (3-8%), Moderate (8-15%), Moderately	Ordinal	4

		steep (15-30%), Steep (30-50%), Very steep (>50%)). The level 'Level to nearly level (0-1%)' is used as reference category.		
Terrain/Slope	Terrain	Average elevation of land in each grid cell.	Continuous	6
Political boundaries	State dummies	Dummy-coded variable indicating which state administrative division each grid cell belongs to. We fix one state as the reference category relative (abbreviation: 'rel') to which we evaluate the effects. The following state names have been abbreviated as follows: MP (Madhya Pradesh), AP (Andhra Pradesh), UP (Uttar Pradesh).	Categorical	12
Other variables	Protected areas	Protected areas (national parks and wildlife sanctuaries) in each grid cell.	Continuous	7
	Mined-out areas	Area that was mined in each grid cell.	Continuous	5
	Sacred groves	Area of sacred forest groves in each grid cell.	Continuous	3
	Cattle density	Density of cattle population in each grid cell.	Continuous	14

Table S16. AEZ-wise correlation analysis (2001 census) between average farm size and soil degradation (against two measures: erosion and salinization). All three variables: average farm size, soil erosion and soil salinity were ordered qualitative variables (Table S13). We used the Goodman-Kruskal gamma (g) statistic to measure the association between the ordinal variables. |g| = 1 indicates perfect correlation between the two variables. Negative g implies that soil erosion/salinization increases as farm size decreases, and vice-versa for positive gamma. All results reported at 95% confidence level from a one-sided test. Insignificant relationships are marked by hifen ('-'). We did the analysis at 1km x 1km resolution, and each grid was weighed by the average number of farms (grid crop area/average farm size). AEZs with negative 'g' are regions where smaller farms are prone to higher soil degradation.

	Soil Erosion			Soil Salinity		
Spatial Domain	**Goodman-Kruskal's gamma statistic (g)**	**Goodman-Kruskal's asymptotic standard error**	**z-value**	**Goodman-Kruskal's gamma statistic (g)**	**Goodman-Kruskal's asymptotic standard error**	**z-value**
AEZ1	0.4733	0.0064	73.7361	-	-	-
AEZ2	0.4164	0.0002	2265.7084	0.4212	0.0003	1643.0032
AEZ3	0.0490	0.0005	106.5499	0.3622	0.0040	90.5521
AEZ4	-0.2270	0.0001	-1603.4043	0.0123	0.0001	84.7032
AEZ5	-0.1425	0.0002	-669.1248	0.1045	0.0003	301.3107
AEZ6	-0.1961	0.0001	-1505.6446	-	-	-
AEZ7	-0.0020	0.0002	-9.5359	-0.3545	0.0015	-240.0589
AEZ8	-0.0489	0.0002	-257.1600	-0.0803	0.0009	-89.5300
AEZ9	-0.1135	0.0004	-320.2257	-0.1488	0.0002	-658.9260
AEZ10	-0.1492	0.0002	-687.7616	0.1708	0.0003	489.6151
AEZ11	-0.0051	0.0004	-14.4712	-0.3381	0.0020	-170.2594
AEZ12	0.1987	0.0001	1460.7426	0.8416	0.0002	4183.3123
AEZ13	0.2800	0.0003	942.9212	-0.4896	0.0003	-1666.8518
AEZ14	-0.1759	0.0004	-424.8247	-0.3320	0.0018	-186.3924
AEZ15	0.2161	0.0003	755.6250	0.7128	0.0005	1471.9808
AEZ16	-0.0473	0.0014	-34.8690	0.8520	0.0018	473.0399
AEZ17	-0.2706	0.0008	-347.7385	-0.1786	0.0003	-137.8766
AEZ18	0.0810	0.0003	265.2050	0.5389	0.0006	916.3367
AEZ19	0.0155	0.0004	42.8529	0.4518	0.0009	501.7510

Figures

Figure S1. Visualization of the seamless village-level boundaries of India prepared for this study. We manually digitized the village boundaries from publicly available village boundary maps (hard copy maps obtained from respective district headquarters) of each state of India. We first complied the digitized village maps to state level, and then combined from state to national level. The national boundaries are from Openstreet map (opendatacommons.org) distributed under the Open Database License (http://www.openstreetmap.org/copyright).

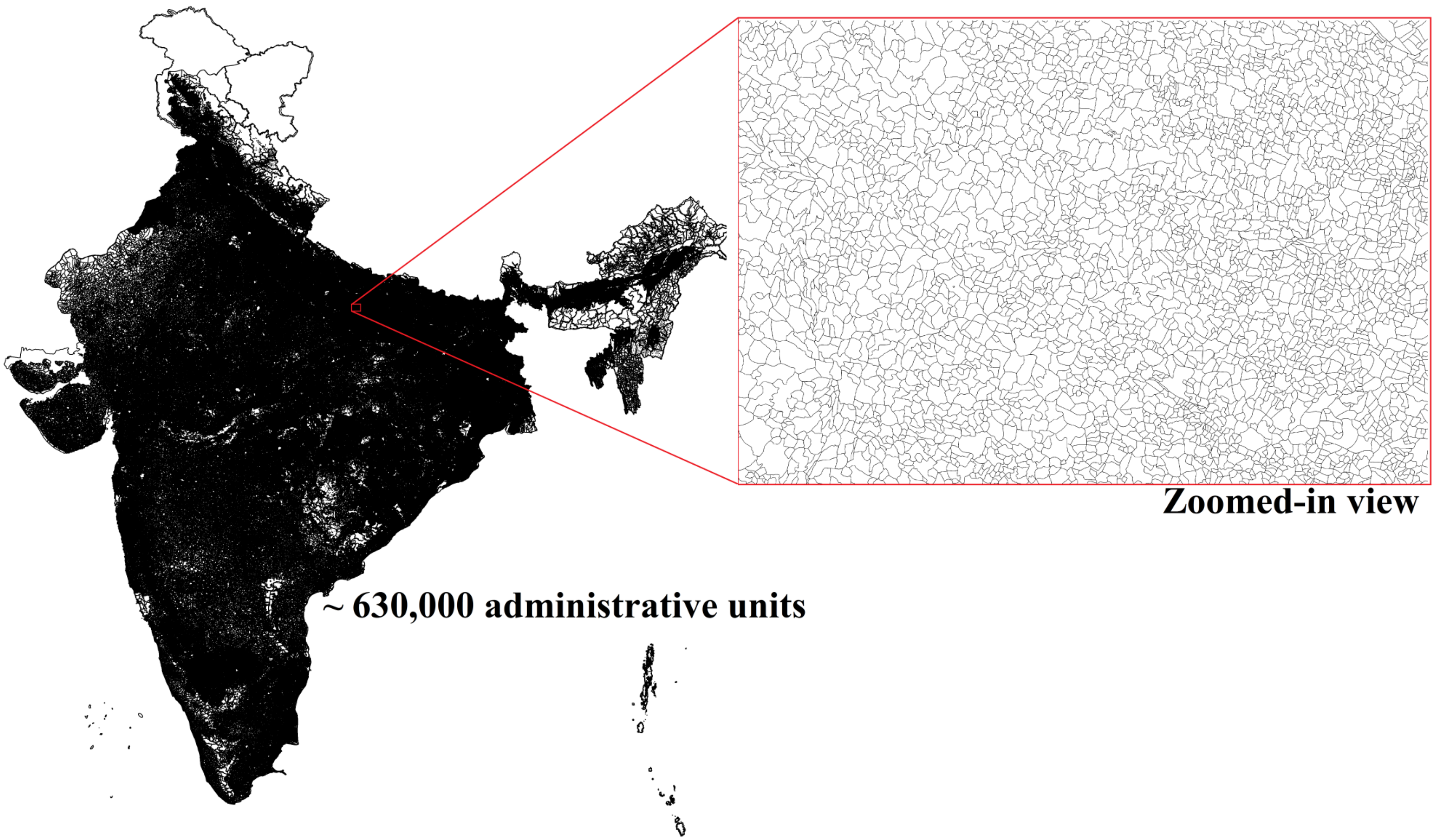
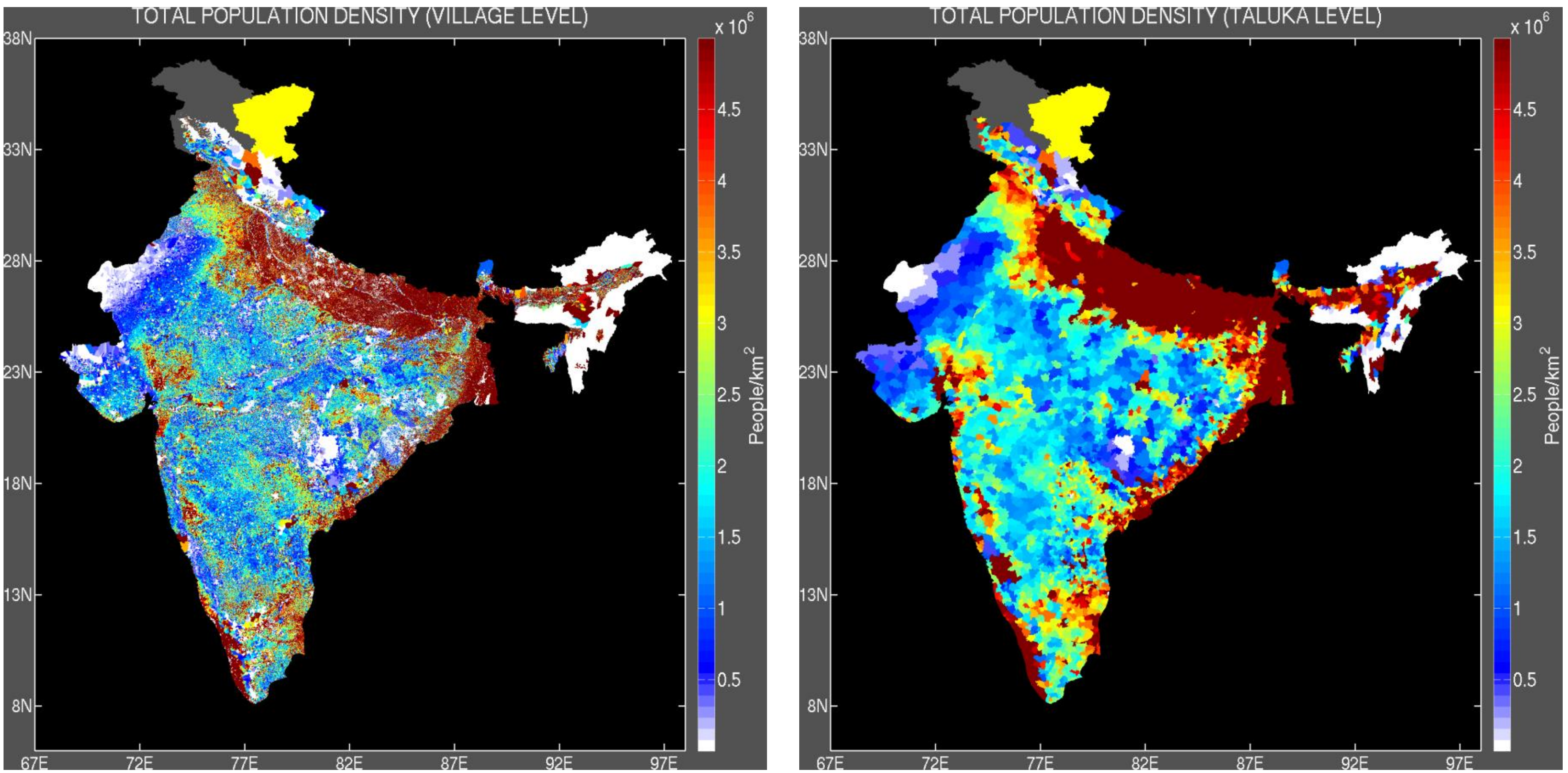
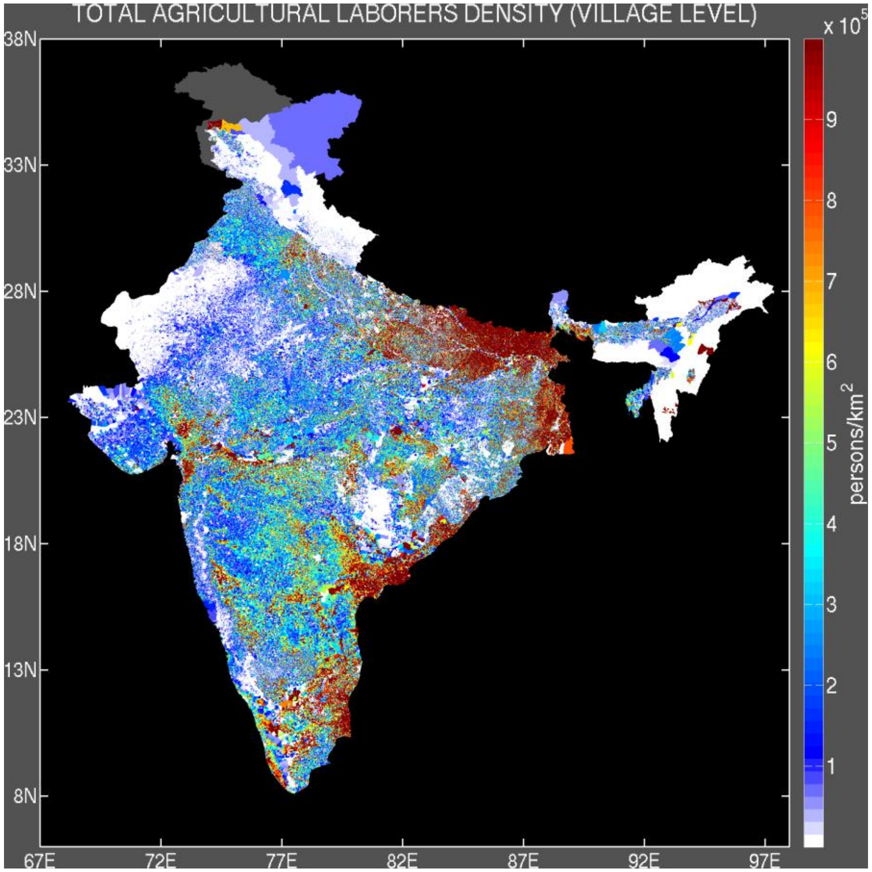


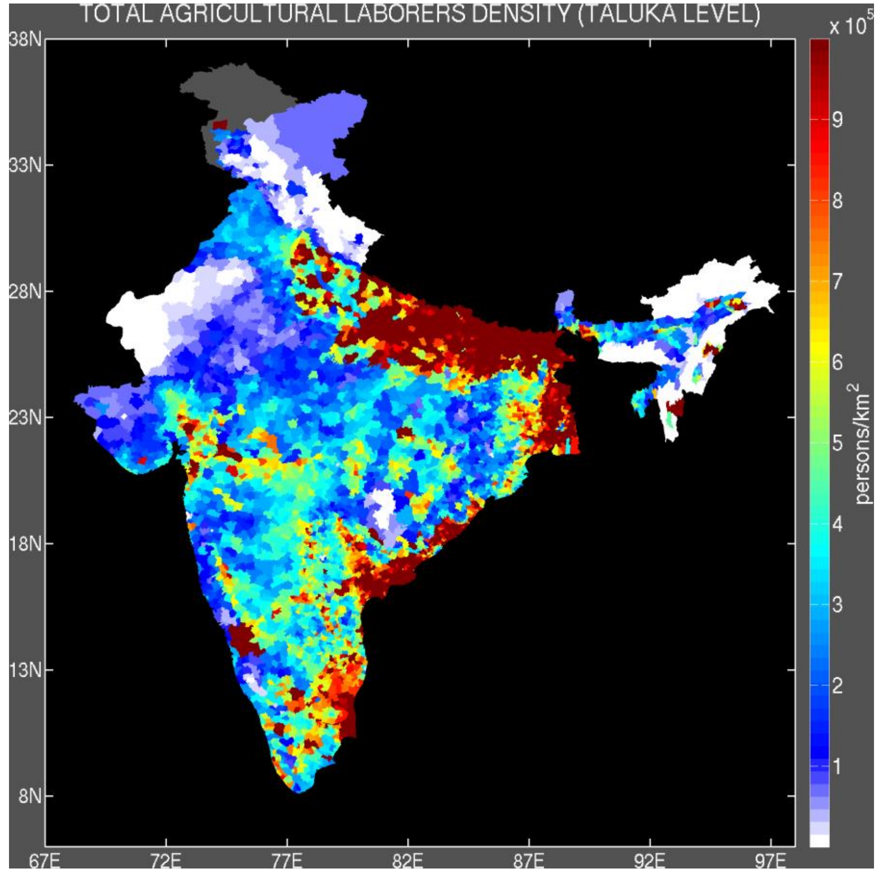
Figure. S2. Four examples illustrating the granularity of census data (2001). The adjacent panels compare the same data at two different spatial levels of disaggregation: village/town (used in our study), and taluka level (the subsequent administrative hierarchy). Four examples shown: (a) Total population data, (b) Total agricultural laborers density, (c) Mining/Quarrying worker density, and (d) Irrigation by tube well with electricity.

Sub-plot (a)

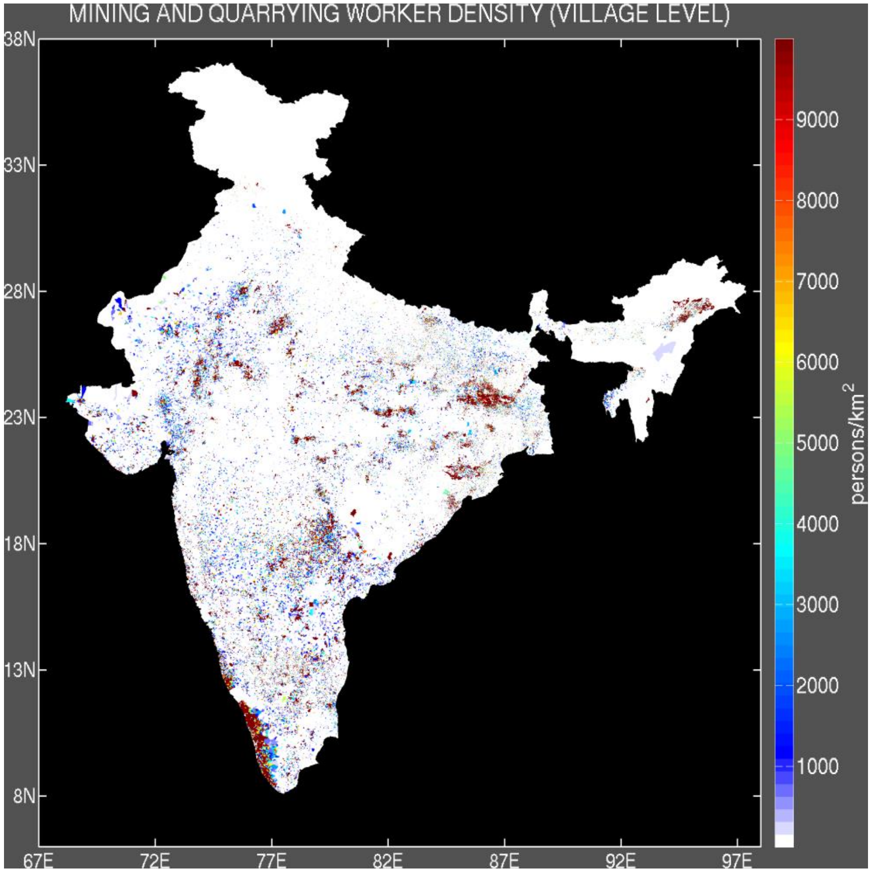


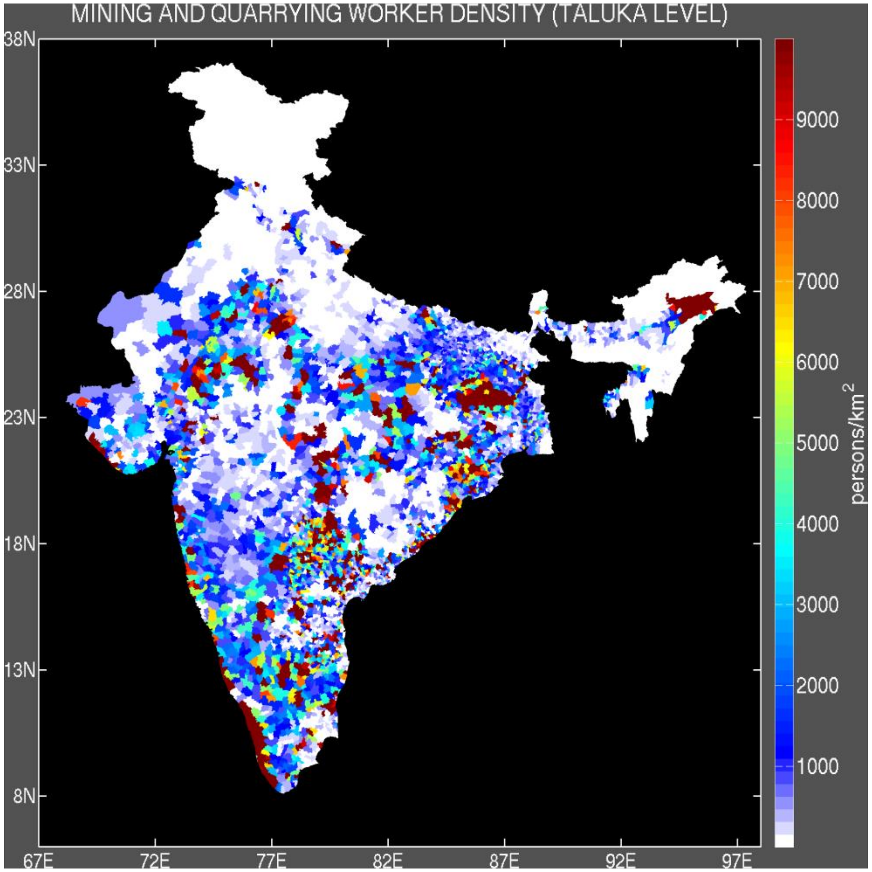
Sub-plot (b)


TOTAL AGRICULTURAL LABORERS DENSITY (VILLAGE LEVEL)
x 10^5
persons/km^2
38N
33N
28N
23N
18N
13N
8N
67E
72E
77E
82E
87E
92E
97E
1
2
3
4
5
6
7
8
9

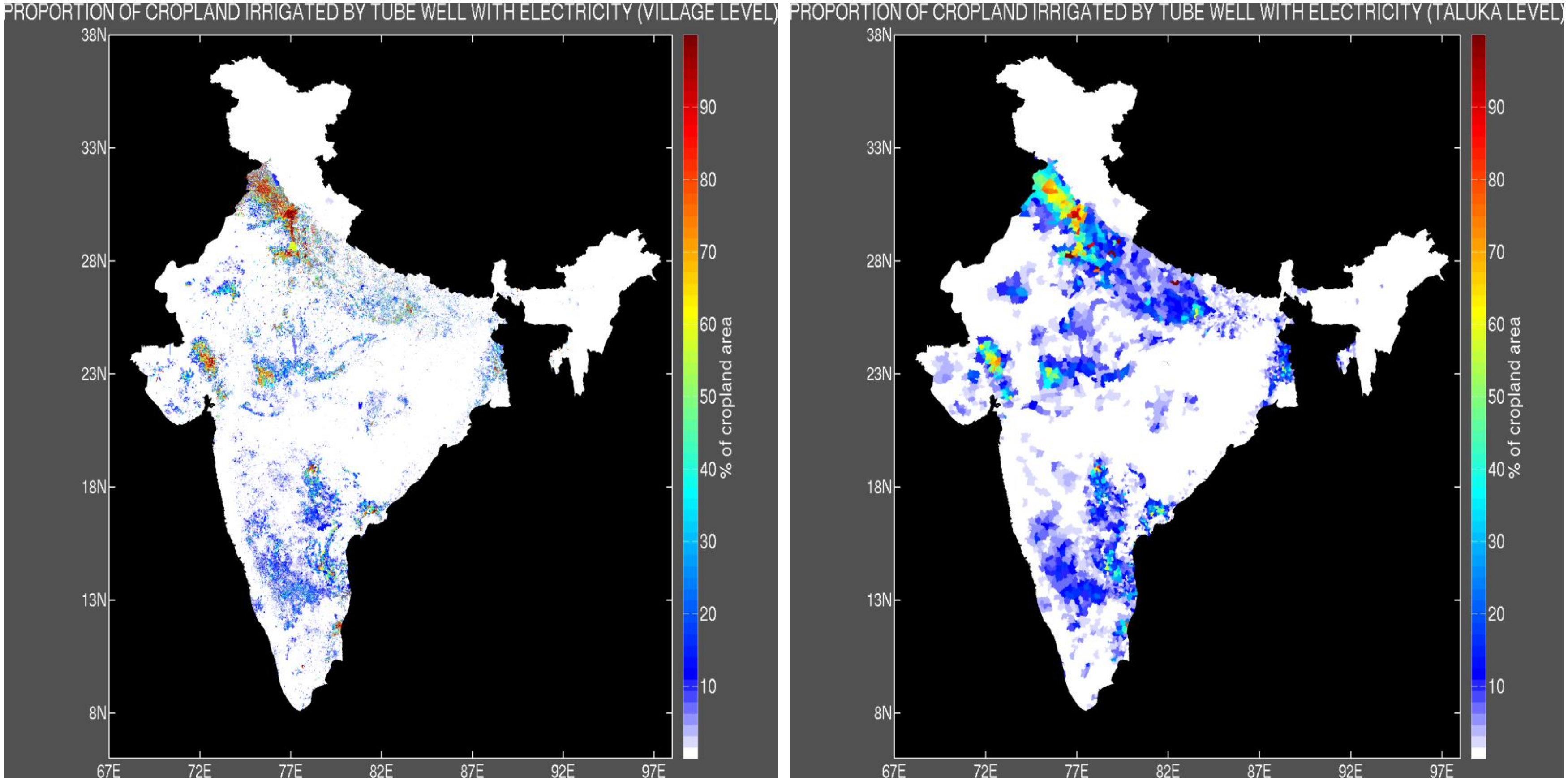

TOTAL AGRICULTURAL LABORERS DENSITY (TALUKA LEVEL)
x 10^5
persons/km^2
38N
33N
28N
23N
18N
13N
8N
67E
72E
77E
82E
87E
92E
97E
1
2
3
4
5
6
7
8
9

Sub-plot (c)


MINING AND QUARRYING WORKER DENSITY (VILLAGE LEVEL)
38N
33N
28N
23N
18N
13N
8N
67E
72E
77E
82E
87E
92E
97E
9000
8000
7000
6000
5000
4000
3000
2000
1000
persons/km2


MINING AND QUARRYING WORKER DENSITY (TALUKA LEVEL)
38N
33N
28N
23N
18N
13N
8N
67E
72E
77E
82E
87E
92E
97E
9000
8000
7000
6000
5000
4000
3000
2000
1000
persons/km2

Sub-plot (d)



PROPORTION OF CROPLAND IRRIGATED BY TUBE WELL WITH ELECTRICITY (VILLAGE LEVEL)
PROPORTION OF CROPLAND IRRIGATED BY TUBE WELL WITH ELECTRICITY (TALUKA LEVEL)
38N
33N
28N
23N
18N
13N
8N
67E
72E
77E
82E
87E
92E
97E
90
80
70
60
50
40
30
20
10
% of cropland area

Figure S3. Location of the 102 studies included in our synthesis.

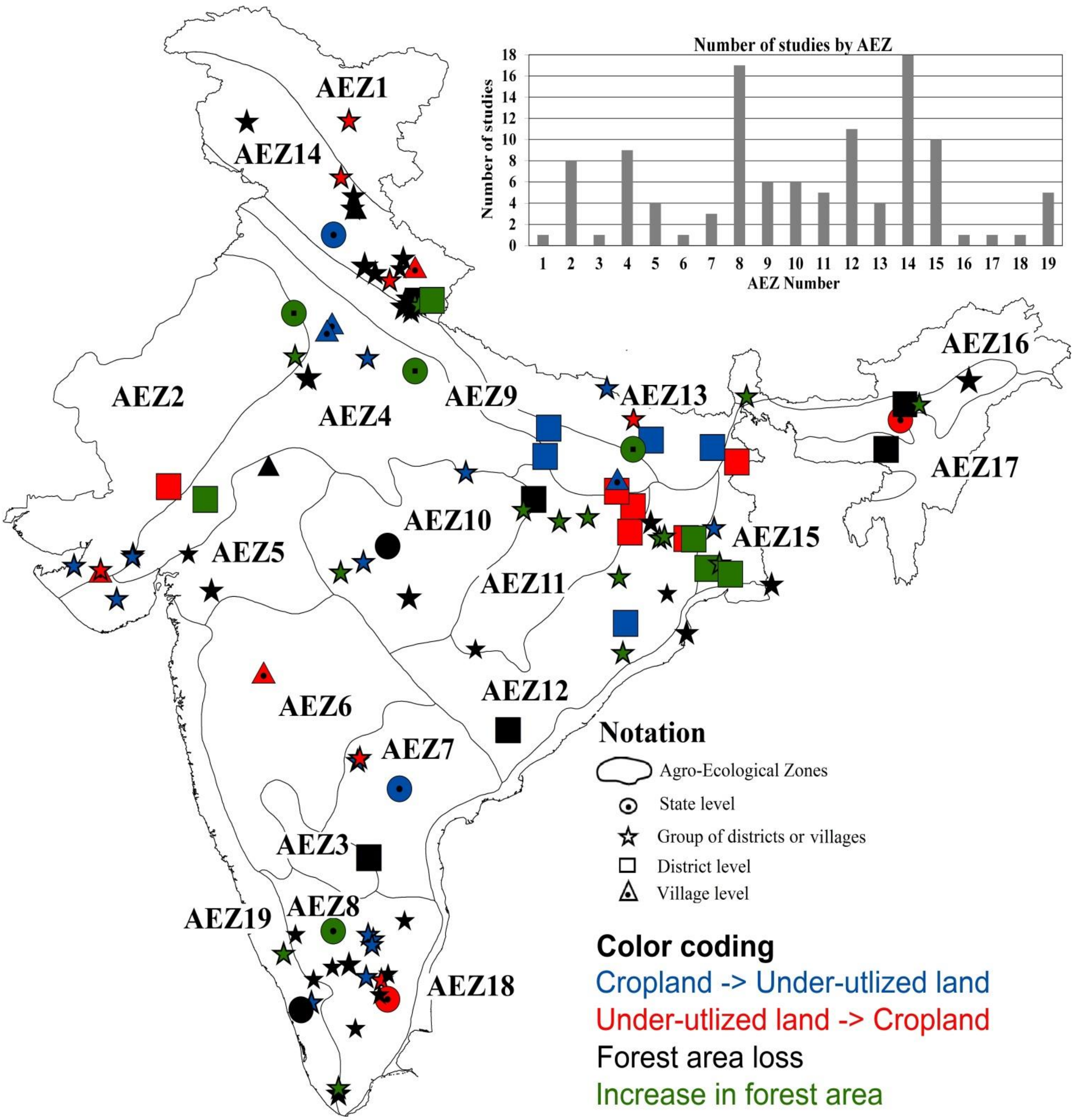


Figure S4. Extension to Fig. 2 showing the regional breakdown of key land-cover conversions. The bar plots show the percent contribution by Agro-Ecological Zones (AEZ) to the national total (national total shown besides bar; units in x1000 km^2/decade and rounded to nearest integer). See Table S6 for definition of AEZs.

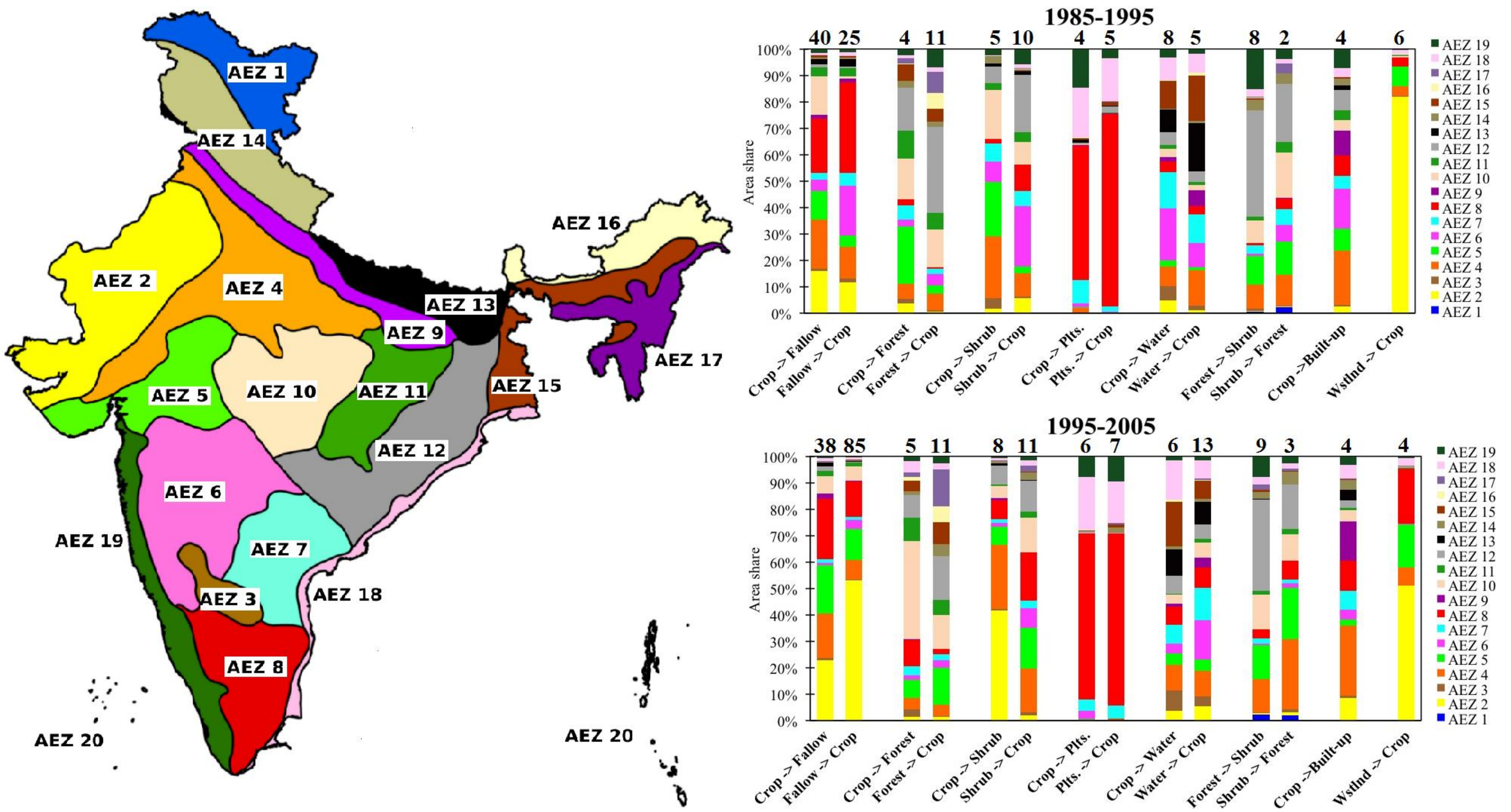
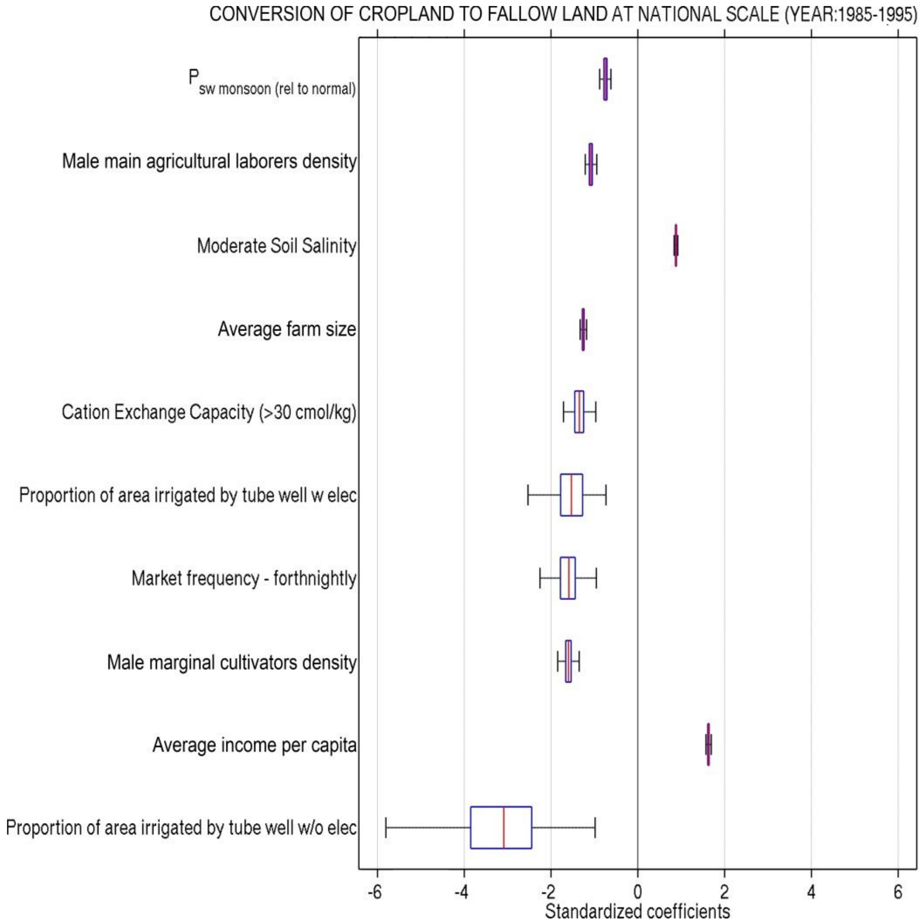


Figure. S5. Similar to Fig. 3 but for 1985-1995. Factors most prominent in explaining: (a) conversion of cropland to fallow land at national scale (1985-1995), and (b) vice-versa conversion i.e. conversion of fallow land to cropland at national scale (1985-1995).



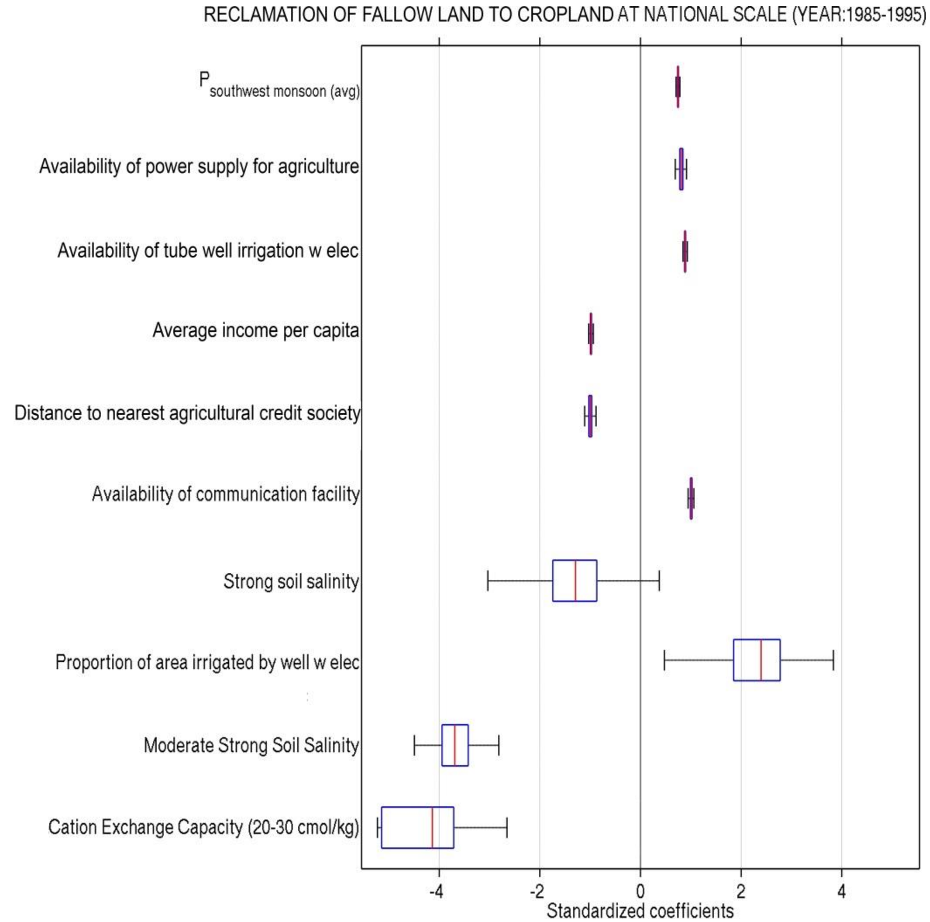


Figure. S6. The series of 14 figures show changes (between 1991 and 2001) in spatial patterns of farm labor calculated from village level census database (~630,000 political units). The detailed breakdown is shown for broad interpretation of results, and also because this is the first time Indian farm labor force is being visualized at this level of spatial and demographic detail. The data is broken down by three broad components: (1) by gender, (2) agricultural laborers and cultivators, and (3) main and marginal laborers. Agricultural laborers are people who worked in another person's land for wages in cash, kind or share. Such a person had no risk in cultivation but merely worked in another person's land for wages. An agricultural laborer had no right of lease or contract on land on which he worked. Cultivators are people who was engaged either as employer, single worker or family worker in cultivation of land owned or held from government of held from private persons or institutions for payment in money, kind or share of crop. Cultivation included supervision or direction of cultivation. Main workers were those who had worked for the major part of the year preceding the date of enumeration i.e., those who were engaged in any economically productive activity for 183 days (or six months) or more during the year. Marginal workers were those who worked any time at all in the year preceding the enumeration but did not work for a major part of the year, i.e., those who worked for less than 183 days (or six months).

Sub-plot captions are as follows: (a) Total agricultural laborers density, (b) Total cultivators density, (c) Main agricultural laborers density (male + female), (d) Marginal agricultural laborers density (male + female), (e) Male main agricultural laborers density, (f) Female main agricultural laborers density, (g) Male marginal agricultural laborers density, (h) Female marginal agricultural laborers density, (i) Main cultivators density, (j) Marginal cultivators density, (k) Male main cultivators density, (l) Female main cultivators density, (m) Male marginal cultivators density, and (n) Female marginal cultivators density. Positive values indicate an increase in population from 1991 to 2001, and negative values indicate the vice-versa.

Fig. S6 (Continued). Sub-plots (a) and (b)

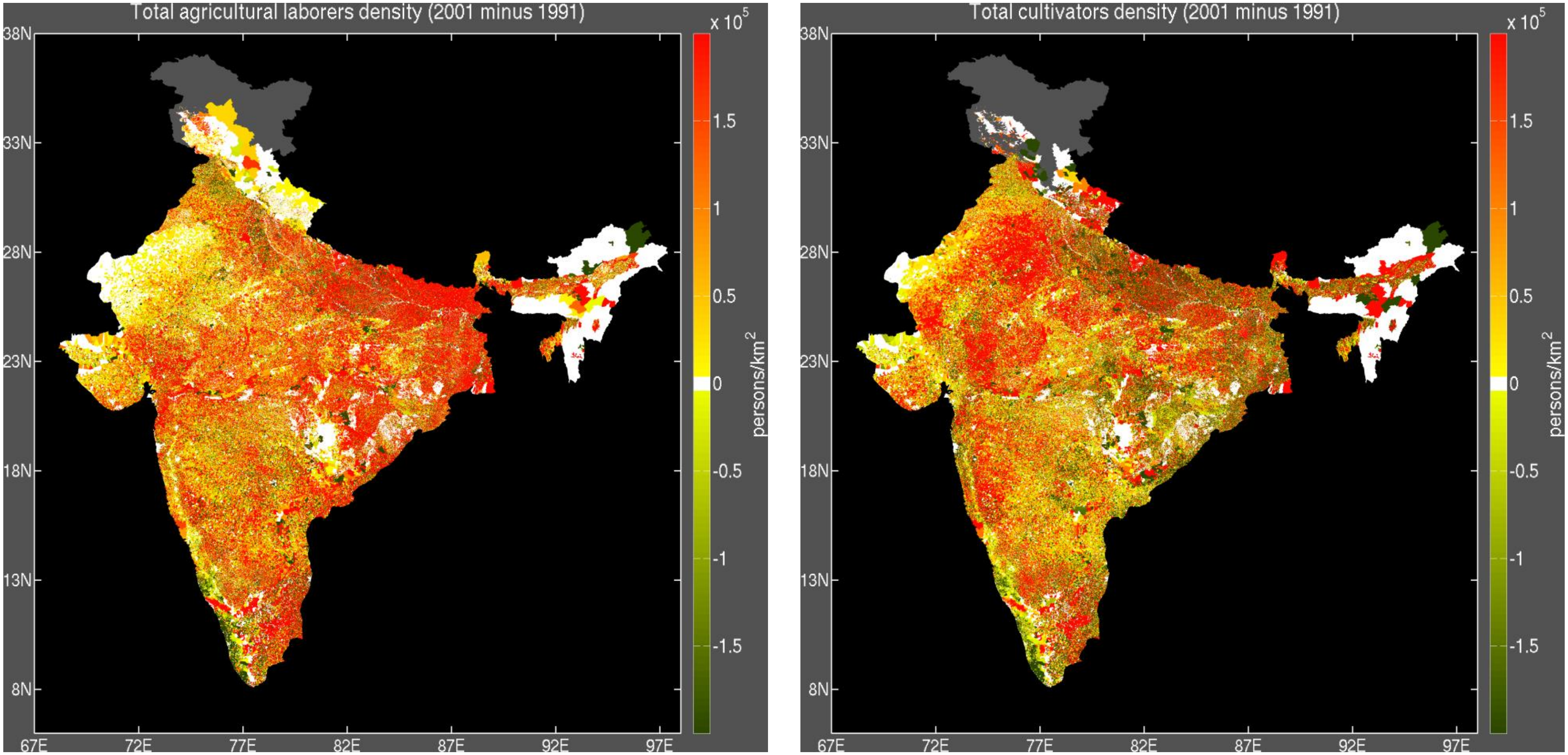
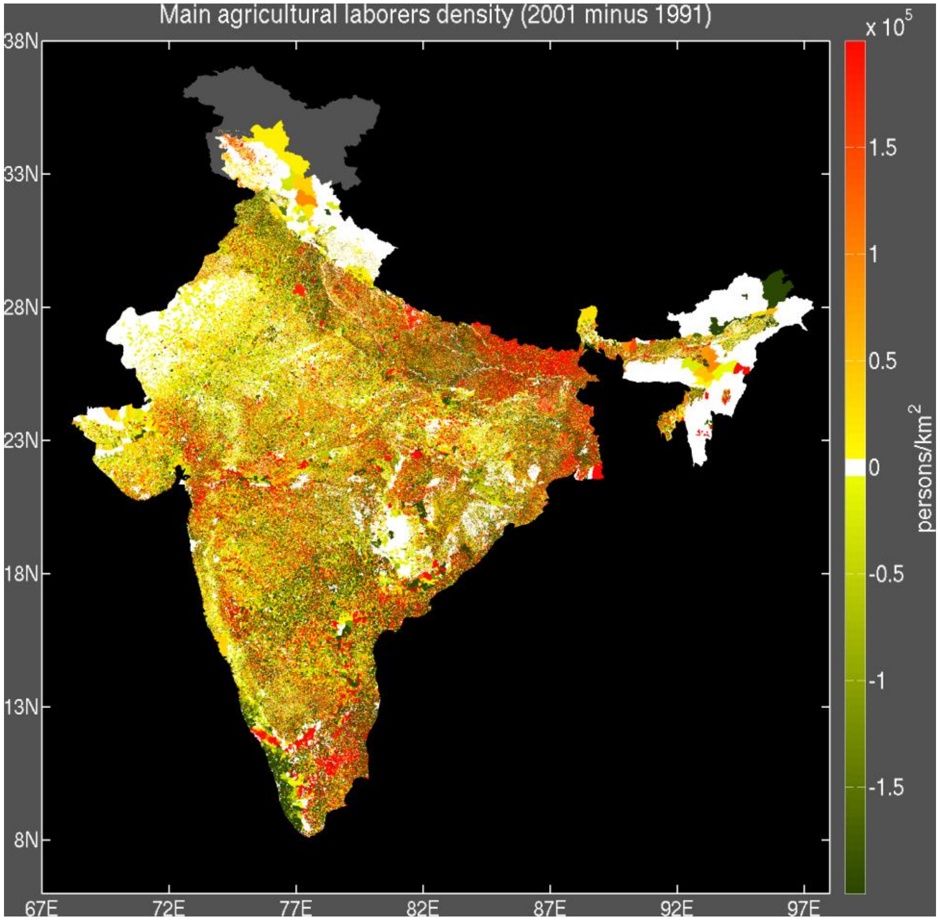


Fig. S6 (Continued). Sub-plots (c) and (d)



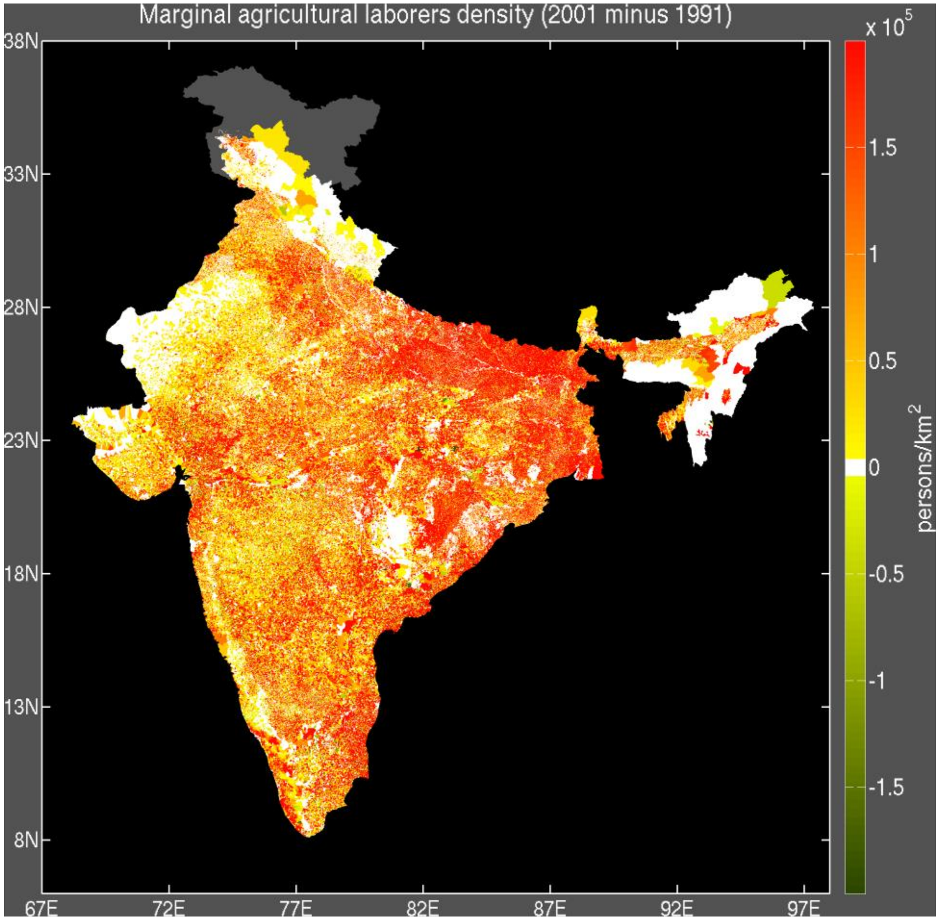
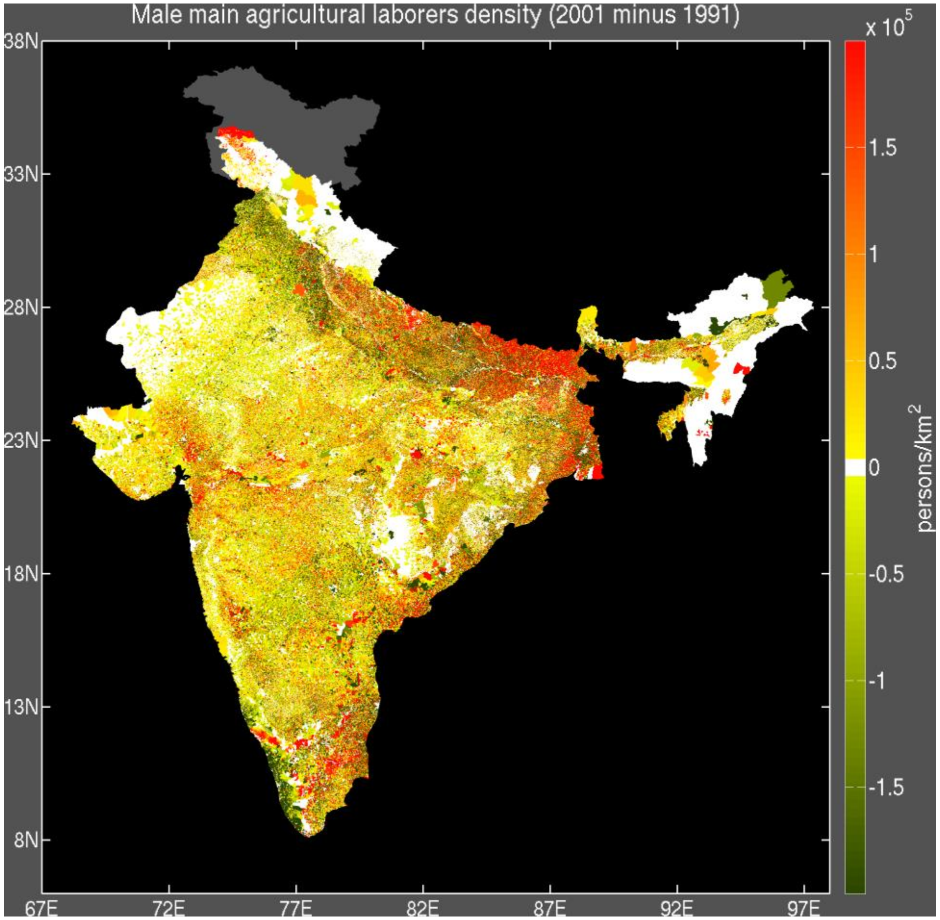


Fig. S6 (Continued). Sub-plots (e) and (f)



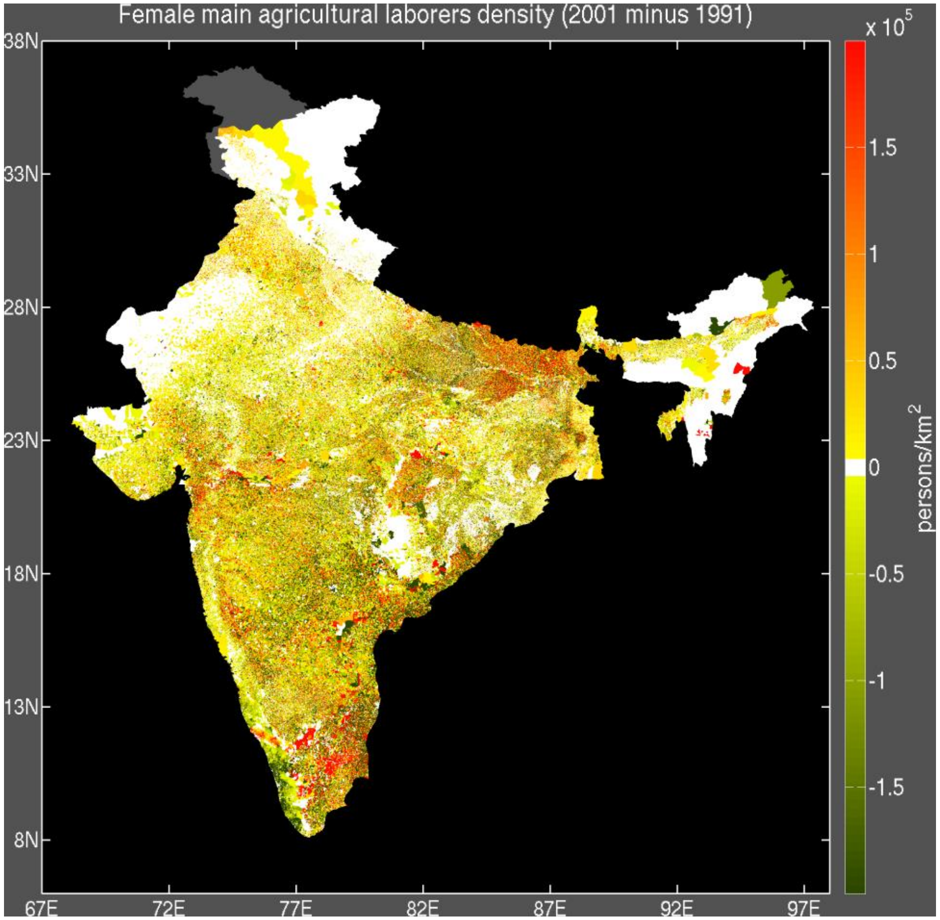
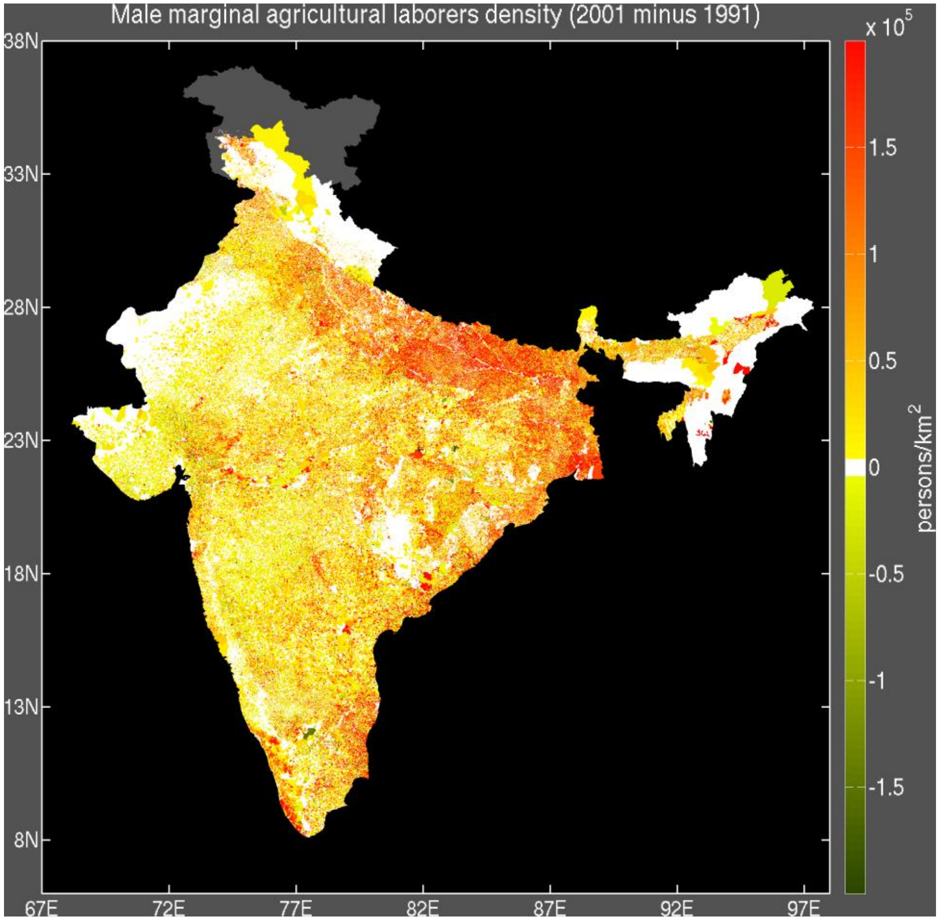


Fig. S6 (Continued). Sub-plots (g) and (h)



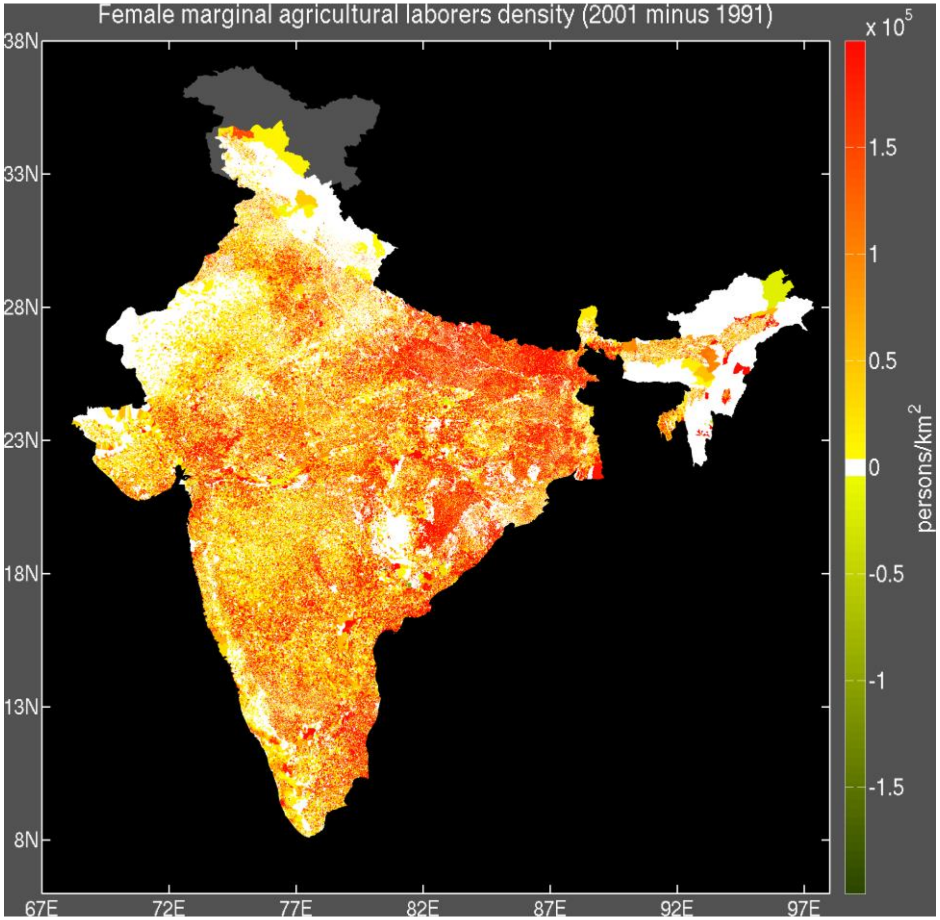
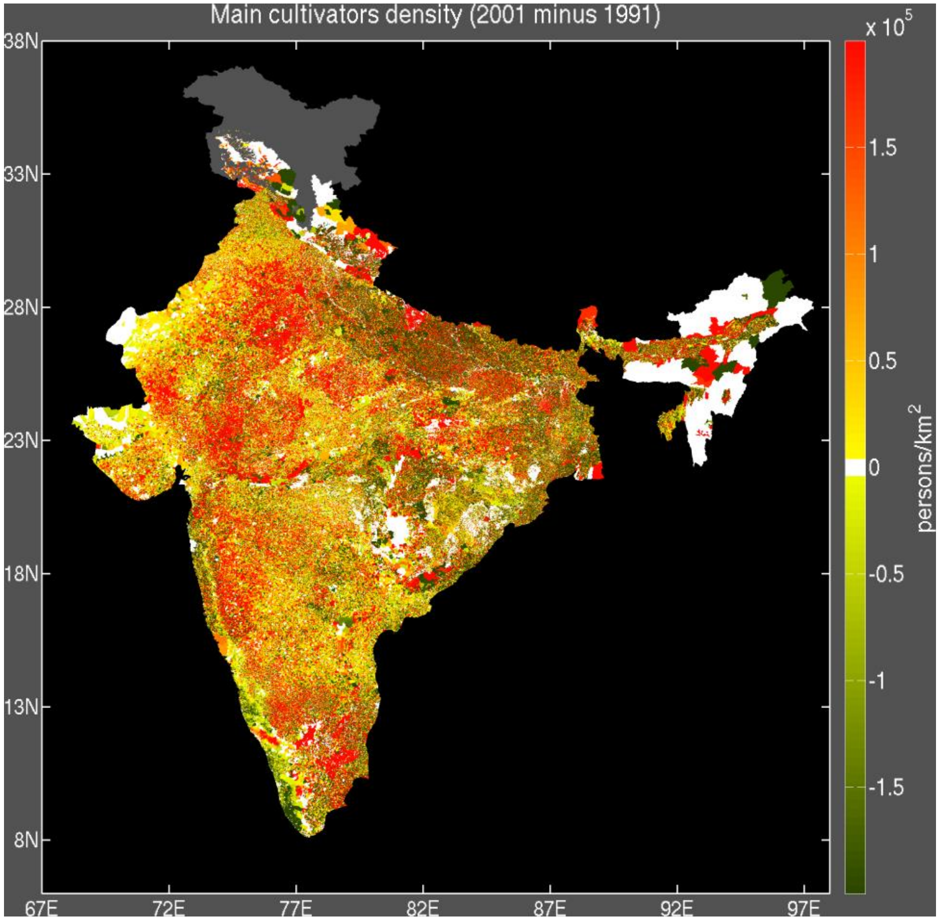


Fig. S6 (Continued). Sub-plots (i) and (j)



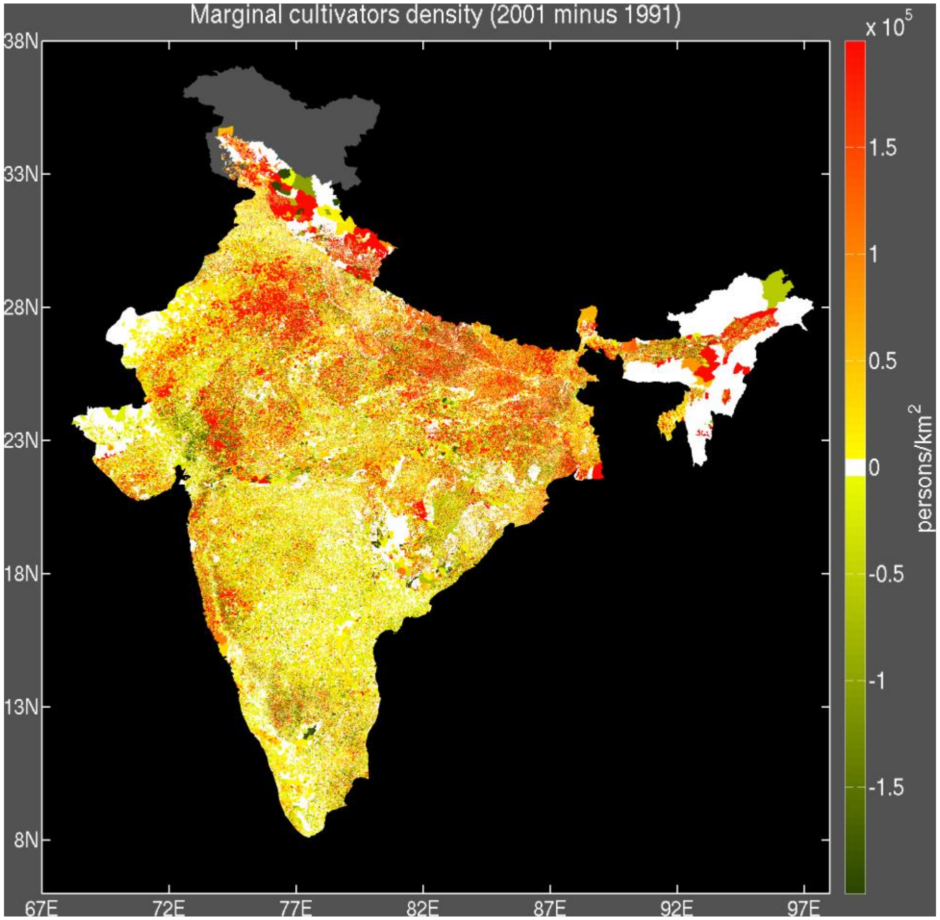
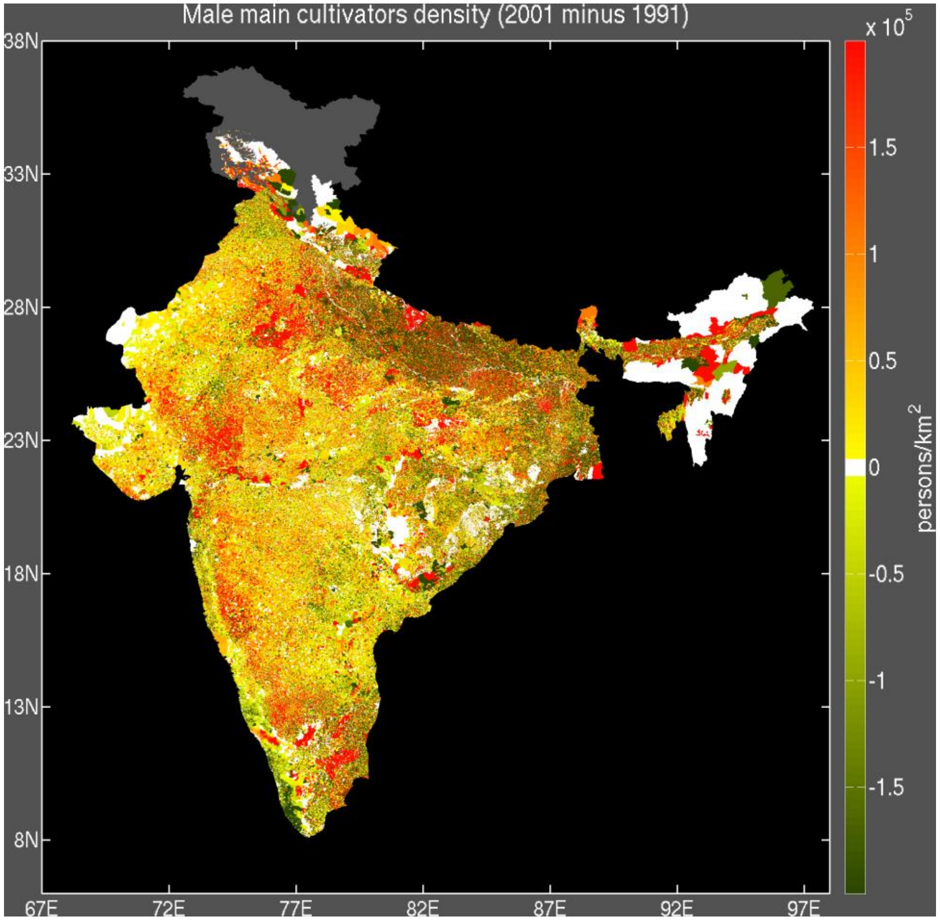


Fig. S6 (Continued). Sub-plots (k) and (l)



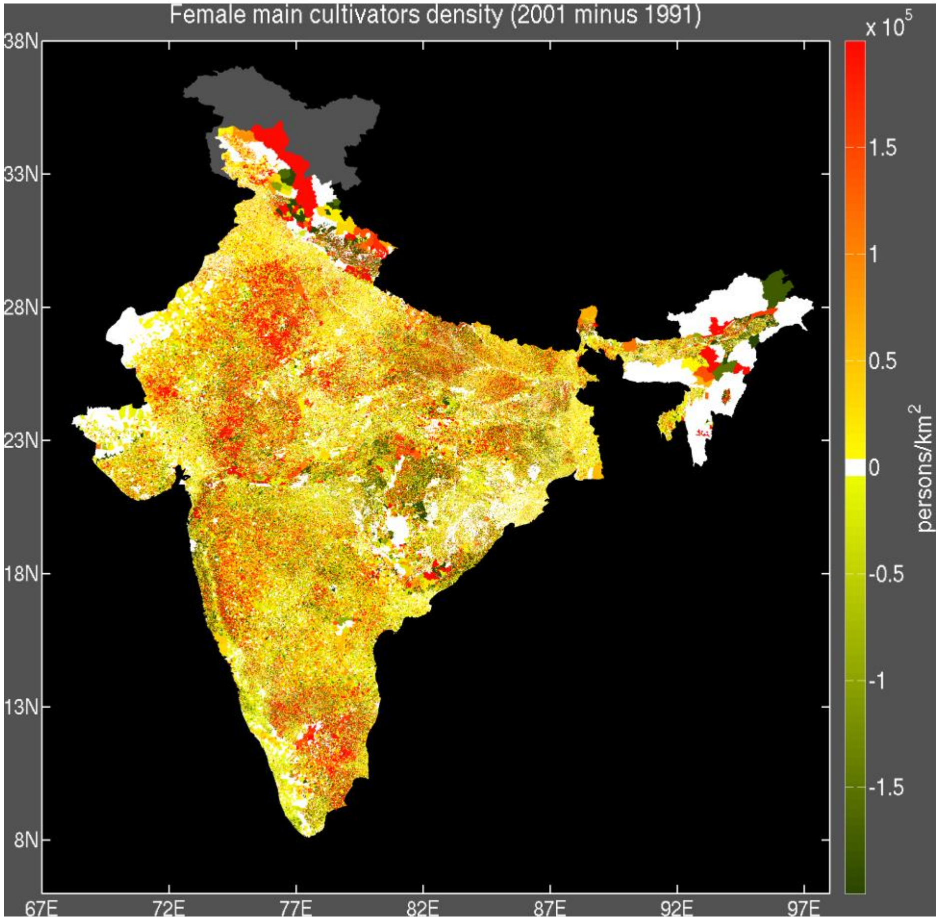
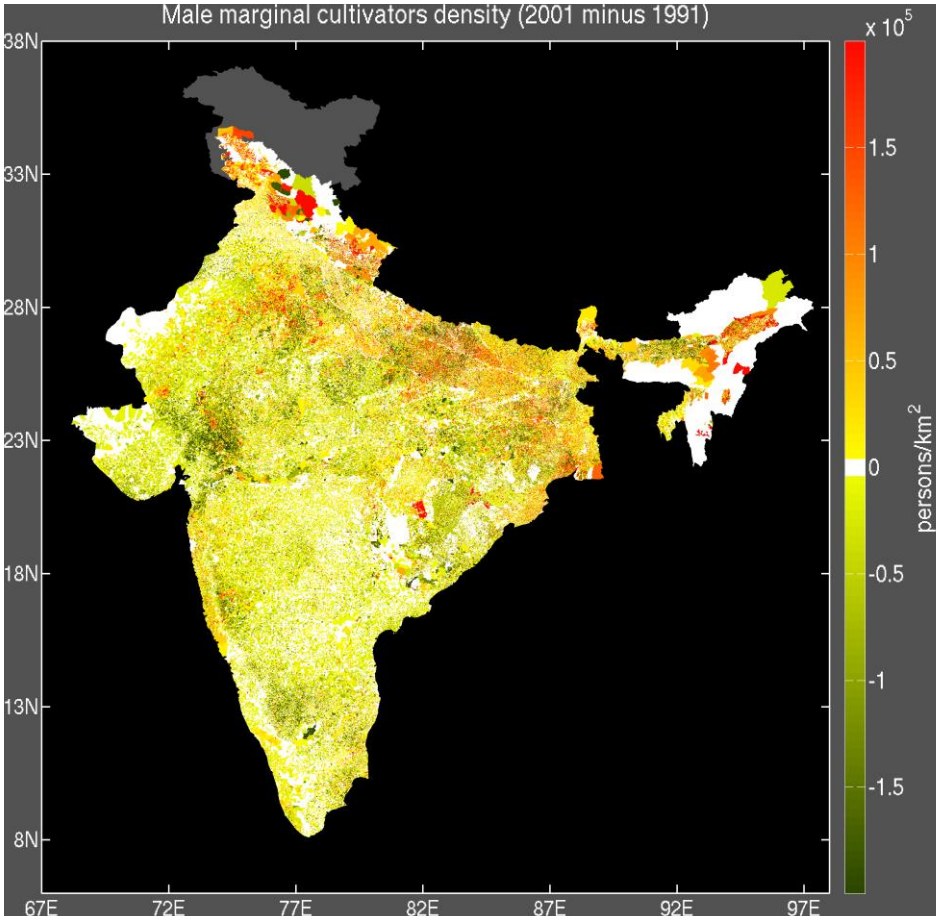


Fig. S6 (Continued). Sub-plots (m) and (n)



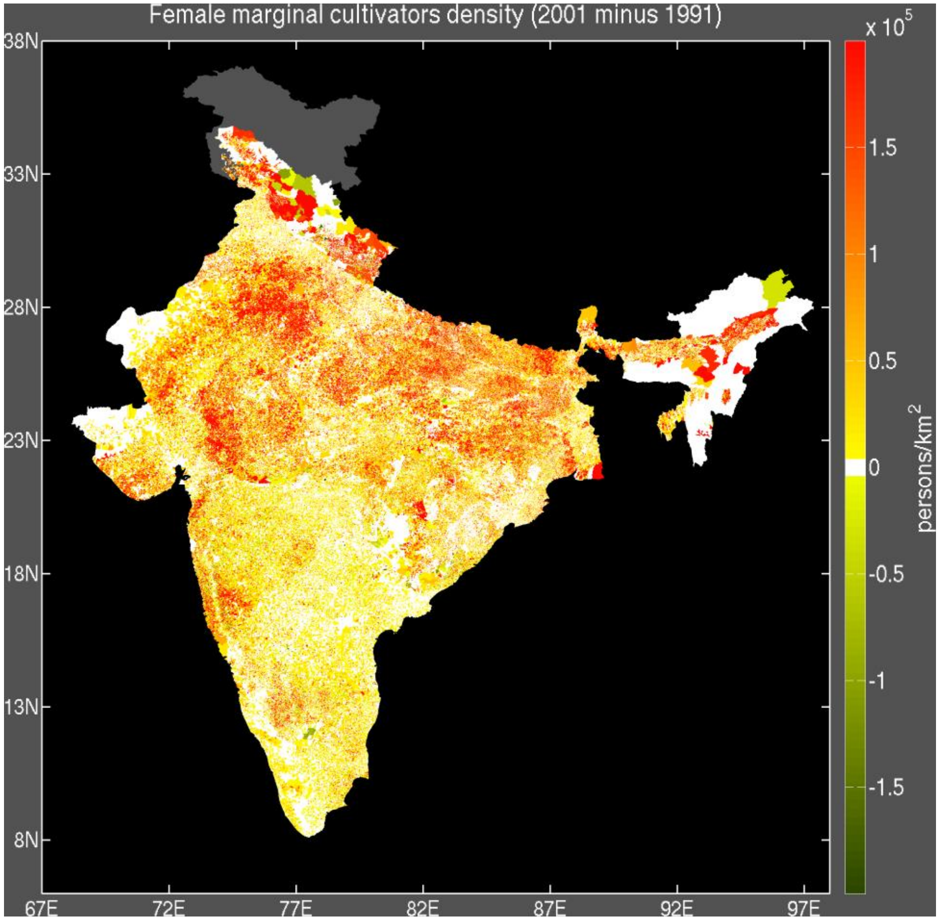
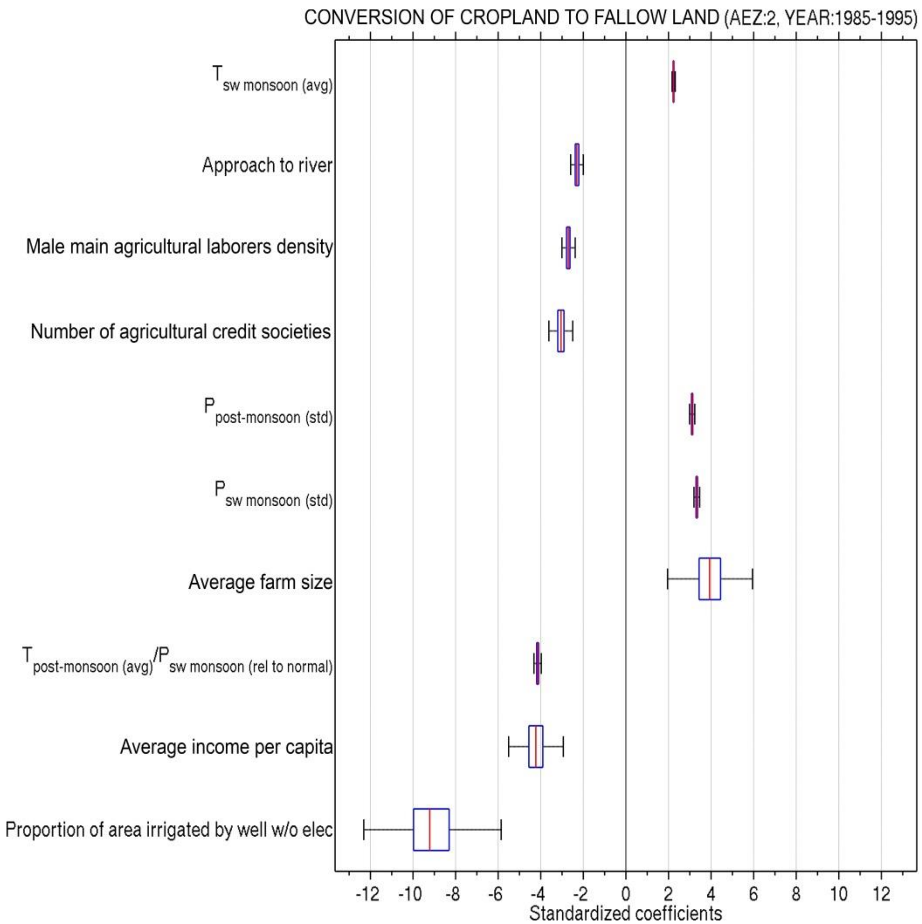


Figure. S7. Similar to Fig. 3a but for AEZ2 (a) 1985-1995, and (b) 1995-2005.



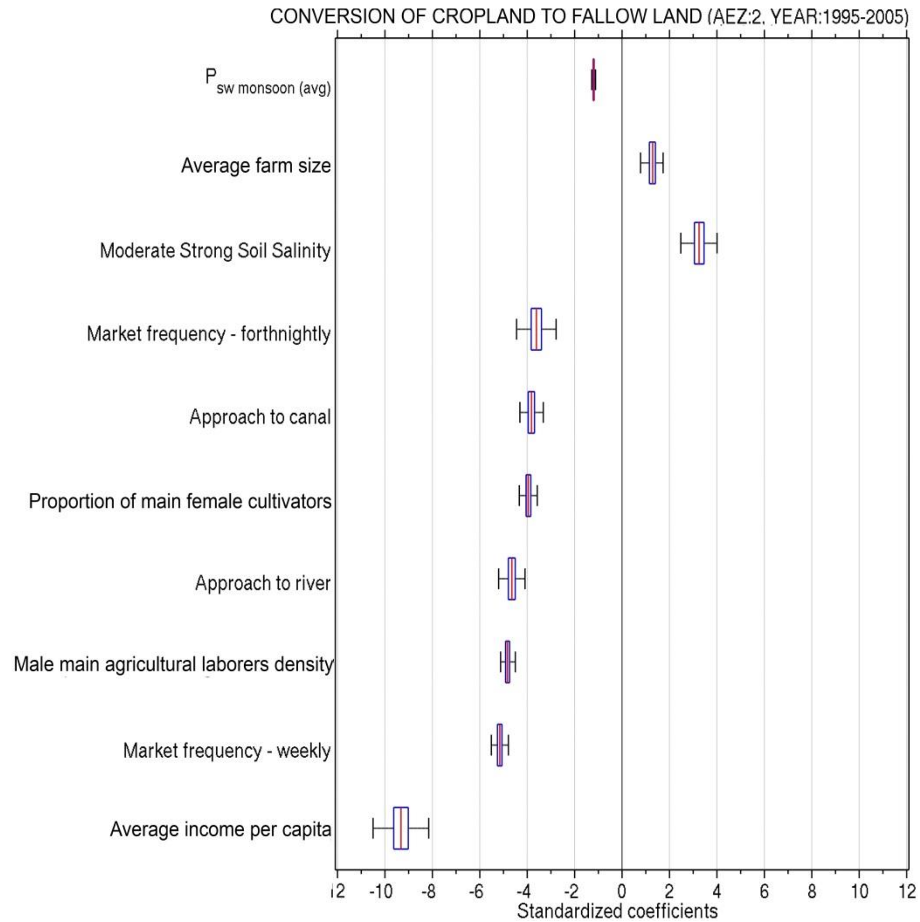


Figure. S8. Similar to Fig. 3a but for AEZ8 (a) 1985-1995, and (b) 1995-2005.

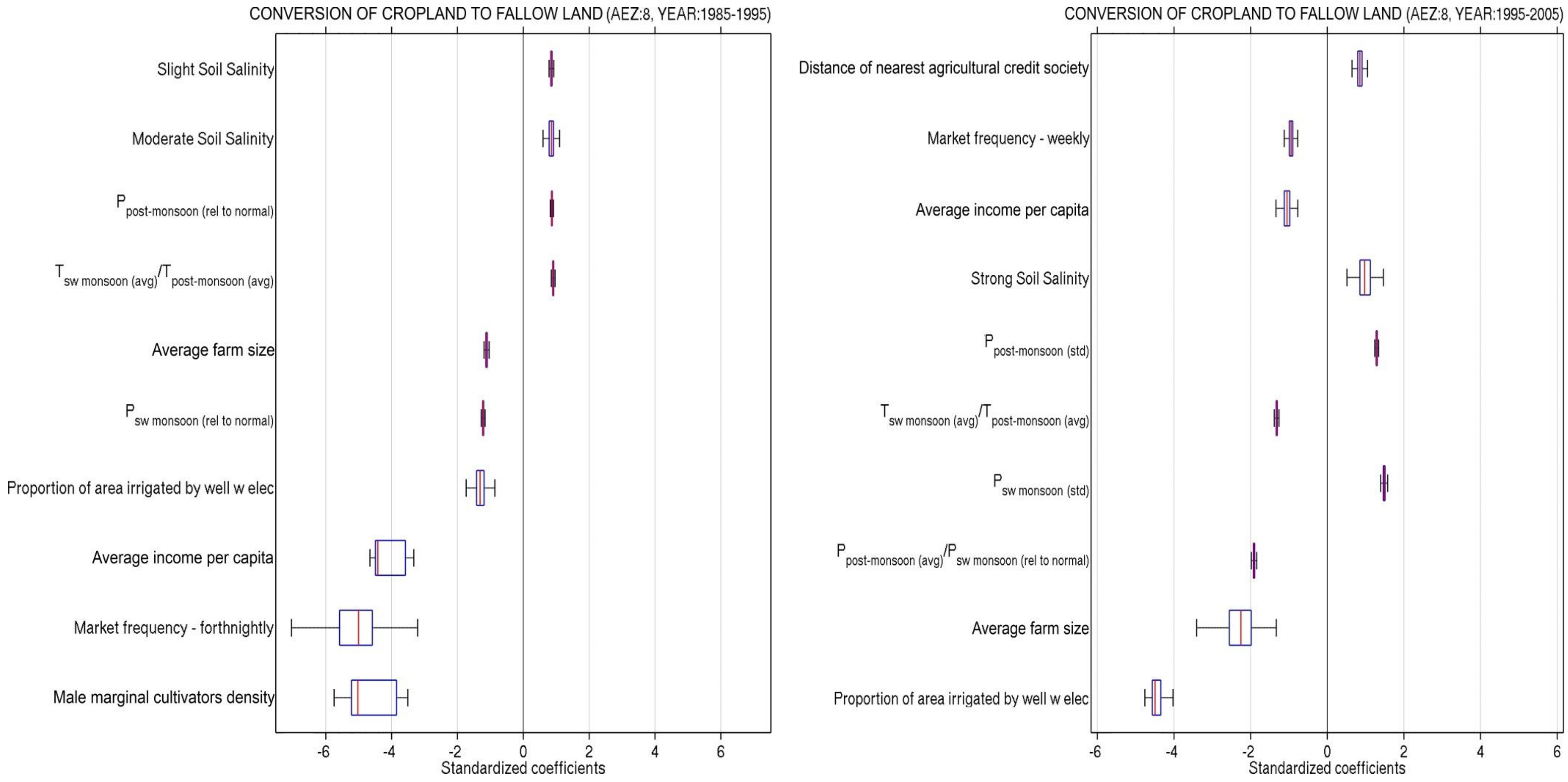


Figure. S9. Similar to Fig. 3a but for AEZ4 and for 1985-1995.

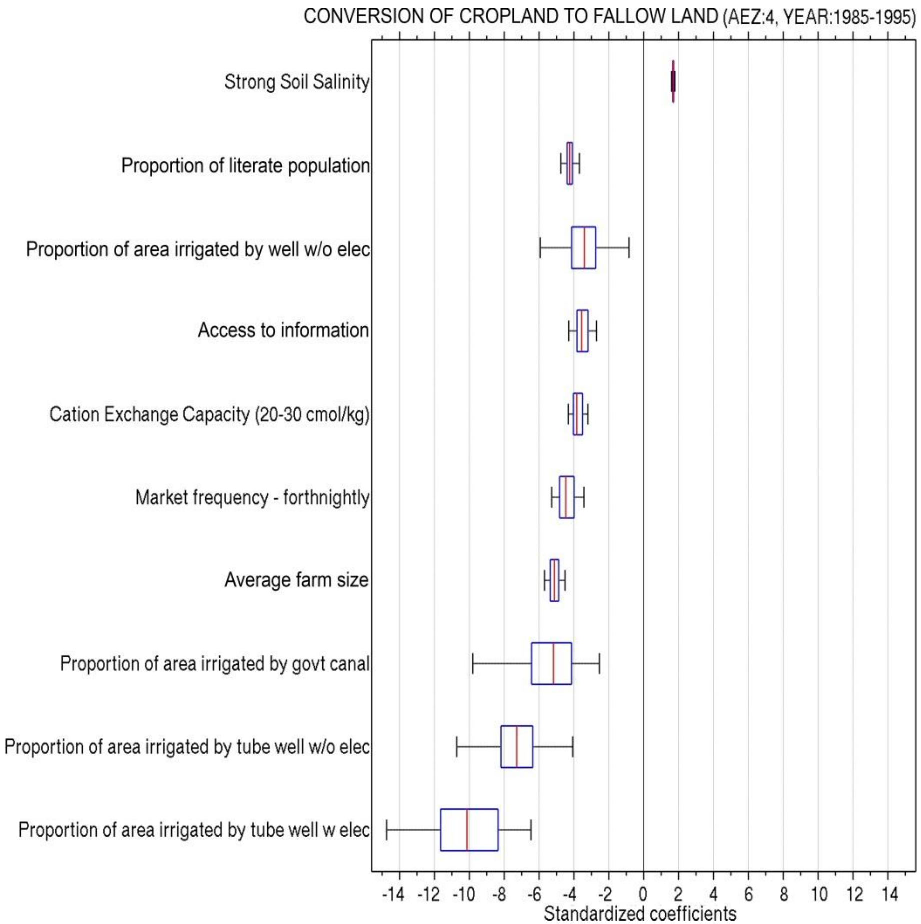


Figure. S10. Similar to Fig. 3a but for AEZ5 and for 1995-2005.

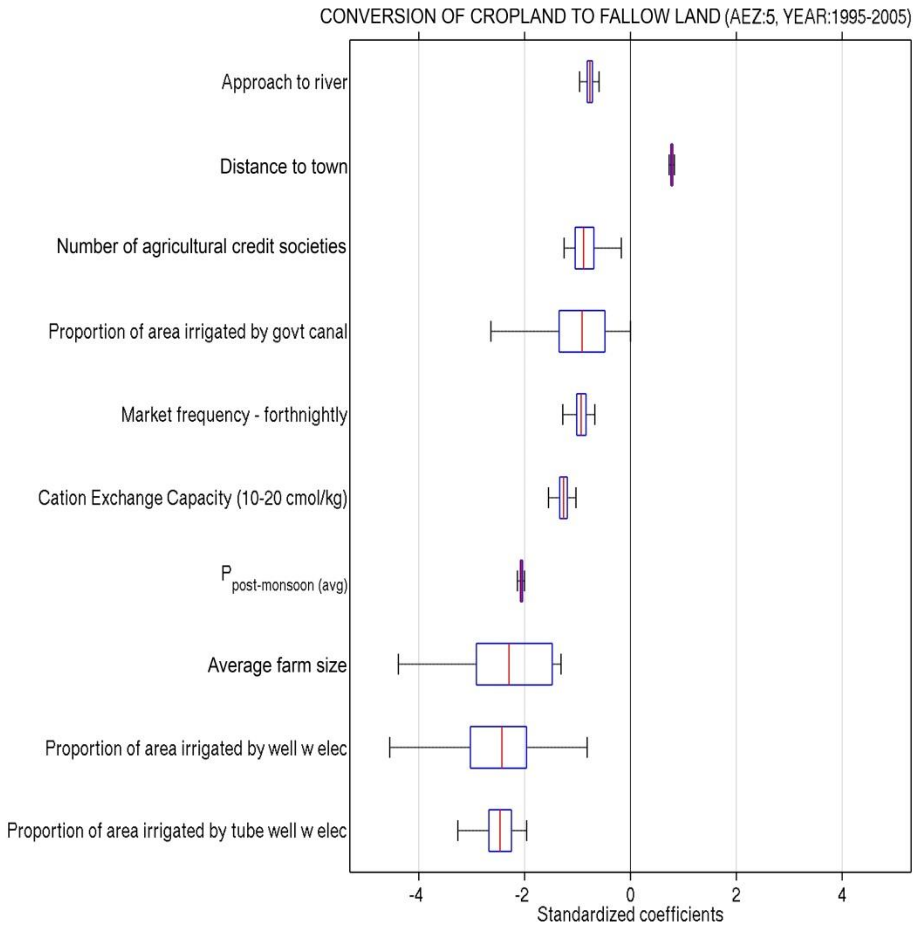


Figure. S11. Similar to Fig. 3b but for AEZ8 (a) 1985-1995, and (b) 1995-2005.

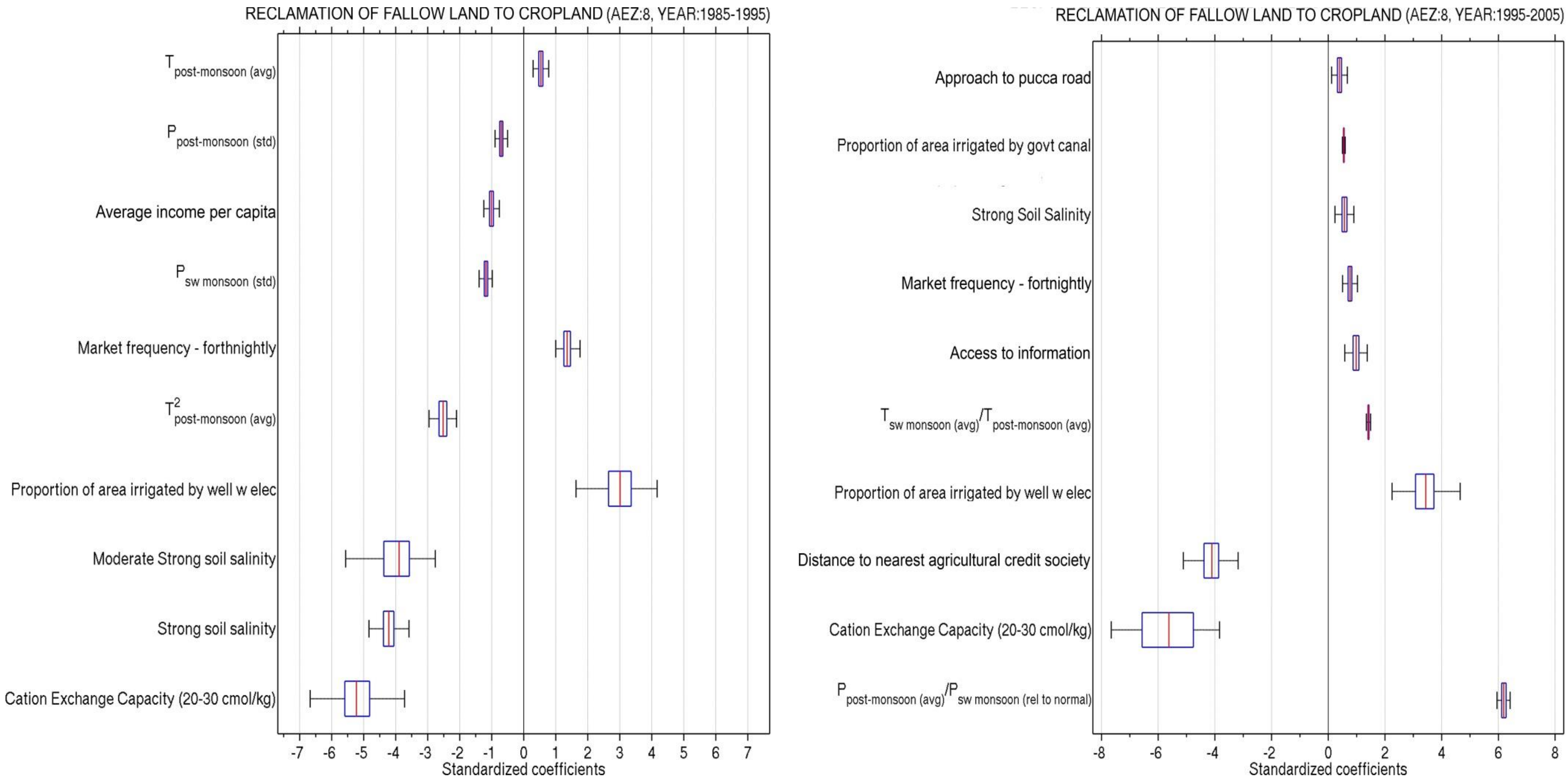


Figure. S12. Similar to Fig. 3b but for AEZ6 and for 1985-1995.

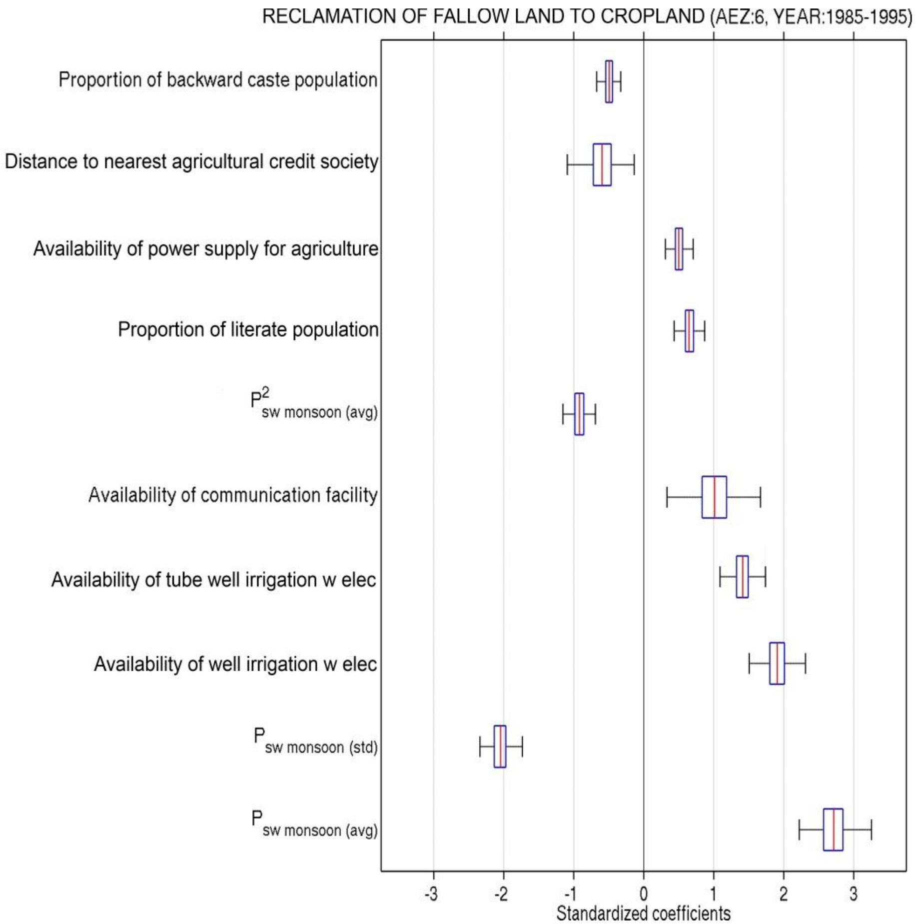


Figure. S13. Similar to Fig. 3b but for AEZ2 and for 1995-2005.

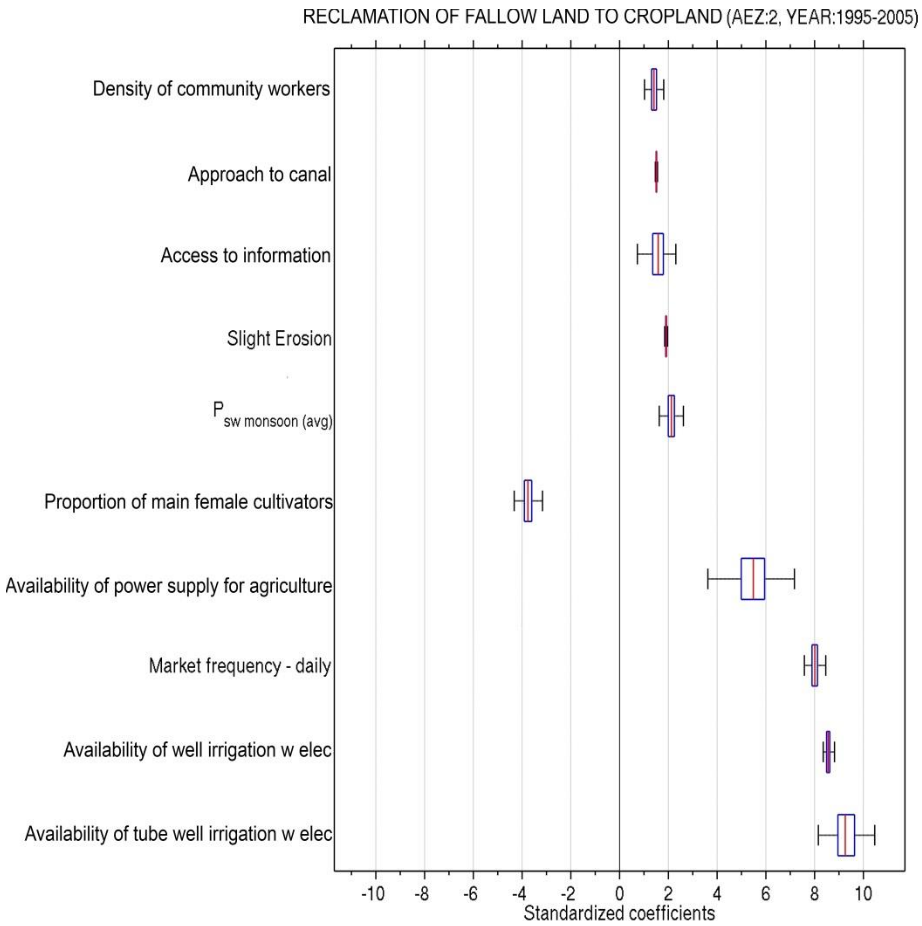


Figure. S14. The series of figures show changes (between 1991 and 2001) in spatial patterns of six key types of irrigation calculated from village level census database (~630,000 political units). (a) Irrigation by well with electricity, (b) Irrigation by well without electricity, (c) Irrigation by tube well with electricity, (d) Irrigation by tube well without electricity, (e) Irrigation by government canal, (f) Irrigation by tanks. The boundaries (black solid lines) show the state boundaries according to 2001 census. The dotted black lines indicate AEZ boundaries.

Sub-plots (a) and (b)

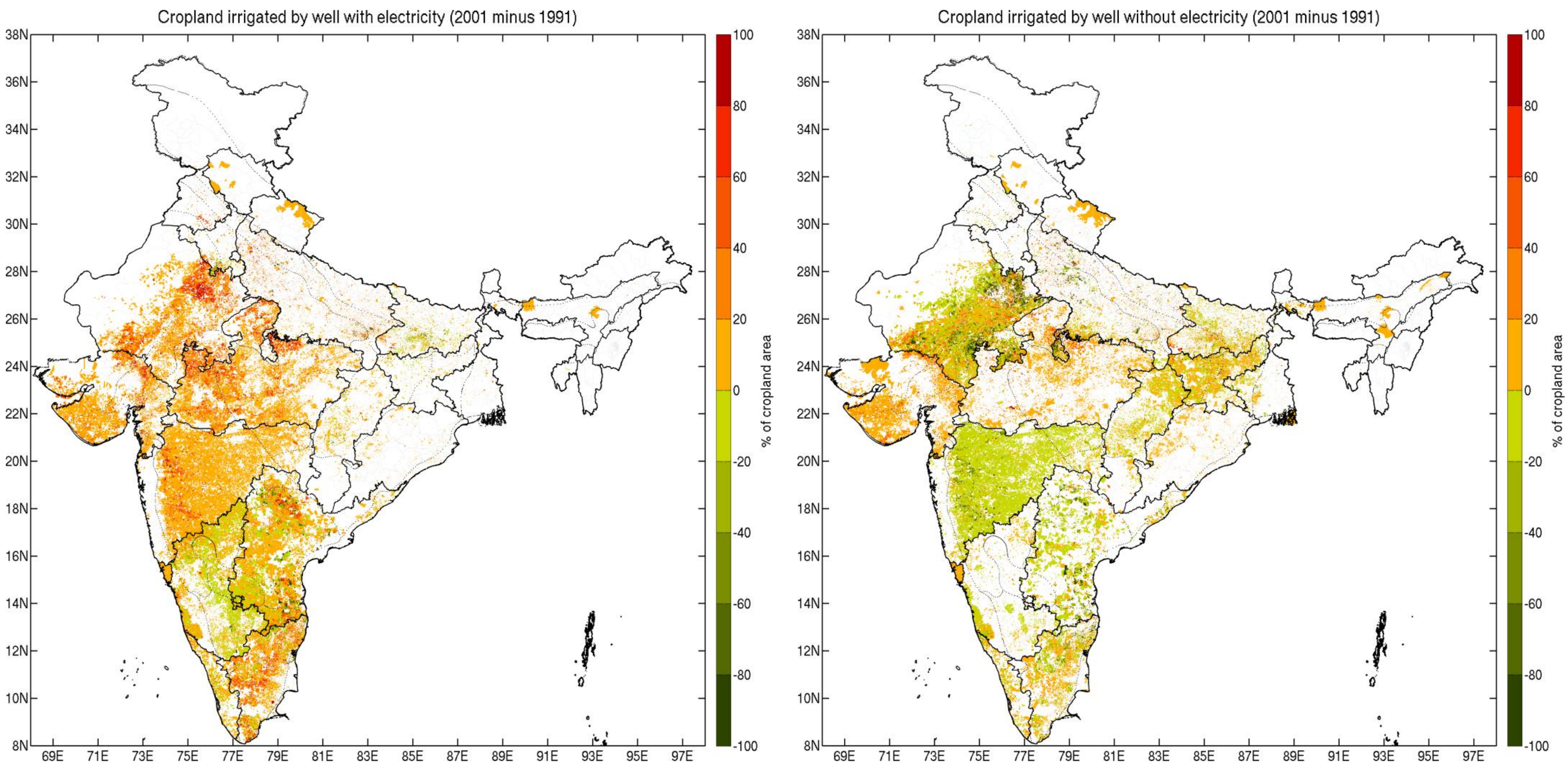
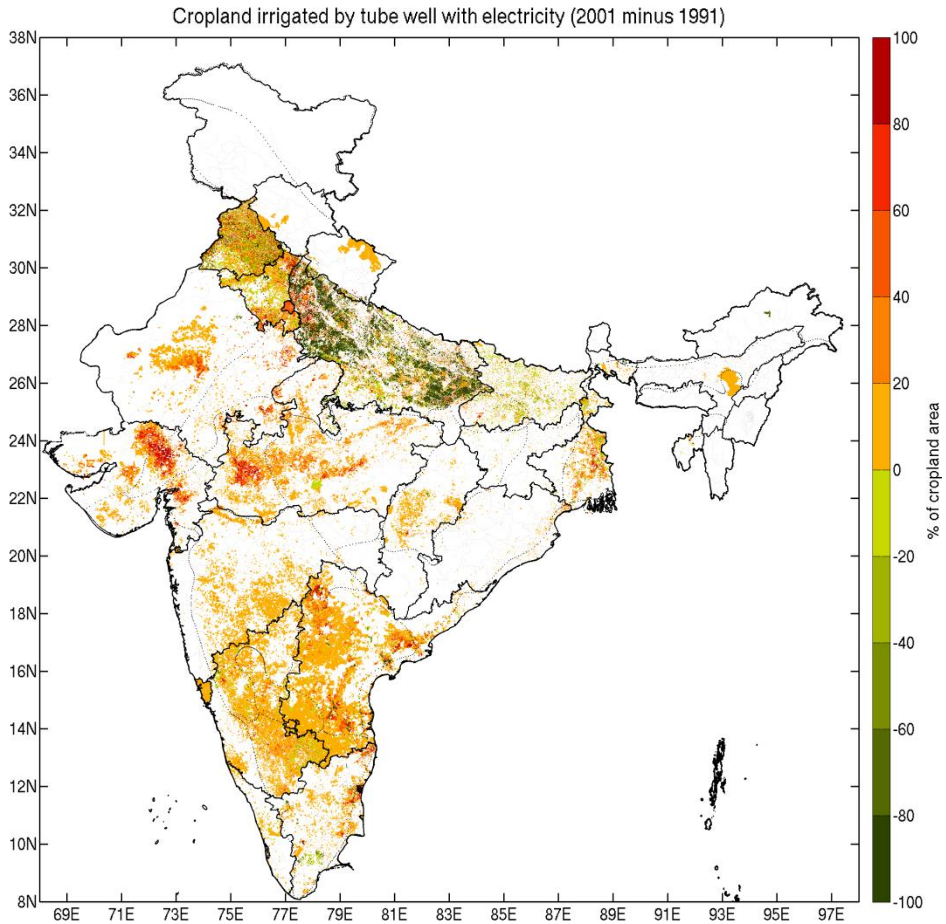


Fig. S14 (continued) Sub-plots (c) and (d)



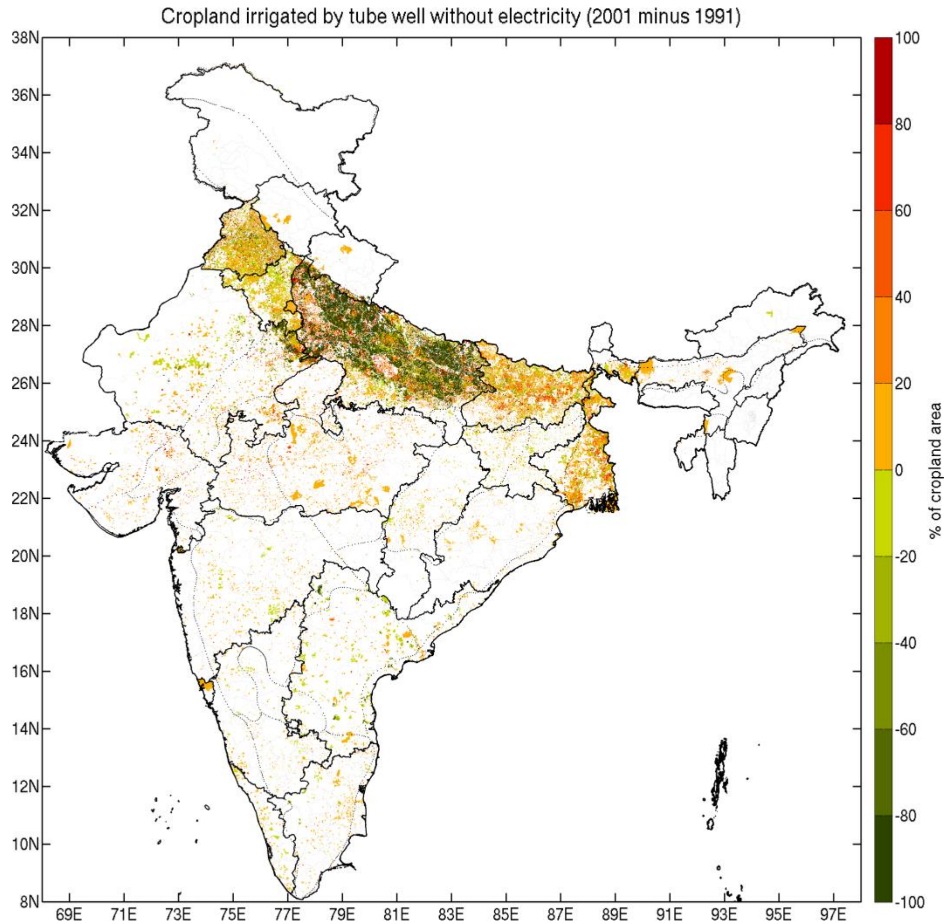
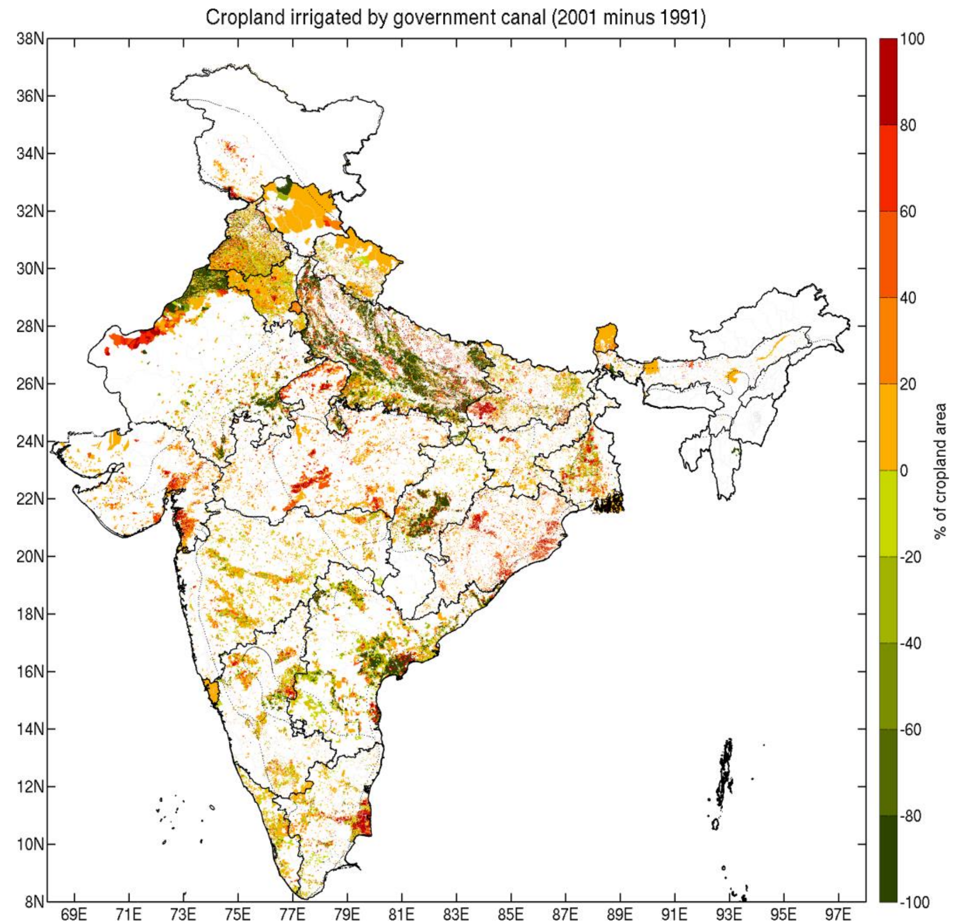


Fig. S14 (continued) Sub-plots (e) and (f)



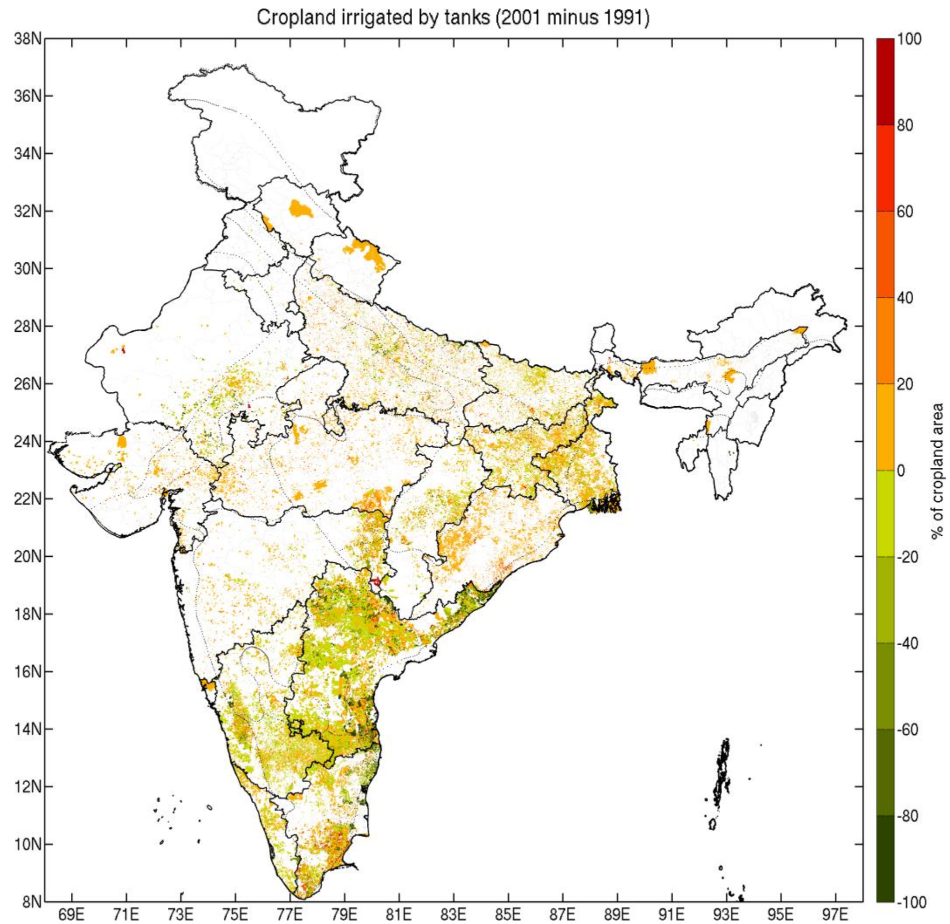


Figure. S15. Similar to Fig. 4a but for 1985-1995.

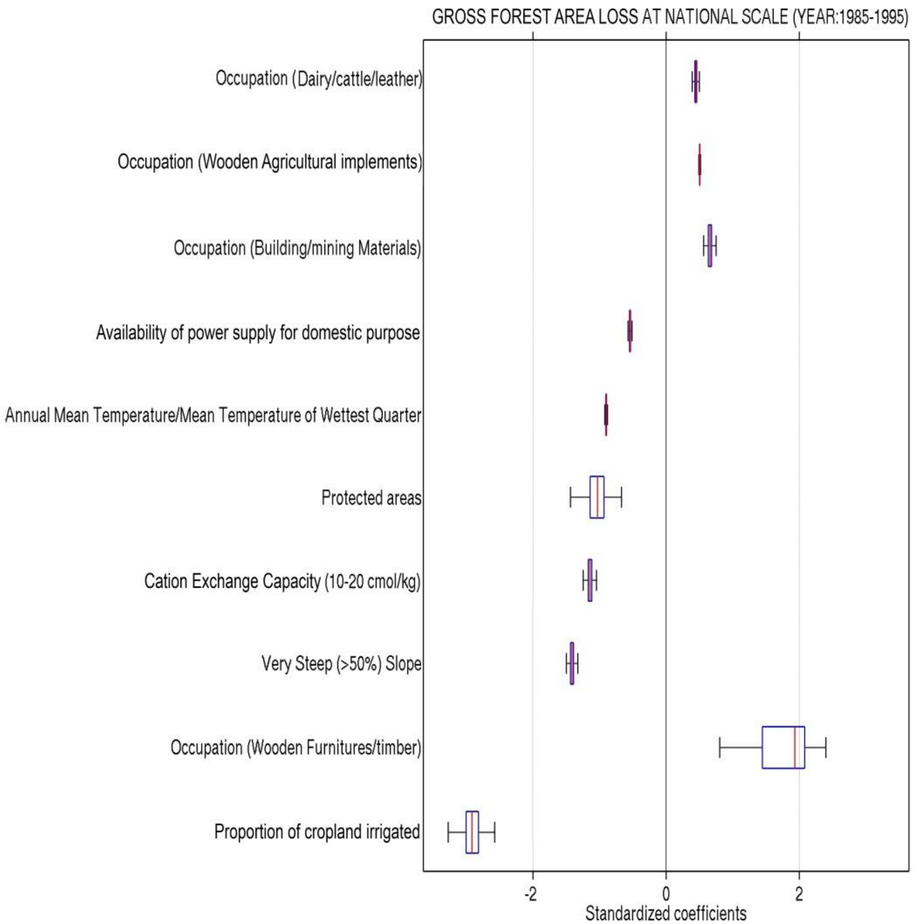


Figure. S16. Grouping of the total forest area loss by type of land protection (y-axis). Analysis is at national scale: (a) 1985-1995, and (b) 1995-2005. Central red line show mean estimate; error bars (blue) show 5% to 95% confidence interval from bootstrap resampling with 500 replicates (to account for spatial autocorrelation); whiskers show 25% to 75% confidence interval.

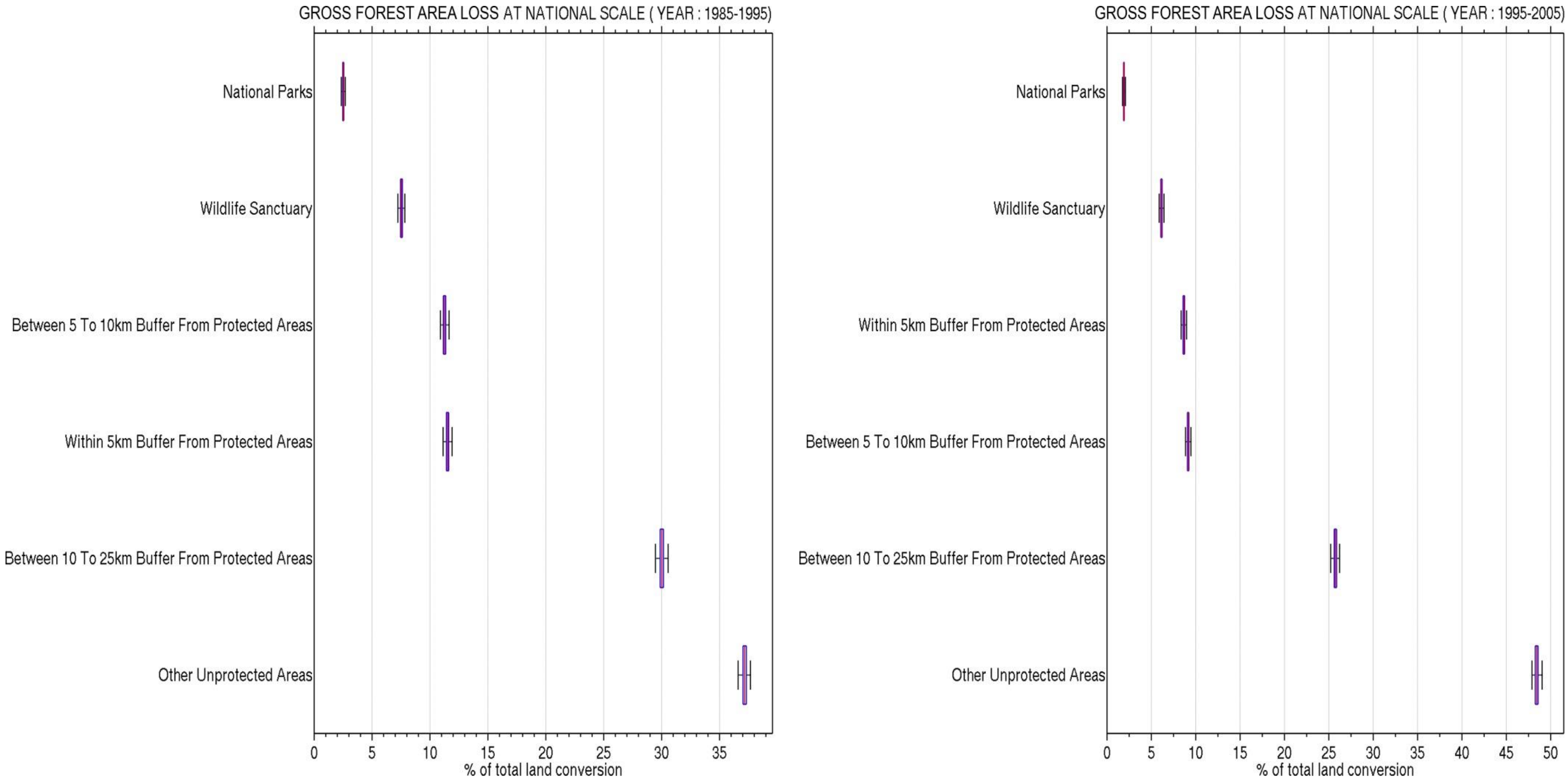


Figure. S17. Similar to Fig. 4a but for AEZ10 (a) 1985-1995, and (b) 1995-2005.

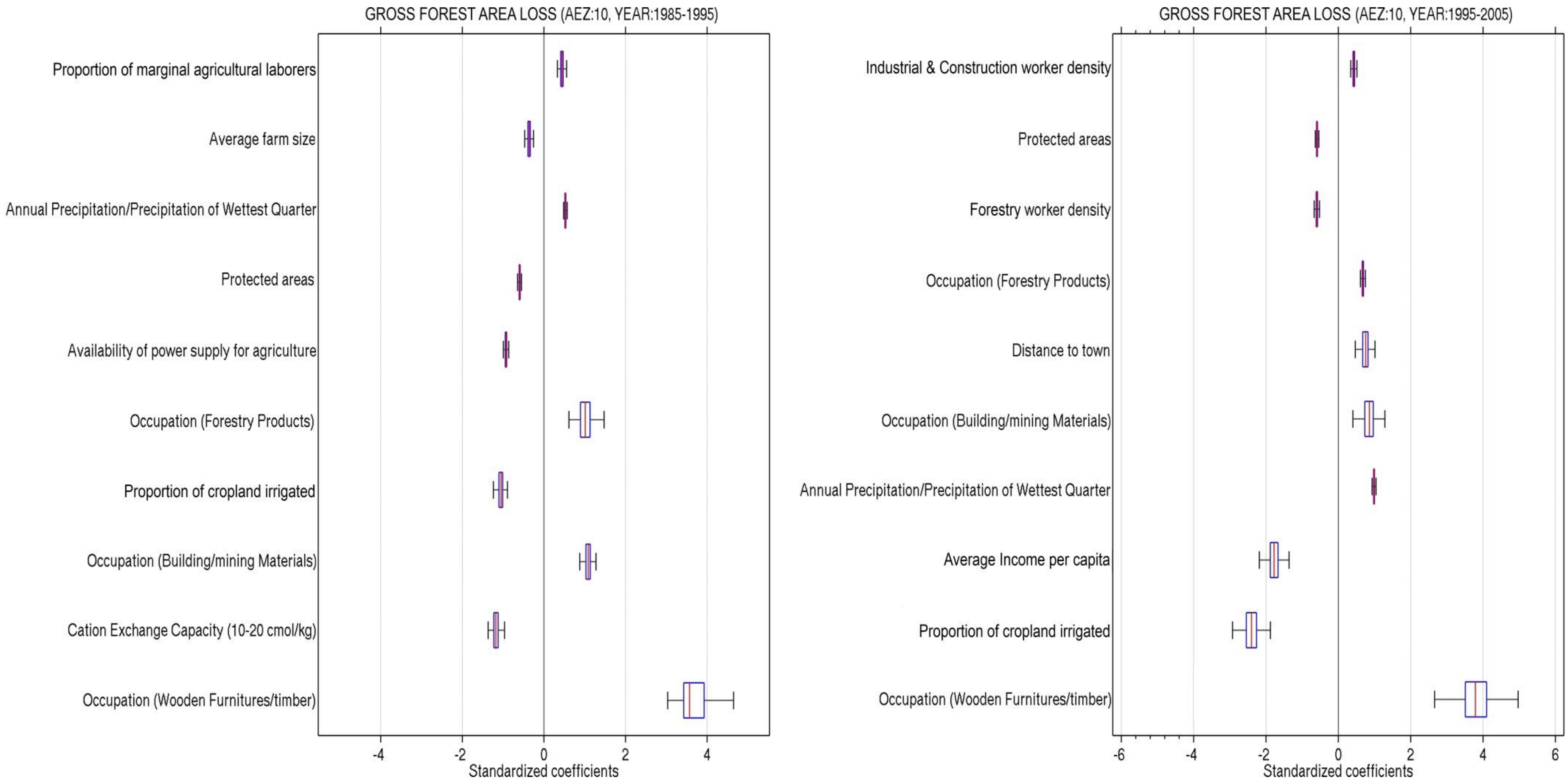


Figure. S18. Similar to Fig. 4a but for AEZ12 (a) 1985-1995, and (b) 1995-2005.

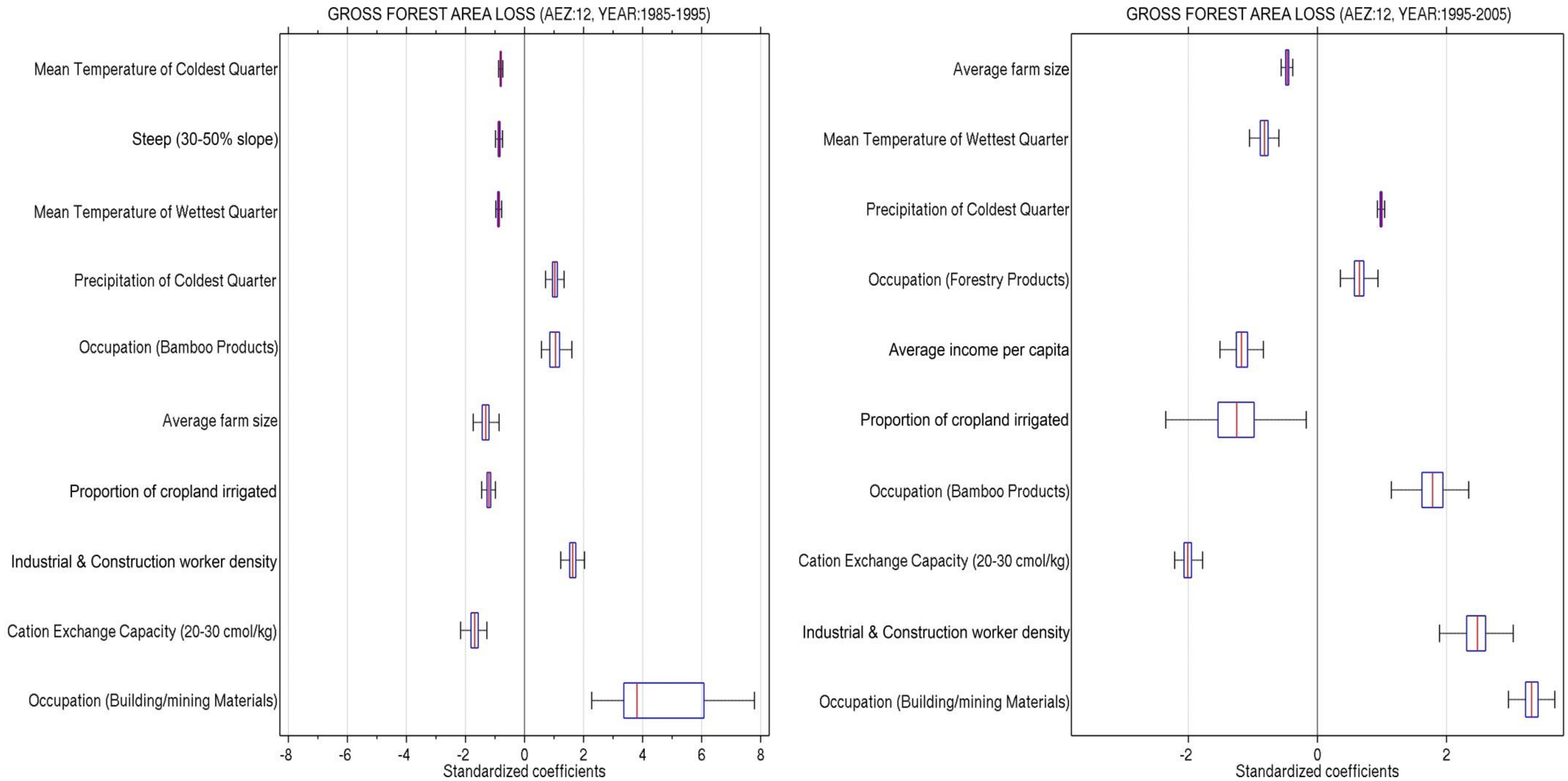


Figure. S19. Similar to Fig. 4a but for AEZ19 and for 1985-1995.

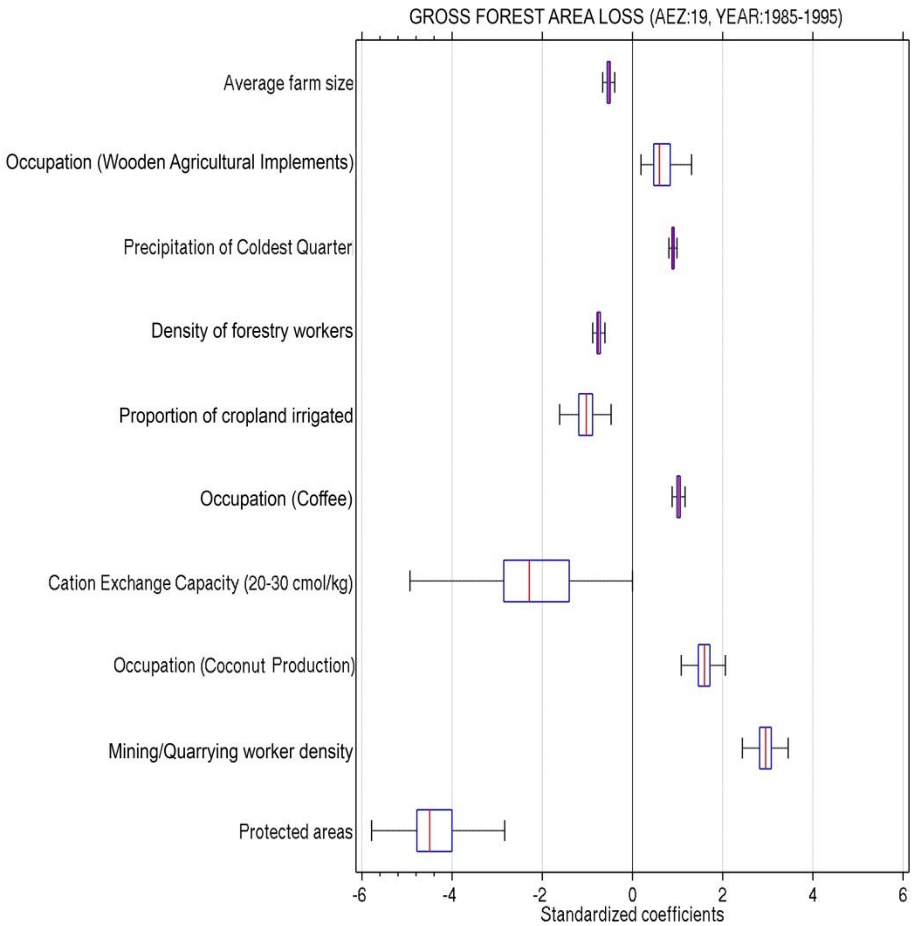


Figure. S20. Similar to Fig. 4a but for AEZ5 and for 1995-2005.

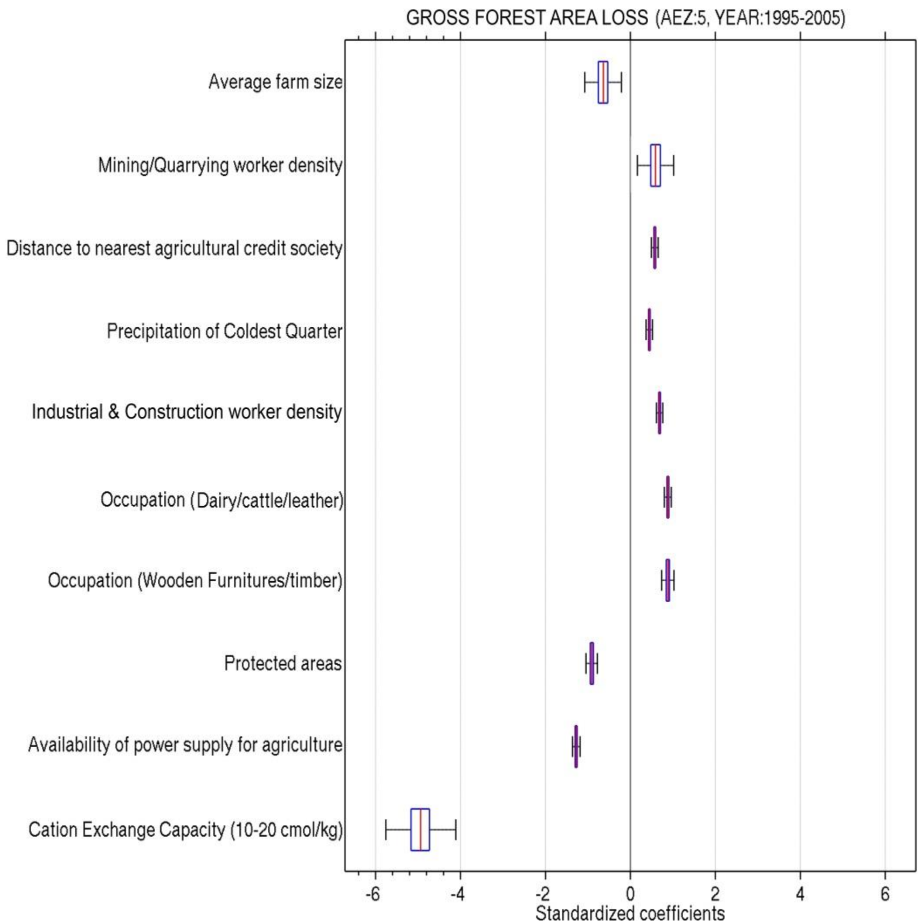


Figure. S21. Similar to Fig. 4a but for AEZ14 and for 1995-2005.

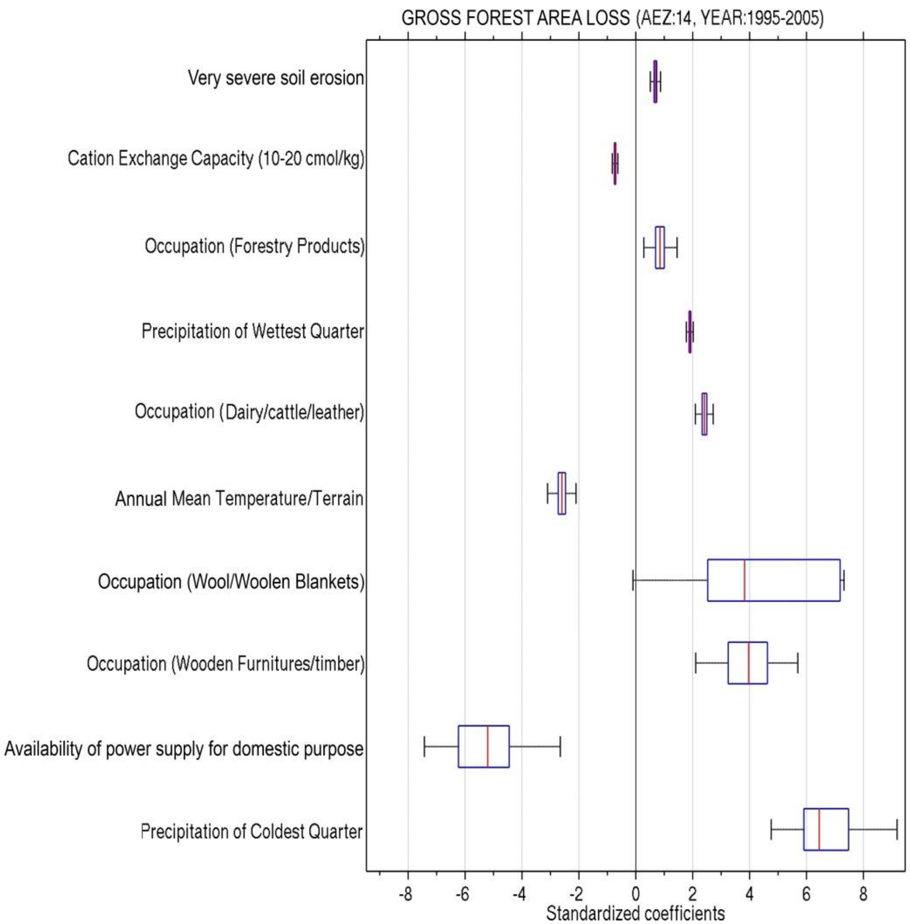


Figure. S22. Similar to Fig. 4b but for 1985-1995.

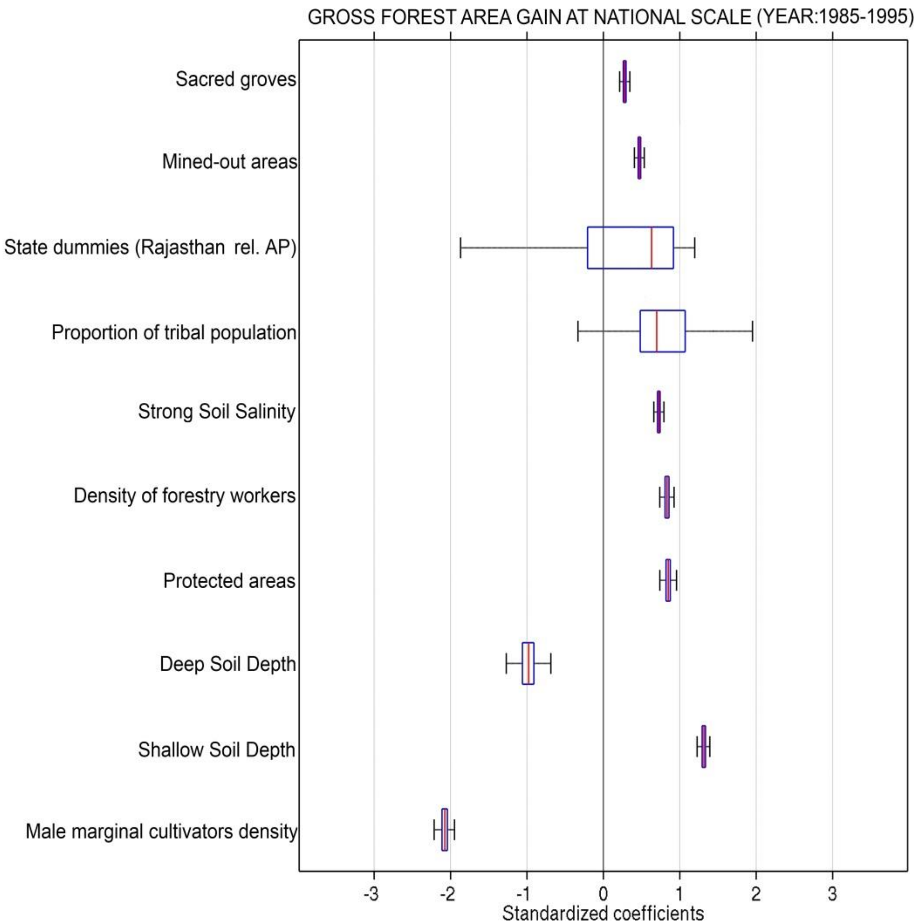


Figure. S23. Similar to Fig. 4b but for AEZ5 (a) 1985-1995, and (b) 1995-2005.

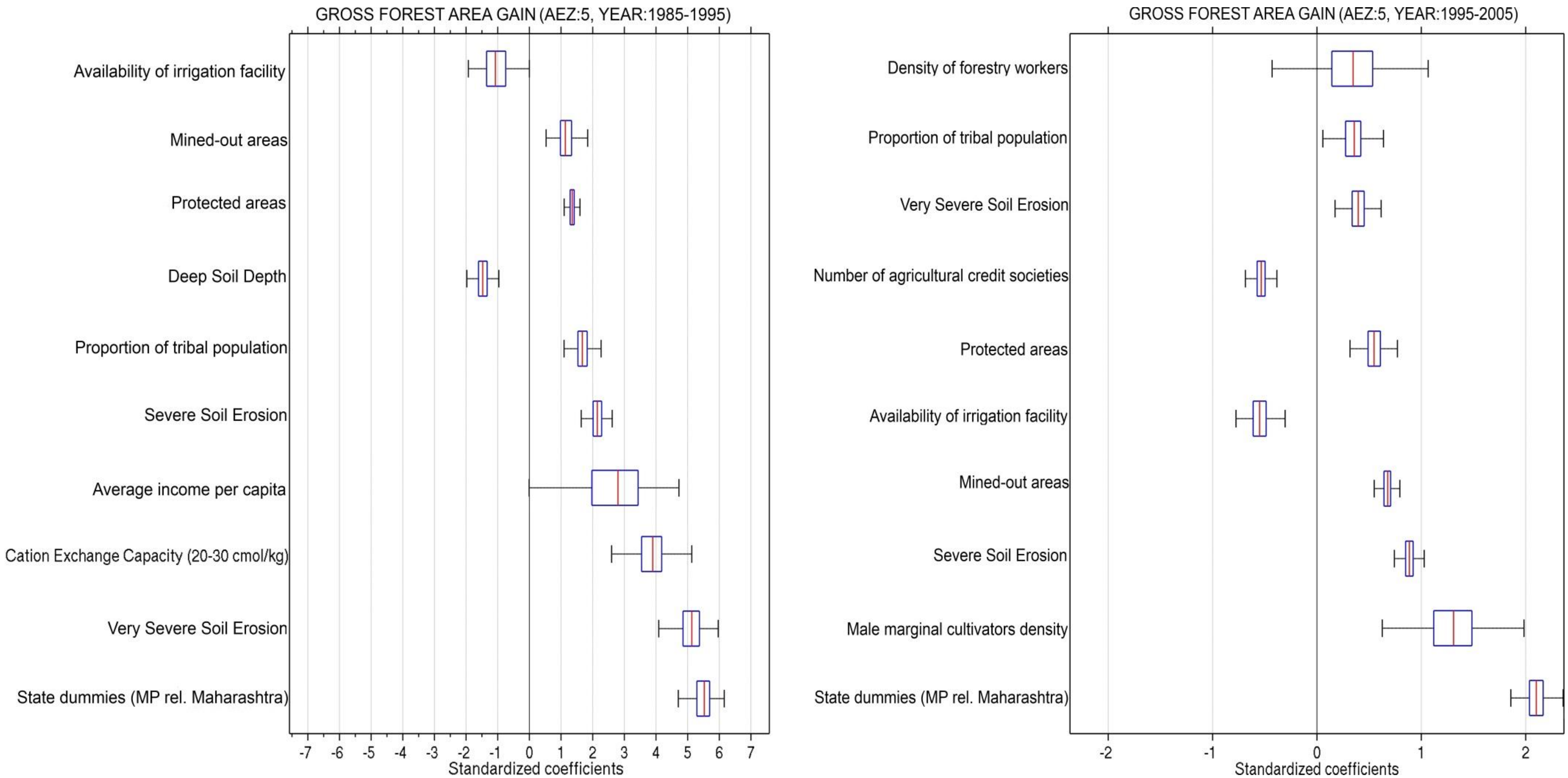


Figure. S24. Similar to Fig. 4b but for AEZ12 and for 1985-1995.

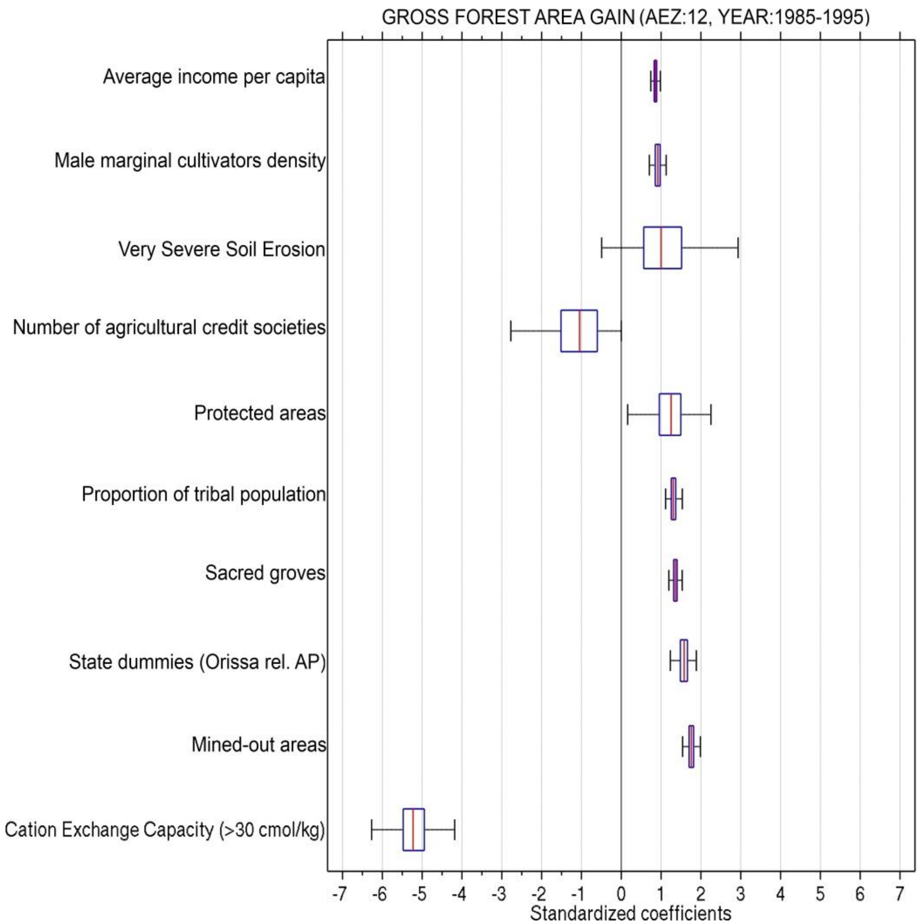


Figure. S25. Similar to Fig. 4b but for AEZ4 and for 1995-2005.

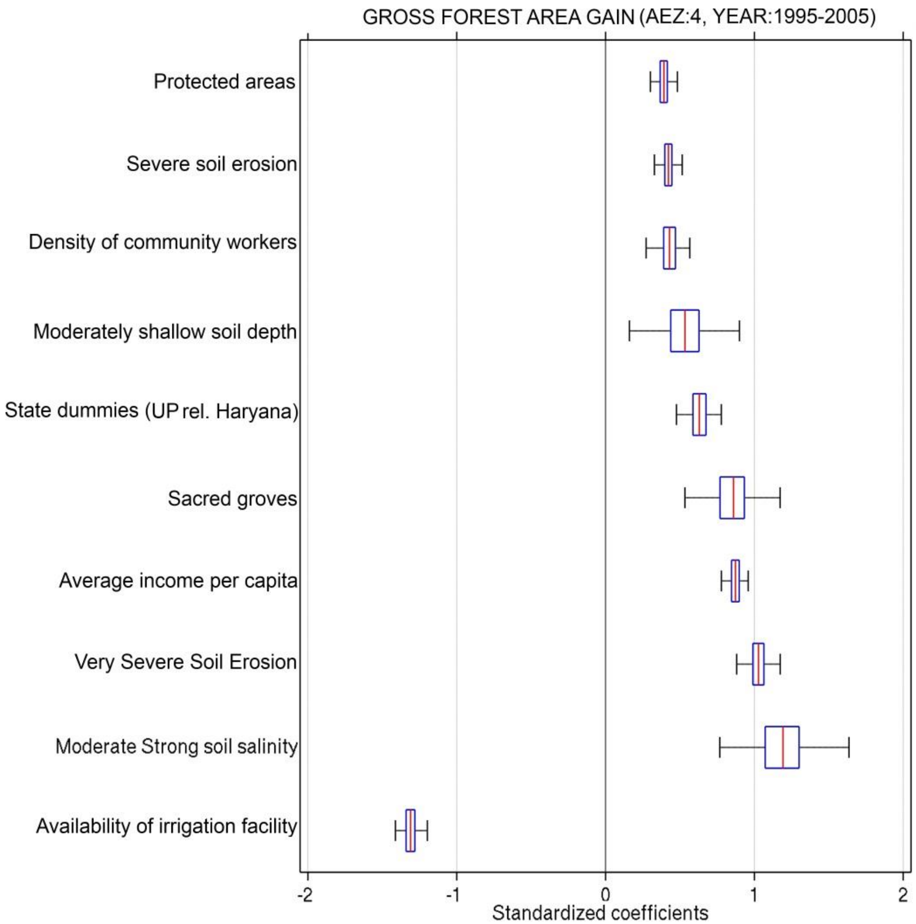


Figure. S26. Similar to Fig. 4b but for AEZ10 and for 1995-2005.

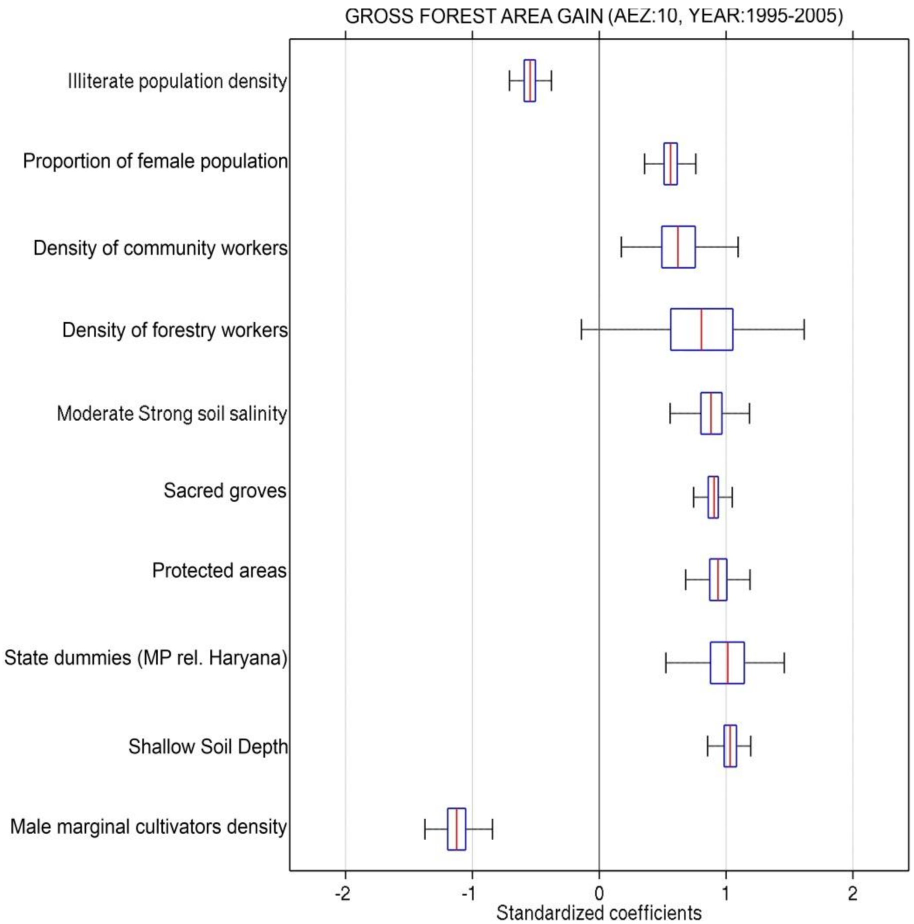
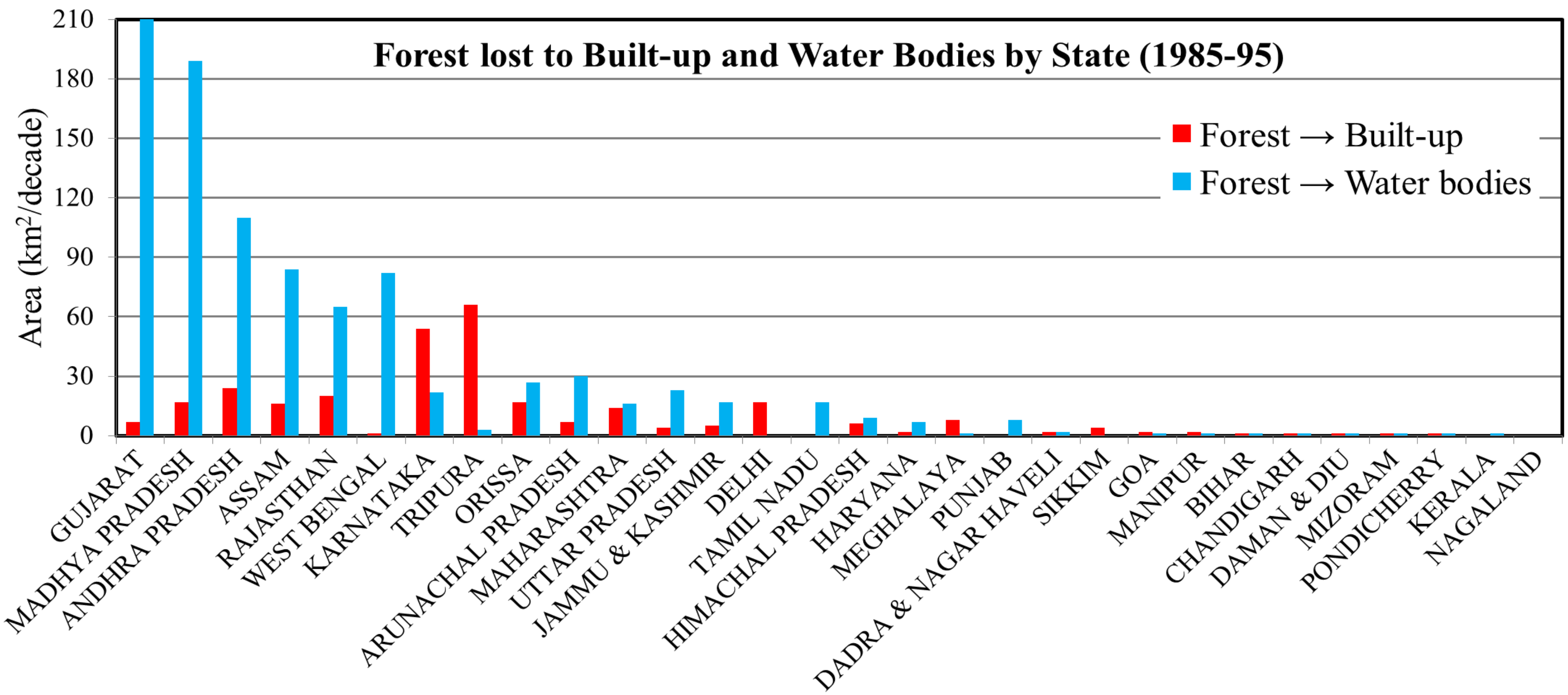


Figure S27. State-wise analysis of forest area diverted to built-up land and water bodies analyzed through Landsat data: (a) 1985-1995, and (b) 1995-2005. For 1985-1995 analysis, state boundaries correspond to 1991 census. For 1995-2005 analysis, state boundaries correspond to 2001 census. For Gujarat state, we have excluded changes within "Rann of Kutch" region which is predominantly covered by shallow wetland which submerges in water during the rainy season and becomes dry during other seasons. Therefore, the changes in water bodies areas observed in this region in our data is because of using Landsat scenes from different season across the decadal maps, thereby representing natural seasonal variations rather than human land conversions.

Sub-plot (a)



Sub-plot (b)

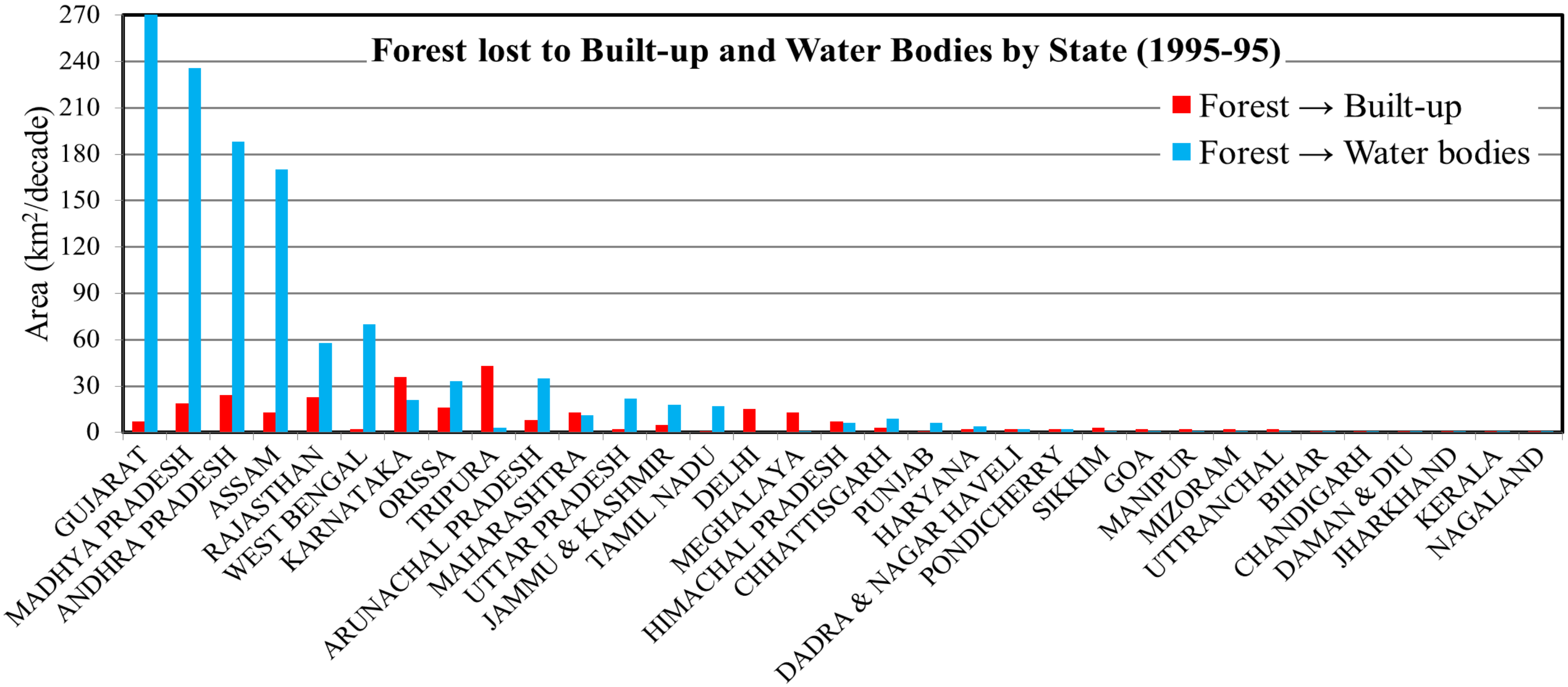

Forest lost to Built-up and Water Bodies by State (1995-95)
Forest → Built-up
Forest → Water bodies
Area (km²/decade)
270
240
210
180
150
120
90
60
30
0
GUJARAT
MADHYA PRADESH
ANDHRA PRADESH
ASSAM
RAJASTHAN
WEST BENGAL
KARNATAKA
ORISSA
TRIPURA
ARUNACHAL PRADESH
MAHARASHTRA
UTTAR PRADESH
JAMMU & KASHMIR
TAMIL NADU
DELHI
MEGHALAYA
HIMACHAL PRADESH
CHHATTISGARH
PUNJAB
HARYANA
DADRA & NAGAR HAVELI
PONDICHERRY
SIKKIM
GOA
MANIPUR
MIZORAM
UTTRANCHAL
BIHAR
CHANDIGARH
DAMAN & DIU
JHARKHAND
KERALA
NAGALAND

Figure S28. Example cross-validation curve from Simulation 1 (Table S14) for $\alpha = 0.4$ (one value of the *10*-fold cross-validation). The sequence of λ's used in the fits is shown in bottom x-axis. The top x-axis show the number of non-zero variables. The type of loss used for validation is binomial deviance (y-axis). The blue points are the mean cross-validated error along the grid of λ sequence; the grey error bars show the upper and lower standard deviation curves along the λ sequence. Two selected λ's are indicated by the vertical yellow dotted lines. The left-most line is the value of λ that gives minimum mean cross-validated error ('best model' corresponding to the chosen value of α). The other λ is the most regularized model such that error is within one standard error of the minimum.