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# Land-Cover Change Trajectories in Northern Ghana

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ABSTRACT / Land-cover change trajectories are an emergent property of complex human–environment systems such as the land-use system. An understanding of the factors responsible for land change trajectories is fundamental for land-use planning and the development of land-related policies. The aims of this study were to characterize and identify the spatial determinants of agricultural land-cover change trajectories in northern Ghana. Land-cover change trajectories were defined using land-cover maps prepared from Landsat Thematic Mapper dataset acquired in 1984, 1992, and 1999. Binary logistic regression was used to model the probability of observing the trajectories as a function of spatially explicit biophysical and socioeconomic independent variables. Population densities generally increased along the continuum of land-use intensity, whereas distance from market and roads generally decreased along this continuum. Apparently, roads and market serve as incentives for settlement and agricultural land use. An increase in population density is an important spatial determinant only for trajectories where the dominant change process is agricultural extensification. A major response to population growth is an increase in cultivation frequency around the main market. Agricultural intensification is highly sensitive to accessibility by roads. The increase in land-use intensity is also associated with low soil quality. These results suggest the need for policies to restore soil fertility for agricultural sustainability. The models also provide a means for identifying functional relationships for in-depth analyses of land-use change in Ghana.

Land-use and land-cover change (LUCC) is among the most important human alterations of the Earth's land surface (Lambin and others 1999). It is a major source and sink for material and energy flow processes of the biosphere and geosphere, impacts biodiversity (Vitousek and others 1997), is a major cause of soil degradation and land fragmentation (Blaikie and Brookfield 1987), and exerts influence on local and regional climate (Intergovernmental Panel on Climate Change 2001). Thus, a detailed assessment of the dynamics of LUCC helps to mitigate negative human impacts on specific places and people (Kasperson and others 1995).

Land-cover change is seldom continuous in space, is sometimes reversible, and usually follows time sequences of successive cover types (Mertens and Lambin 2000). Such temporal dynamics are an inherent property of complex human–environment (adaptive) systems such as the land-use system. Temporal dynamics in LUCC result from the aggregate interactions of diverse agents (land managers) as influenced by climate variability, government policies, market conditions, and demographic changes (Lambin and others 2003). As an emergent property of complex adaptive systems whose future state is not predetermined (Lambin and others 2003), land-use transitions are often characterized by different development pathways (trajectories) in different locales (Martens and Rotmans 2002). An analysis of the spatial determinants of different trajectories is essential for land-use planning and the development of land-related policies.

There has been a focus on the concept of trajectory in LUCC studies in the last few years. Lambin (1997) defined land-cover change trajectory as the succession of land-cover types for a given sampling unit over more than two observation years. He suggested that generic land change pathways, dependent on regional contexts, can be recognized. Boserup (1965) analyzed land change trajectories along a continuum of land-use intensity as part of the process of demography-induced agricultural intensification. In a test of the induced-intensification theory of agricultural change, Turner and Ali (1996) examined agricultural change trajectories for 265 households in 6 villages in Bangladesh from 1950 to 1986. The study showed nonlinearity in the trajectory of agricultural intensification. It also highlighted the relative impact of population growth, household

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*Author to whom correspondence should be addressed; at United Nations University Institute of Advanced Studies; *email:* braimoh@ias.unu.edu class, market and infrastructure, and cropping strategies on cropping frequency and land productivity.

Cropper and others (2001) studied the impact of roads and population pressures on the conversion of forests to agriculture in Thailand between 1976 and 1989. They found that even though both variables affected the amount of cleared land for agriculture, their impact was small. They, therefore, hypothesized that much of the deforestation in Thailand might be due to commercial rather than subsistence agriculture. Southworth and others (2002) studied the relationships between trajectories of forest cover change and biophysical and social variables in western Honduras between 1987 and 1996 using landscape metrics. Patch size was discovered to be a good indicator of economic activity, with patches of swidden agriculture found close to roads, at lower elevations, and on more gradual slopes between 1987 and 1991. Between 1991 and 1996 however, the expansion of export coffee production resulted in forest clearings on steeper slopes and at higher elevations.

Moran and others (2002) have also analyzed the impact of land-use trajectories on soil fertility, forest succession, and cropping strategies in the Amazon. Mertens and Lambin (2000) used a spatial model of land-cover change trajectories based on the agricultural land rent theory to study deforestation processes in southern Cameroon. The study shows that modeling land-cover change trajectories over several observation years improved the prediction of deforestation probabilities over projections based on observations in the previous period alone. McConnell and others (2004) recently analyzed the spatio-temporal determinants of agricultural land change in Madagascar from 1957 to 2000. The study revealed that although the overall land change patterns are largely explained by altitude and proximity to villages, specific trajectories relate to institutional factors that govern access to land resources.

The aim of this study was to identify the spatial determinants of land-cover change trajectories in a semiarid area of Ghana. Our previous studies (Braimoh 2004a, 2004b) show that land change processes in northern Ghana involved the coexistent processes of agricultural extensification and intensification. However, the role and relative importance of population, infrastructure, and markets in the evolution of land trajectories have not been ascertained. In this study, we characterized different land change trajectories on the basis of biophysical and socio-economic variables, on the one hand, and developed spatial statistical models that predict the probabilities of observing the trajectories, on the other. We compare our results with some case studies of land-use change and then highlight the research and policy implications of the findings.

## Paradigms of Land-Use Change

The absence of formal process theories to link the complex social and environmental dimensions of land change implies that theories developed either in the social or natural sciences are adapted for case studies of LUCC (Veldkamp and others 2001). In this article, we use insights from various land-use theories to frame the analyses of land change trajectories in northern Ghana. These theories include the Malthusian and Boserupian paradigms that relate land use to population growth, the Ricardian paradigm that links land use to intrinsic land quality, and the von Thünen paradigm that associates land use to location of land parcels.

Malthus (1967) originally predicted the inability of food production to keep pace with population growth. The neo-Mathusian perspective argues that land-use change follows a degradational pathway in which population pressure not only curtails the food potential but also leads to environmental degradation (Mortimore 1993). Boserup (1965), on the other hand, contended that communities respond to pressures induced by population growth by substituting abundant factors for scarce ones. This might be in the form of shortening of fallow, intensified use of labor per unit of farmland, adoption of land-conserving technologies, and institutional changes. The viewpoint of Malthus and Boserup remain a subject of debate. Some researchers (e.g., Pahari and Murai 1999) found correlation between growing population and forest decline, whereas others (e.g., Leach and Faihead 2000) have challenged the notion that population growth leads to forest loss. They suggested studies to examine the role of social institutions as mediators of human–environment relationships. Others (e.g., Turner and Ali 1996) sought a compromise between the two theories, emphasizing that Boserupian or Malthusian response to population changes depends on specific situations, as opportunities and constraints vary among localities.

The land rent theory is attributable to Ricardo and von Thünen. Land rent, the excess of total revenue over the total variable cost of production on a piece of land, is assumed to be the main determinant of land-use allocation (Chomitz and Gray 1996). A distinction can be made between *natural* rent, which refers to the intrinsic value of a place such as soil quality and climatic factors, and *location* rent, which applies to a place owing to the presence of the surrounding neighborhood. High soil fertility and nearness to market (implying lower transportation cost) might confer a high rent to a parcel of land. As land rent is often unobserved, models based on the land rent theory incorporate proxy variables such as agricultural suitability and measures of accessibility as explanatory variables. In a study of adaptation to climate variability, Polsky and Easterling III (2001) used the Ricardian land-use theory to evaluate relationships between temperature and agricultural land values, and hence the resilience of farmers to climate variability in the US Great Plains. Chomitz and Gray (1996) developed a spatially explicit model of land use for Belize that estimates probabilities of alternative land uses based on the von Thünen land rent theory. Market access, land quality, and tenure status were observed to affect the probability of agricultural land use synergistically, with differential effects on the likelihood of commercial and semisubsistence farming.

An acknowledgment of the fact that land-use patterns are governed by economic change, government policies, land ownership patterns, and demographic factors calls for modeling methods that allow a broad range of factors as independent variables. This might lead to an improved understanding of LUCC processes in a given context.

## Methods

### Study Area

The study area of approximately 5400 km$^2$ is located in the Guinea savannah agroecological zone of northern Ghana. It lies between latitude 8° 50′ and 10° N and stretches between longitudes 0° 30′ to 1° 30′ W (Figure 1). The annual rainfall is about 1100 mm, but the onset and distribution of rainfall in a year is highly unpredictable. Soils of the study area have developed from sandstone parent materials. They are characterized by a layer of ironstone that impedes root growth at shallow depths. The soil is generally sandy, slightly acidic, and highly deficient in organic matter, N, and P (Abekoe and Tiessen 1998).

About 80% of the over 1.8 million population of the northern region of Ghana depends on agriculture for their livelihood. The farming system depends mainly on natural soil fertility and very little on inorganic fertilizers. The population growth rate is about 3% (Ghana Statistical Service 2002). Poverty is widespread in rural areas of Ghana, with the magnitude and incidence of poverty greatest in the north. Food insecurity manifesting in low consumption and high malnutrition and mortality rates is a widespread phenomenon (Nyanteng and Asuming-Brempong 2003). With erratic rainfall and only marginal soil fertility, feeding the growing population is a major challenge and a prerequisite to rural development. Declining soil fertility resulting from continuous cropping and monocropping has led to declining yields of maize, sorghum, and groundnut (Abatania and Albert 1993).

A plurality of land tenure and administration (i.e., state and customary) exists in Ghana (Kasanga and Kotey 2001). Since the colonial era, a significant amount of land has been compulsorily acquired or vested in the state. Such lands are directly managed by delegated public institutions such as the Lands Commission. The customary sector holds a substantial amount of undeveloped land in Ghana. The landholders within the customary sector include individuals and families, communities, and pioneer settlers of an area. Land ownership and tenure in northern Ghana are entrenched in the traditional common property system, with land administration vested in the village chief (Abudulai 1996). It is common for families to control lands and hand them over to younger generations. The right of usage of land is heritable patrilinealy. When land was plentiful, migrants obtained land almost free of charge from the landholders. No economic value was placed on land, and land transactions usually lacked written records and boundary indicators (Kasanga and Kotey 2001). Allocation (lease) to households is done according to needs, without prejudice to the principle of common ownership. Tenure is generally secure so long as the land is actually cropped. However, fallow lands migh be allocated to other users. Customary land tenure has undergone changes in the form of land sales in peri-urban areas of northern Ghana (Abudulai 1996; Kasanga and Kotey 2001). The gradual transition to private land ownership is due to the effects of expansion of residential areas, on the one hand, and cash crop production that generally requires a high demand for land with secure tenure for investment purposes, on the other.

Macroeconomic changes have had a major impact on rural livelihood in Ghana (Pearce 1992). Two major macroeconomic reform eras in Ghana fairly correspond to the period under study. The first is the stabilization/structural adjustment period (1983–1991), in which the Ghanaian currency was progressively devalued and protection of the food sector decreased (Seini 2002). Devaluation and removal of subsidies on agricultural inputs such as fertilizers increased the prices of the inputs to farmers, but made imported food relative more expensive than domestic food, giving the local farmers a competitive advantage (Abdulai and Huffman 2000). The second period is the post-structural adjustment period (1992–present) characterized by a large government deficit and public-sector

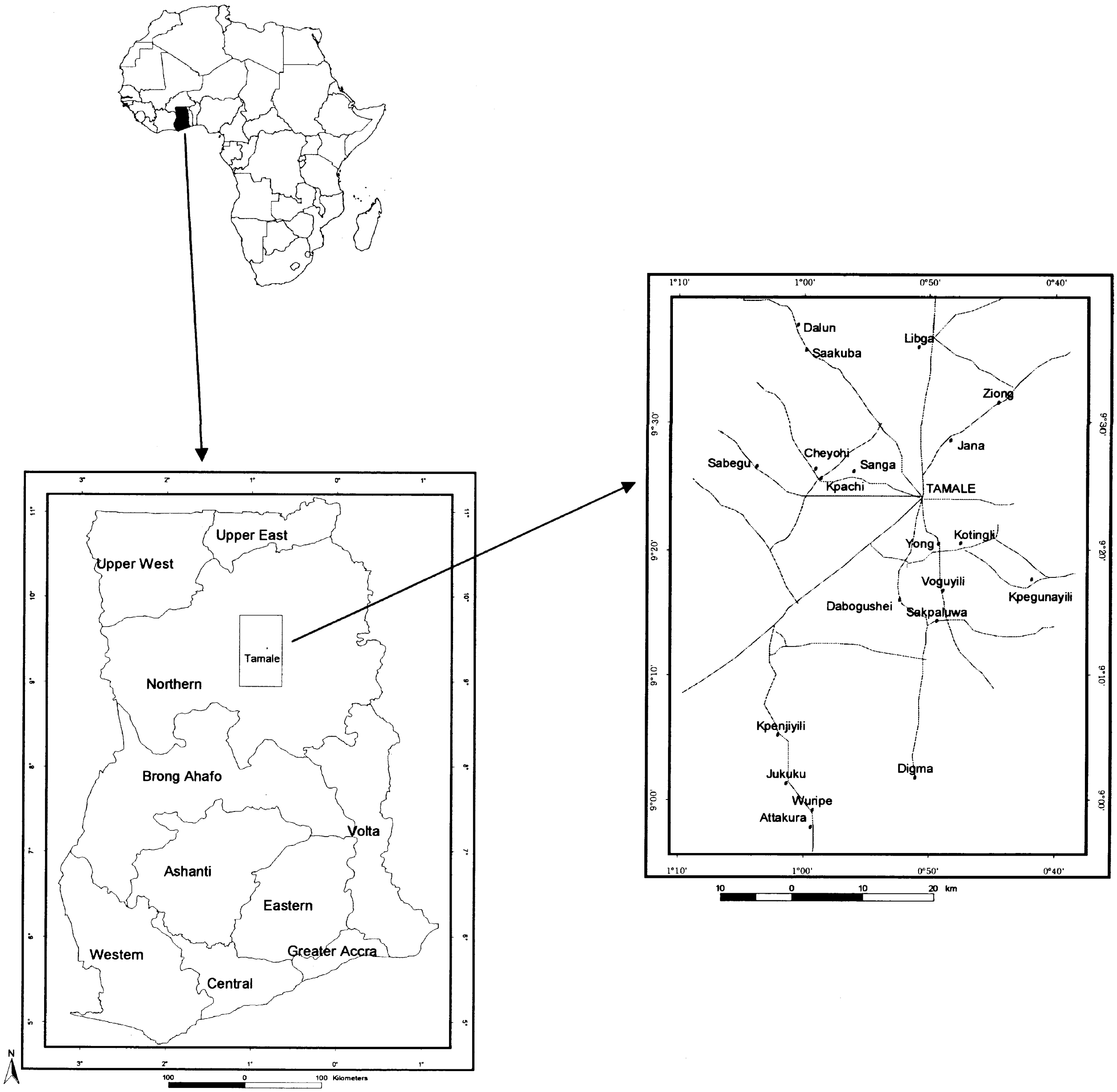

**Figure 1.** Regional map of Ghana. The study area is the rectangle enclosing Tamale, the northern region capital. Other localities around Tamale are also shown.

borrowing. This has led to an intense pressure on credit availability, particularly for farmers, who are among the most credit-constrained (Seini 2002). The possible effects of these policies on agricultural land change will be discussed.

## Data Sources

Three land-cover maps prepared from Landsat TM images for 1984, 1992, and 1999 were used. Six classes were distinguished in each of the images using the maximum likelihood classification algorithm. These were closed woodland, open woodland, grassland, cropland, built-up area, and water. Training samples were obtained from aerial photos and field studies conducted between August and December 2001. The accuracies of the land-cover maps estimated from 312 independent samples measuring approximately 50 m × 50 m each were 85%, 81%, and 88%, respectively.

Land-cover change trajectories were defined by successive transitions between land-cover types from

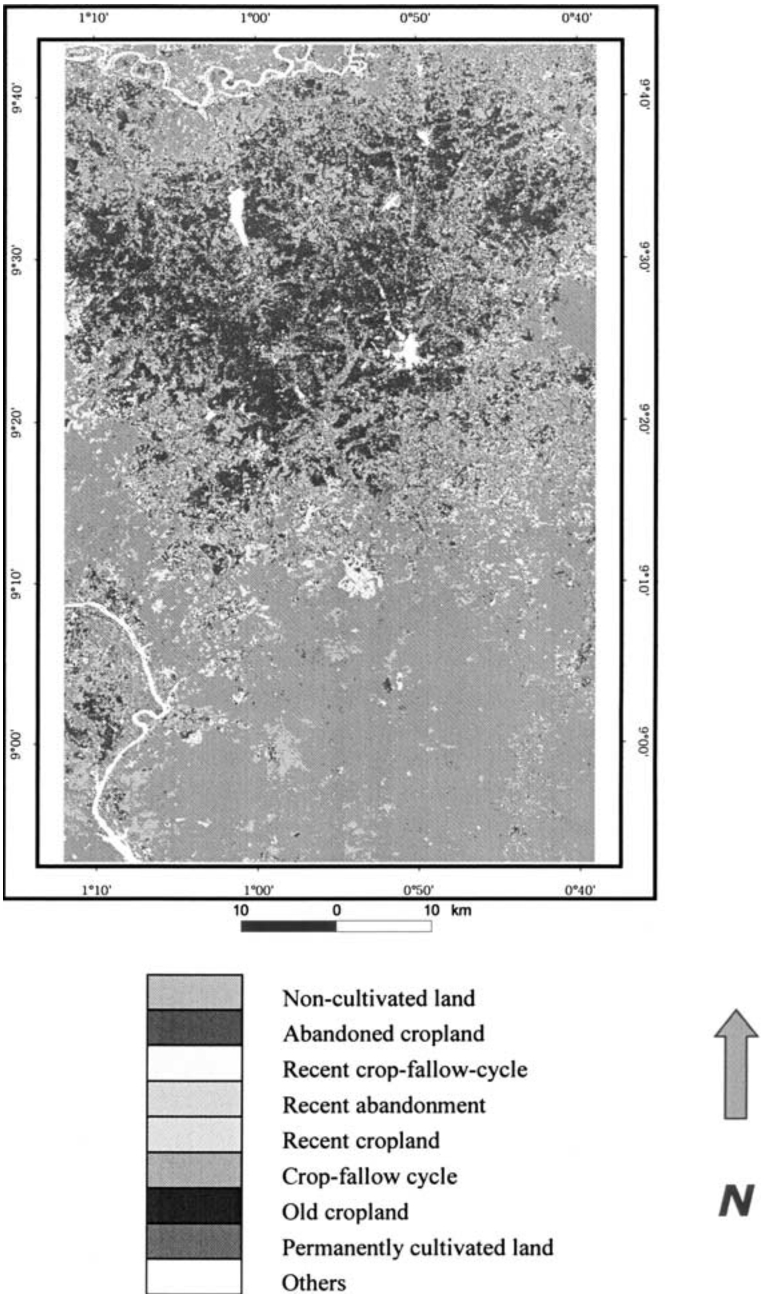

**Figure 2.** Land-cover change trajectories 1984, 1992, and 1999.

1984 to 1999 (Figure 2). All possible land-cover trajectories were reduced to nine based on *cropland*, *natural vegetation*, and *others* categories (Table 1). These improved the classification accuracies to 94%, 95%, and 97% for 1984, 1992, and 1999, respectively. Thus, the accuracy of the resulting land-cover trajectory map was 87% (i.e., the product of the accuracies of the three simplified, constituent maps containing three land-cover categories each.

Other spatially explicit (independent) variables were created within a geographic information system (GIS). Linear regression of one independent variable against the others was used to examine multicollinearity. The multicollinearity test eliminated variables with $R^2 > 0.8$ (Menard 1995). Twelve variables summarized in Table 2 were eventually retained for modeling.

### Modeling Land-Cover Change Trajectories

We used binary logistic regression to model the probability of observing a given trajectory as a function of the independent variables in Table 2. The depen-

Table 1. Description of the land-cover trajectories

| Sequence | Land cover in 1984 | 1992 | 1999 | Description | Abbreviation | Proportion (%) |
|---|---|---|---|---|---|---|
| 1 | Natural vegetation | Natural vegetation | Natural vegetation | Noncultivated | non | 46.91 |
| 2 | Cropland | Natural vegetation | Natural vegetation | Abandoned cropland | abd | 2.54 |
| 3 | Natural vegetation | Cropland | Natural vegetation | Recent crop–fallow cycle | rcf | 7.38 |
| 4 | Cropland | Cropland | Natural vegetation | Recent abandonment | rbd | 1.74 |
| 5 | Natural vegetation | Natural vegetation | Cropland | Recent cropland | rcp | 11.65 |
| 6 | Cropland | Natural vegetation | Cropland | Crop–fallow cycle | cfc | 6.13 |
| 7 | Natural vegetation | Cropland | Cropland | Old cropland | ocp | 9.47 |
| 8 | Cropland | Cropland | Cropland | Permanently cultivated | pcl | 11.65 |
| 9 | | | Others[a] | | | 2.53 |

[a] Included in this category are all trajectories involving built-up areas and water.

Table 2. List of independent variables

| Variables | Description | Data source |
|---|---|---|
| ALTITUDE | Digital elevation model (DEM) was derived from 50-ft vertical interval contour lines | Environmental Protection Agency (1999) |
| DOMINANCE | Landscape index calculated for 3 × 3 kernel size of land-cover map as DOMINANCE = $\ln(n) + \left(\sum_{i=1}^{n} p_i \ln(p_i)\right)$ where $p_i$ is the proportion of each class $i$ the kernel and $n$ is the number of classes present. DOMINANCE was calculated at the start of the period, (i.e., using the six classes of the land-cover map for 1984) | |
| CLAY | Clay content of the soil at 0–20 cm depth, measured in % | Braimoh (2004a) |
| PH | Soil pH at 0–20 cm depth. | Braimoh (2004a) |
| SOC | Soil organic C at of 0–20 cm depth, measured in % | Braimoh (2004a) |
| ECEC | Effective cation exchange capacity of the soil at 0–20 cm depth, measured in cmol/kg | Braimoh (2004a) |
| ROADS | Distance from roads (km) | Environmental Protection Agency (1999) |
| MARKET | Distance from Tamale, the major market center (km) | Environmental Protection Agency (1999) |
| VILLAGES | Distance from villages (km) | Environmental Protection Agency (1999) |
| PD84 | Population density in 1984 (persons/km$^2$) | Ghana Statistical Service (1989) |
| PD00-84 | Difference in population density 1984–2000 (persons/km$^2$) | Ghana Statistical Service (1989, 2002) |
| TENURE | Land tenure, mapped as binary layer with TENURE = 1 if state land, and 0 otherwise | Environmental Protection Agency (1999) |

dent variable for the logistic regression was a presence or absence event where $y = 1$ means a given trajectory is observed in a 30-m-sized pixel and $y = 0$ otherwise. The logistic regression model is of the form

$$\ln\left[\frac{p(y=1|X)}{1-p(y=1|X)}\right] = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + e \qquad (1)$$

where $p(y = 1|X)$ is the probability that $y$ takes the value 1, given the vector of independent variables $X$, β's are model parameters to be estimated, and $e$ is the residual error. The quantity $p(y=1|X)/1-p(y=1|X)$ is referred to as the odds ratio, whereas $\ln p(y=1|X)/[1-p(y=1|X)]\}$ is called the logit. The corresponding logit function, is given by

Table 3. Means of the independent variables with their standard deviations in parentheses

| | Biophysical variables | | | | | |
|---|---|---|---|---|---|---|
| Trajectories | ECEC | SOC | CLAY | PH | ALTITUDE | DOMINANCE |
| non | 4.87(1.85)f | 1.29(0.12)f | 7.69(0.92)g | 5.21(0.15)f | 185(101)c | 0.143(0.134)b |
| abd | 3.60(1.54)d | 1.15(0.10)c | 6.73(0.79)f | 5.07(0.12)c | 168(34)a | 0.162(0.138)e |
| rcf | 4.31(1.68)e | 1.20(0.11)e | 7.06(0.74)e | 5.14(0.14)e | 166(34)a | 0.153(0.136)cd |
| rbd | 3.42(1.41)c | 1.12(0.06)a | 6.60(0.59)b | 5.05(0.10)b | 174(22)b | 0.145((0.127)b |
| rep | 4.11(1.66)d | 1.20(0.12)e | 6.93(0.78)d | 5.14(0.14)e | 166(48)a | 0.149(0.135)bc |
| cfc | 3.16(1.23)b | 1.13(0.06)b | 6.40(0.54)a | 5.04(0.08)a | 171(17)a | 0.140(0.132)ab |
| ocp | 3.60(1.40)d | 1.16(0.09)d | 6.67(0.59)c | 5.10(0.12)d | 168(21)a | 0.159(0.136)d |
| pcl | 2.90(0.92)a | 1.12(0.04)ab | 6.37(0.46)a | 5.04(0.07)a | 175(23)b | 0.134(0.130)a |
| | Socioeconomic variables | | | | | |
| | PD84 | PD00-84 | ROADS | MARKET | VILLAGES | TENURE |
| non | 8(20)a | 6(18)a | 12.77(12.39)e | 35.75(11.68)g | 18.74(11.38)f | 0.015(0.122)bc |
| abd | 45(66)d | 32(49)d | 4.23(4.64)c | 26.47(10.94)e | 8.93(5.89)c | 0.004(0.065)a |
| rcf | 26(52)b | 17(34)b | 6.01(6.59)d | 26.24(11.18)e | 12.11(7.51)e | 0.003(0.057)a |
| rbd | 70(91)f | 46(59)f | 3.13(3.34)b | 7.39(4.74)a | 21.56(9.40)g | 0.018(0.136)cd |
| rcp | 35(62)c | 25(47)c | 6.09(8.16)d | 29.77(12.90)f | 10.51(8.02)d | 0.006(0.079)ab |
| cfc | 94(98)g | 66(69)g | 2.35(2.78)a | 21.88(9.18)c | 5.90(3.56)a | 0.020(0.141)c |
| ocp | 61(82)e | 38(50)e | 3.63(4.34)bc | 24.38(11.29)d | 7.65(4.97)b | 0.010(0.102)abc |
| pcl | 118(107)h | 74(62)h | 2.08(1.69)a | 19.25(8.93)b | 5.40(3.11)a | 0.034(0.181)e |

*Note:* Means with the same letter along the same column are not significantly different ($P < 0.05$) using the Duncan multiple range test; Abbreviation of trajectories as in Table 1.

$$g(x) = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + e \tag{2}$$

After back-transformation, the result of the regression can be expressed in terms of conditional probability as

$$\hat{p}(y = 1|X) = \frac{e^{\hat{\beta}_0 + \sum_{i=1}^{n} \hat{\beta}_i x_i}}{1 + e^{\hat{\beta}_0 + \sum_{i=1}^{n} \hat{\beta}_i x_i}} \tag{3}$$

where the hat notation is used to indicate estimated values. Equation 3 shows logistic regression results in continuous predicted values in the interval [0, 1], although the dependent variable is categorical.

A major interest of this study is to assess the relative importance of biophysical and socioeconomic determinants of the agricultural land-cover change trajectories. The unstandard logit coefficients that is, the $\hat{\beta}'$sin Equation 3) measure the absolute contribution of variables in determining the probability of observing a trajectory. However, this information might be misleading when a unit change in a variable is not equivalent from variable to variable as a result of disparities in scale of measurement and variances. Thus, prior to performing the logistic regression, we standardized the independent variables to zero mean and unit variance, using the formula

$$x_i' = \frac{x_i - \bar{x}_i}{x_i\text{max} - x_i\text{min}} \tag{4}$$

where $x_i$ is the value of the original variable, $\bar{x}_i$ is the mean, $x_i$max is the maximum value, $x_i$min is the minimum value, and $x_i'$ is the standardized variable. This procedure ensures that the resulting logit coefficients and odds ratio are standardized, suitable for assessing the relative contribution of independent variables in the models.

The goodness of fit of the models was evaluated using the relative operating characteristics (ROC) (Pontius and Schneider 2001). The ROC compares observed values—that is, the binary data over the whole range of predicted probabilities. It aggregates into a single index of agreement, the ability of the model to predict the probability of observing the trajectory at various locations on the landscape. Its value ranges from 0.5, for a model that assigns the probability at random, to 1, for a model that perfectly assigns the probability of observing the trajectory on the landscape.

## Results and Discussion

### Characterization of the Trajectories

Descriptive statistics of the trajectories are presented in Table 3. On average, the noncultivated trajectory is located on the highest elevation (mean = 185 m). It also has the highest effective cation-exchange capacity (ECEC) (mean = 4.87 cmol/kg), pH (mean = 5.21), soil organic C (SOC) (mean = 1.29%), and clay con-

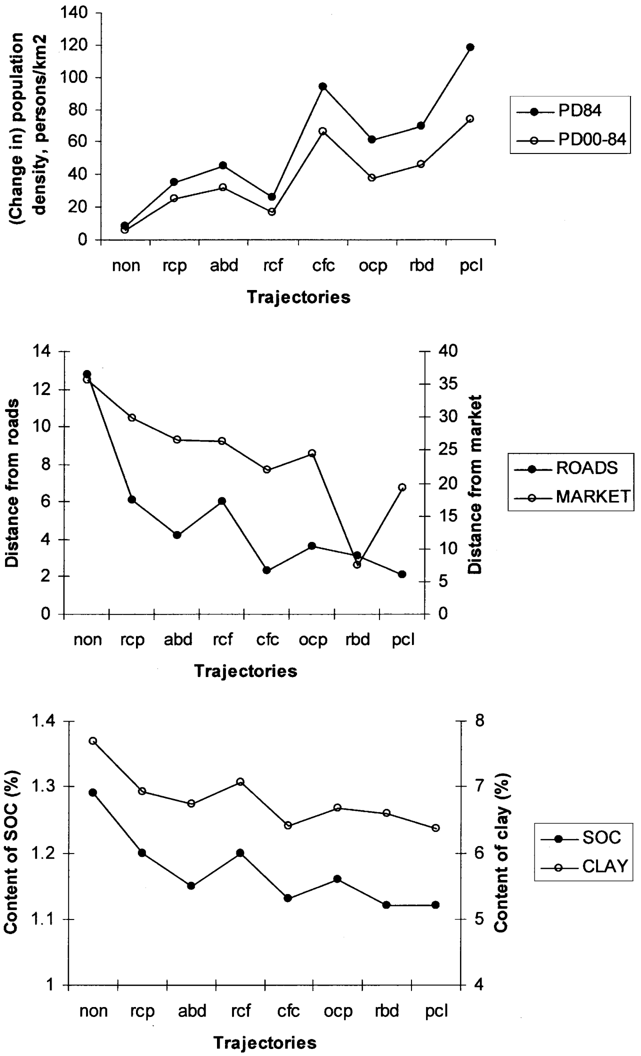

**Figure 3.** Display of selected variables along the continuum of land-use intensity.

tent (mean = 7.69%). The permanently cultivated trajectory is located on the next highest elevation (mean = 175 m) and has the lowest ECEC (mean = 2.90 cmolkg$^{-1}$), pH (mean = 5.04), SOC (mean = 1.12%), and clay content (mean = 6.37%). The initial population density (PD84) and change in population density between 1984 and 2000 (PD00-84) are lowest for the noncultivated trajectory (mean of PD84 = 8 persons/km$^2$; mean of PD00-84 = 6 persons/km$^2$). The highest values of the population variables were observed for permanently cultivated trajectory (mean of PD84 = 118 persons/km$^2$; mean of PD00-84 = 74 persons/km$^2$). The permanently cultivated trajectory is closest to roads (mean = 2.08 km) and villages (5.4 km), whereas the recent abandonment trajectory is closest to the main market (mean = 7.39 km). The proportion of permanently cultivated trajectory pixels on state land is the highest (3.4%), whereas that of recent crop–fallow cycle is the lowest (0.3%). Landscape dominance measures landscape heterogeneity effects. It is the deviation from the maximum possible landscape diversity given a number of land-cover types contained in the landscape. Values of dominance approaching 1 indicate a landscape that is dominated by one or a few land classes, whereas low values nearing 0 indicates a landscape covered by many land classes. The dominance values are generally low; the permanently cultivated trajectory has the lowest dominance (mean = 0.13), whereas abandoned cropland has the highest (mean = 0.16).

Among the biophysical variables, clay content produces the highest discrimination among the trajectories. It classifies the trajectories into seven groups, with permanently cultivated and crop–fallow cycle belonging to the group with the lowest clay contents (Table 3). Elevation produces the lowest discrimination among the trajectories. It groups the trajectories into three groups, with recent crop–fallow cycle, old cropland, recent cropland, abandoned cropland, and crop–fallow cycle belonging to group 1, recent abandonment and permanently cultivated trajectory belongig to group 2, and the noncultivated trajectory is in group 3 (Table 3). The population variables discriminate best among the socioeconomic variables, with each trajectory having its own group. TENURE that produces three classes performs poorest in discriminating the trajectories.

In Figure 3, we plot values of selected descriptive variables along the continuum of land-use intensity (measured by frequency of cultivation) from virgin land (non: i.e., the non-cultivated trajectory) to the most intensely cultivated land (pcl: i.e., the permanently cultivated trajectory). Distance from roads and distance from the main market generally decrease along the continuum. This implies that the most intensely cultivated land areas are closest to roads and the main market. The structural adjustment program impacted the market orientation of local farmers in Ghana (Abdulai and Huffman 2000; Braimoh 2004b). The removal of import subsidies made the price of imported cereals, especially rice, prohibitive, giving the local rice farmers a competitive edge. To take advantage of this market opportunity, more hectares of land around Tamale have been put under rice cultivation within the last two decades (Abdulai and Huffman 2000). The availability of improved rice cultivars and access to irrigation facilities around Tamale provided further incentives for the rice growers (Gyasi and others 2002).

Population densities generally increased along the continuum, implying that the most intensely cultivated land areas are those with the highest population pressures. It also implies that the highest population densities are found around Tamale, the main market. This reflects the settlement pattern in Northern Ghana (Abdulai 1996). Tamale is well connected by roads to other urban locations in Ghana. It is the hub of intense settlement in northern Ghana because it offers the opportunity for the buying of seeds and farm chemicals, on the one hand, and the sale of agricultural produce, on the other.

Soil organic C and clay contents are observed to decrease as land-use intensity increases. This might be a direct consequence of continuous cultivation that depletes organic matter and erodes the topsoil, leading to the removal of fine clay particles. The increase in population density appears to have led to an increase in cultivation frequency that was probably not matched with appropriate changes in inputs such as fertilizer necessary to compensate the decrease in soil organic C. With the adoption of high-yielding varieties that tend to require more nutrients, inorganic fertilizer supplements become imperative. However, the withdrawal of subsidies during the structural adjustment era led to an increase in fertilizer prices and subsequently reduced fertilizer use by farmers (Jebuni and Seini 1992; International Fertilizer Development Center 2000). During 1987–1990, the government's control in the distribution of agricultural inputs was removed, leading to a fourfold increase in the real price of fertilizers and a threefold increase in the real price of pesticides and other agrochemicals. Tabor and others (2002) observed that before subsidies removal, farmers used only about 60,000 tons of chemical fertilizer, whereas after subsidies removal, total fertilizer use fell to about 20,000 tons. Apart from land abandonment (i.e., the recent abandonment trajectory closest to the main market), another major response of farming households to low soil fertility is migration to previously uncultivated areas (Braimoh 2004b).

### The Land-Cover Trajectories Model

The results of the binary logit model for the trajectories are presented in Table 4. Positive values of the standardized logit coefficients indicate that higher values of the independent variables increase the probability of observing the trajectories. The fourth columns in Table 4,$e^{\beta}$, is the standardized odds ratio. It measures the likelihood of observing the trajectory if the independent variable is increased by one unit, with $\beta > 0$, $e^{\beta}>1$, indicating that the odds of observing the trajectory increases, and $\beta < 0$, $e^{\beta}< 1$, implying that the likelihood of observing the trajectory decreases. When $\beta = 0$, $e^{\beta}= 1$, signifying that the likelihood of observing the trajectory is not affected. The ROC (last rows of Table 4) ranges from 0.65 for recent cropland to 0.90 for permanently cultivated trajectories. This suggests the ability of the variables to satisfactorily predict the trajectories.

*Socioeconomic variables.* With the exception of the noncultivated trajectory, the probabilities of all the other trajectories increase with increasing proximity to roads. The probability of occurrence of permanently cultivated and crop–fallow-cycle trajectories is highest at the shortest distances from roads (Tables 4A and 4F). Distance from villages is not important for predicting the recent crop–fallow cycle ($P > 0.05$; Table 4C). The probability of observing the noncultivated trajectory increases with increasing distance from villages (Table 4A). Proximity to villages has the greatest effect on permanently cultivated trajectory, followed by crop–fallow cycle (Tables 4A and 4F). Distance to market is not important for explaining the likelihood of occurrence of abandoned farmlands ($P > 0.05$; Table 4B), whereas the probabilities of observing permanently cultivated (Table 4H), recent crop–fallow cycle (Table 4C), crop–fallow-cycle (Table 4F), and old cropland (Table 4G) trajectories increase with increasing proximity to market. The standardized logit coefficient for distance to market is positive for the noncultivated (Table 4A) and recent cropland trajectories (Table 4E), indicating that the probabilities of observing these trajectories increase with increasing distance from market. The effect of expansion of urban areas (i.e., built-up and paved surfaces) has markedly reduced access to farmland around Tamale (Abudulai 1996).

TENURE is a significant spatial determinant of recent cropland (Table 4E), old cropland (Table 4G), and permanently cultivated trajectories (Table 4G). Its standardized logit coefficients are negative, indicating that the probability of observing the trajectories decreases on state land. This might be due to two reasons. The first is the fact that non-state land is virtually free to landholders. The second reason might be due to inefficiencies in state management of land. Kasanga and Kotey (2001) observed that the state management of land has generally benefited government bureaucracy to the detriment of the poorer and vulnerable groups.

The initial population density (PD84) is not important in explaining the likelihood of observing the old cropland trajectory ($p > 0.05$; Table 4G). Low population density in 1984 increased the likelihood of observing the noncultivated (Table 4A), abandoned cropland

Table 4. Land-cover trajectories binomial logit models

| | β | Standard error (β) | Significance probability | exp (β) |
|---|---|---|---|---|
| (A) Noncultivated trajectory, $n$ = 30,000 (natural vegetation–natural vegetation–natural vegetation) | | | | |
| PD84 | −9.106 | 0.544 | 0.000 | 0.000 |
| PD00-84 | −1.393 | 0.382 | 0.000 | 0.248 |
| ROADS | 1.460 | 0.152 | 0.000 | 4.304 |
| MARKET | 1.722 | 0.118 | 0.000 | 5.593 |
| VILLAGES | 2.821 | 0.148 | 0.000 | 16.789 |
| TENURE | 0.020 | 0.131 | 0.876 | 1.021 |
| ALTITUDE | 0.302 | 0.241 | 0.210 | 1.353 |
| CLAY | 2.830 | 0.090 | 0.000 | 16.941 |
| ECEC | −0.064 | 0.156 | 0.679 | 0.938 |
| SOC | 2.187 | 0.147 | 0.000 | 8.908 |
| pH | −1.830 | 0.141 | 0.000 | 0.160 |
| DOMINANCE | 0.025 | 0.046 | 0.594 | 1.025 |
| INTERCEPT | −0.282 | 0.024 | 0.000 | 0.754 |
| ROC statistic = 0.89 | | | | |
| (B) Abandoned cropland, $n$= 30,000 (cropland–natural vegetation–natural vegetation | | | | |
| PD84 | −1.487 | 0.606 | 0.014 | 0.226 |
| PD00-84 | −0.953 | 0.517 | 0.065 | 0.386 |
| ROADS | −2.040 | 0.566 | 0.000 | 0.130 |
| MARKET | 0.066 | 0.294 | 0.822 | 1.068 |
| VILLAGES | −1.511 | 0.460 | 0.001 | 0.221 |
| TENURE | −0.851 | 0.595 | 0.153 | 0.427 |
| ALTITUDE | −2.616 | 1.034 | 0.011 | 0.073 |
| CLAY | −0.521 | 0.232 | 0.025 | 0.594 |
| ECEC | −0.457 | 0.419 | 0.275 | 0.633 |
| SOC | −1.384 | 0.359 | 0.000 | 0.251 |
| pH | −0.466 | 0.339 | 0.168 | 0.627 |
| DOMINANCE | 0.293 | 0.110 | 0.008 | 1.340 |
| INTERCEPT | −4.087 | 0.058 | 0.000 | 0.017 |
| ROC statistic = 0.69 | | | | |
| (C) Recent crop–fallow-cycle, $n$ = 30,000 (natural vegetation– cropland–natural vegetation) | | | | |
| PD84 | −6.157 | 0.603 | 0.000 | 0.002 |
| PD00-84 | −3.122 | 0.525 | 0.000 | 0.044 |
| ROADS | −0.995 | 0.249 | 0.000 | 0.370 |
| MARKET | −2.678 | −0.182 | 0.000 | 0.069 |
| VILLAGES | 0.136 | 0.211 | 0.521 | 1.145 |
| TENURE | −0.229 | 0.392 | 0.558 | 0.795 |
| ALTITUDE | −2.787 | 0.556 | 0.000 | 0.062 |
| CLAY | −1.248 | 0.131 | 0.000 | 0.287 |
| ECEC | 0.534 | 0.212 | 0.012 | 1.705 |
| SOC | −0.994 | 0.203 | 0.000 | 0.370 |
| pH | 1.218 | 0.197 | 0.000 | 3.382 |
| DOMINANCE | 0.086 | 0.067 | 0.197 | 1.090 |
| INTERCEPT | −2.851 | 0.031 | 0.000 | 0.058 |
| ROC statistic = 0.70 | | | | |
| (D) Recent abandonment, $n$ = 20,000 (cropland–cropland–natural vegetation) | | | | |
| PD84 | 0.903 | 0.426 | 0.034 | 2.467 |
| PD00-84 | −0.150 | 0.460 | 0.744 | 0.860 |
| ROADS | −1.649 | 0.789 | 0.037 | 0.192 |
| MARKET | −1.209 | 0.325 | 0.000 | 0.299 |
| VILLAGES | 0.001 | 0.620 | 0.998 | 1.001 |
| TENURE | −0.157 | 0.339 | 0.642 | 0.854 |
| ALTITUDE | 3.212 | 0.533 | 0.000 | 24.817 |
| CLAY | −2.416 | 0.347 | 0.000 | 0.089 |

Table 4. Continued.

| | β | Standard error (β) | Significance probability | Exp (β) |
|---|---|---|---|---|
| ECEC | −0.403 | 0.527 | 0.444 | 0.668 |
| SOC | −4.400 | 0.420 | 0.000 | 0.012 |
| pH | 2.683 | 0.376 | 0.000 | 14.624 |
| DOMINANCE | 0.190 | 0.128 | 0.138 | 1.209 |
| INTERCEPT | −4.071 | 0.080 | 0.000 | 0.017 |
| ROC-statistic = 0.74 | | | | |
| (E) Recent cropland, *n* = 30,000 (natural vegetation–cropland) | | | | |
| PD84 | −1.582 | 0.317 | 0.000 | 0.205 |
| PD00-84 | −0.349 | 0.265 | 0.188 | 0.706 |
| ROADS | −1.230 | 0.191 | 0.000 | 0.292 |
| MARKET | 1.047 | 0.136 | 0.000 | 2.849 |
| VILLAGES | −1.568 | 0.185 | 0.000 | 0.208 |
| TENURE | −0.617 | 0.234 | 0.008 | 0.539 |
| ALTITUDE | −1.443 | 0.297 | 0.000 | 0.236 |
| CLAY | −0.941 | 0.106 | 0.000 | 0.390 |
| ECEC | 1.339 | 0.187 | 0.000 | 3.815 |
| SOC | −1.885 | 0.160 | 0.000 | 0.152 |
| pH | 1.737 | 0.154 | 0.000 | 5.682 |
| DOMINANCE | 0.038 | 0.055 | 0.493 | 1.039 |
| INTERCEPT | −2.209 | 0.021 | 0.000 | 0.110 |
| ROC statistic = 0.65 | | | | |
| (F) Crop–fallow cycle *n* = 30,000 (cropland–natural vegetation–cropland) | | | | |
| PD84 | 0.669 | 0.246 | 0.006 | 1.953 |
| PD00-84 | 0.231 | 0.242 | 0.340 | 1.260 |
| ROADS | −5.211 | 0.764 | 0.000 | 0.005 |
| MARKET | −1.703 | 0.226 | 0.000 | 0.182 |
| VILLAGES | −4.394 | 0.482 | 0.000 | 0.012 |
| TENURE | −0.225 | 0.202 | 0.265 | 0.799 |
| ALTITUDE | −4.262 | 1.063 | 0.000 | 0.014 |
| CLAY | −3.337 | 0.238 | 0.000 | 0.036 |
| ECEC | 0.192 | 0.338 | 0.571 | 1.211 |
| SOC | −2.520 | 0.292 | 0.000 | 0.080 |
| pH | 1.244 | 0.290 | 0.000 | 3.468 |
| DOMINANCE | −0.131 | 0.081 | 0.105 | 0.878 |
| INTERCEPT | −4.472 | 0.089 | 0.000 | 0.011 |
| ROC statistic = 0.83 | | | | |
| (G) Old cropland, *n* = 30,000 (cropland–cropland–cropland) | | | | |
| PD84 | 0.032 | 0.261 | 0.902 | 1.033 |
| PD00-84 | −1.285 | 0.274 | 0.000 | 0.277 |
| ROADS | −2.331 | 0.339 | 0.000 | 0.097 |
| MARKET | −1.165 | 0.164 | 0.000 | 0.312 |
| VILLAGES | −2.755 | 0.279 | 0.000 | 0.064 |
| TENURE | −0.729 | 0.208 | 0.000 | 0.482 |
| ALTITUDE | −1.668 | 0.575 | 0.004 | 0.189 |
| CLAY | −1.995 | 0.152 | 0.000 | 0.136 |
| ECEC | −0.157 | 0.237 | 0.507 | 0.855 |
| SOC | −2.459 | 0.187 | 0.000 | 0.086 |
| pH | 2.774 | 0.198 | 0.000 | 16.026 |
| DOMINANCE | 0.207 | 0.060 | 0.001 | 1.230 |
| INTERCEPT | −2.861 | 0.035 | 0.000 | 0.057 |
| ROS statistic = 0.72 | | | | |

continued

Table 4. Continued.

| | β | Standard error (β) | Significance probability | Exp (β) |
|---|---|---|---|---|
| (H) Permanently cultivated, $n$ = 30.000 (cropland–cropland–cropland) | | | | |
| PD84 | 2.134 | 0.208 | 0.000 | 8.452 |
| PD00-84 | −0.607 | 0.222 | 0.006 | 0.545 |
| ROADS | −5.180 | 0.723 | 0.000 | 0.006 |
| MARKET | −3.849 | 0.194 | 0.000 | 0.021 |
| VILLAGES | −5.509 | 0.440 | 0.000 | 0.004 |
| TENURE | −0.501 | 0.146 | 0.001 | 0.606 |
| ALTITUDE | 2.845 | 0.773 | 0.000 | 17.205 |
| CLAY | −4.942 | 0.214 | 0.000 | 0.007 |
| ECEC | −3.380 | 0.329 | 0.000 | 0.034 |
| SOC | −3.774 | 0.260 | 0.000 | 0.023 |
| PH | 3.286 | 0.251 | 0.000 | 26.742 |
| DOMINANCE | −0.338 | 0.066 | 0.000 | 0.714 |
| INTERCEPT | −4.510 | 0.085 | 0.000 | 0.011 |
| ROC statistic = 0.90 | | | | |

Table 5. Ranking of the independent variables based on the absolute values of the standardized logit coefficients

| | non | abd | rcf | rbd | rcp | cfc | ocp | pcl | Average ranking | Overall ranking |
|---|---|---|---|---|---|---|---|---|---|---|
| PD84 | 1 | 4 | 1 | 7 | 3 | 8 | 12 | 9 | 5.6 | 7 |
| PD00-84 | 8 | 6 | 2 | 11 | 11 | 9 | 7 | 10 | 8.0 | 9 |
| ROADS | 7 | 2 | 7 | 5 | 7 | 1 | 4 | 2 | 4.4 | 2 |
| MARKET | 6 | 12 | 4 | 6 | 8 | 6 | 8 | 4 | 6.8 | 8 |
| VILLAGES | 3 | 3 | 11 | 12 | 4 | 2 | 2 | 1 | 4.8 | 4 |
| TENURE | 12 | 7 | 10 | 10 | 10 | 10 | 9 | 11 | 9.9 | 11 |
| ALTITUDE | 9 | 1 | 3 | 2 | 5 | 3 | 6 | 8 | 4.6 | 3 |
| CLAY | 2 | 8 | 5 | 4 | 9 | 4 | 5 | 3 | 5.0 | 5 |
| ECEC | 10 | 10 | 9 | 8 | 6 | 11 | 11 | 6 | 8.9 | 10 |
| SOC | 4 | 5 | 8 | 1 | 1 | 5 | 3 | 5 | 4.0 | 1 |
| PH | 5 | 9 | 6 | 3 | 2 | 7 | 1 | 7 | 5.0 | 5 |
| DOMINANCE | 11 | 11 | 12 | 9 | 12 | 12 | 10 | 12 | 9.9 | 11 |

*Note:* 1 = most important, 12 = least important.
Abbreviation of trajectories as in Table 1.

(Table 4B), recent crop–fallow-cycle (Table 4C), and recent cropland (Table 4E) trajectories. The likelihood of recent abandonment (Table 4D), crop–fallow-cycle (Table 4F), and permanently cultivated (Table 4G) trajectories, however, increased with high population densities. These trajectories have high population densities in 1984 (70–118 persons/km$^2$; Table 3). The largest effect of initial population density occurs for the noncultivated trajectory (β = −9.10), which has the lowest average population density of 8 personsthe km$^2$, whereas the smallest effect (β = 0.03) occurs for old cropland trajectory, with a moderate average population density of 61 persons/km$^2$ (Table 3).

An increase in population density between 1984 and 2000 was not a significant determinant ($p > 0.05$) of abandoned cropland (Table 4B), recent abandonment (Table 4D), recent cropland (Table 4E), and crop–fallow cycle (Table 4F). However, an increase in population density between 1984 and 2000 significantly decreased ($p < 0.05$) the probability of observing the noncultivated (Table 4A), recent crop–fallow-cycle (Table 4C), old cropland (Table 4G), and permanently cultivated trajectories (Table 4H). This suggests an increasing pressure, leading to more intensive cultivation of land. The largest effect of the population increase occurred for recent crop–fallow cycle (Table 4C). Braimoh (2004a, pp. 128–129) already observed that the average fallow length for farming households in the study area decreased from more than 4 years in 1984 to about 2 years in 1999.

*Biophysical variables.* The ECEC is the sum of cations (exchangeable bases and acidity) that a soil can adsorb in its natural state. It is an indicator of soil fertility, as it measures of the ability of the soil to supply nutrients (Ca, Mg, and K) for plant growth. It is a fairly stable property of the soil. Changes in its value are relatively

Table 6. Classification of the variables into three essentiality classes

| Trajectory | Essentiality class | | | Paradigm supported/dominant change process |
|---|---|---|---|---|
| | Most essential | Moderately essential | Least essential | |
| non | PD84, CLAY, VILLAGES, SOC | PH, MARKET, ROADS, PD00-84 | ALTITUDE, ECEC, DOMINANCE, TENURE | Extensification[a]–rent theory |
| rcp | SOC, PH, PD84, VILLAGES | Altitude, ECEC, ROADS, MARKET | CLAY, TENURE, PD00-84, DOMINANCE | Extensification–rent theory |
| abd | ALTITUDE, ROADS, VILLAGES, PD84 | SOC, PD00-84, TENURE, CLAY | PH, ECEC, DOMINANCE MARKET | Extensification–intensification–rent theory |
| rcf | PD84, PD00-84, ALTITUDE, MARKET | CLAY, PH, ROADS, SOC | ECEC, TENURE, VILLAGES, DOMINANCE | Extensification–intensification–rent theory |
| cfc | ROADS, VILLAGES, ALTITUDE, CLAY | SOC, MARKET, PH, PD84 | PD00-84, TENURE, ECEC, DOMINANCE | Rent theory |
| ocp | PH, VILLAGES, SOC, ROADS | CLAY, ALTITUDE, PD00-84, MARKET | TENURE, DOMINANCE, ECEC, PD84 | Intensification–rent theory |
| rbd | SOC, ALTITUDE, PH, CLAY | ROADS, MARKET, PD84, ECEC | DOMINANCE, TENURE, PD00-84, VILLAGES | Rent theory |
| pcl | VILLAGES, ROADS, CLAY, MARKET | SOC, ECEC, PH, PALTITUDE | PD84, PD00-84, TENURE, DOMINANCE | Rent theory |
| All trajectories | SOC, ROADS, ALTITUDE, VILLAGES | CLAY, PH, PD84, MARKET | PD00-84, ECEC, DOMINANCE, TENURE | Rent theory |

*Note:* Abbreviation of trajectories as in Table 1.

[a] This trajectory is the proportion of land still available for agricultural extensification

slow and happen largely due to changes in pH and soil organic carbon. The ECEC is important in explaining only three trajectories: recent crop–fallow cycle (Table 4C), recent cropland (Table 4E), and permanently cultivated land (Table 4H). The standardized odds ratio ($e^{\beta}$) for ECEC in the recent crop–fallow-cycle model is 1.7. Thus, an increase in ECEC increases the likelihood of observing the recent crop–fallow-cycle trajectory by a factor of about 2. SOC and clay content (CLAY) are significantly associated with the probability of observing all the trajectories (Table 4). With the exception of the noncultivated trajectory (Table 4A), the coefficients of SOC and CLAY are negative for the models. Thus, the probability of observing the noncultivated trajectory increases with increasing content of SOC and clay. The decrease in SOC is most strongly associated with the permanently cultivated trajectory ($\beta = -3.77$, Table 4H), whereas the effect of a decrease in SOC is least on the probability of recent crop–fallow-cycle ($\beta = -0.99$, Table 4C). Similarly, the decrease in clay content is mostly associated with the permanently cultivated trajectory ($\beta = -4.94$, Table 4H), but least with abandoned cropland ($\beta = -0.52$, Table 4B). Thus, the frequency of cultivation explains the associations between the likelihood of observing the trajectories and SOC and clay content. With the exception of the abandoned cropland trajectory (Table 4B), soil pH is significantly associated with the probability of observing the trajectories. The likelihood of observing the noncultivated trajectory decreases with an increase in pH, but decreases for the other trajectories.

Elevation is not significant in determining the likelihood of the noncultivated trajectory (Table 4A), but significantly explains the probability of occurrence of the other trajectories ($p < 0.05$). An increase in elevation increases the probability of observing permanently cultivated (Table 4H) and recent abandonment (Table 4D) trajectories, whereas a decrease in elevation increases the probability of abandoned cropland (Table 4B), recent crop–fallow-cycle (Table 4C), recent cropland (Table 4E), crop–fallow-cycle (Table 4F), and old cropland (Table 4G) trajectories. The effect of elevation across trajectories is highest for crop–fallow-cycle ($\beta = -4.26$, Table 4F) and least for the noncultivated trajectory ($\beta = 0.30$, Table 4A). The effect of elevation on the trajectories might be due to the indirect effect of Tamale on population distribution/settlement. For instance, for permanently cultivated land, the most intensely cultivated trajectory is largely concentrated around Tamale, which is at a higher elevation than other villages.

Landscape dominance at the outset (1984) is a significant determinant of abandoned cropland (Table 4B), old cropland (Table 4G) and permanently cultivated (Table 4H) trajectories. A decrease in landscape dominance increases the probability of observing the permanently cultivated trajectory, whereas the likelihood of abandoned and old croplands is associated with an increase in dominance.

### Importance of Variables Across Trajectories

The relative importance of the variables in determining the trajectories was assessed by ranking the variables on the basis of the absolute value of their standardized logit coefficients from 1 (most important) to 12 (least important). The most important spatial determinant varies among the trajectories (Table 5). Population density in 1984 ranks most important for the noncultivated trajectory and recent crop–fallow cycle. Land characteristics rank highest as the spatial determinants of abandoned farmlands (ALTITUDE), recent cropland and recent abandonment (SOC), and old cropland (pH). Accessibility variables rank most important for the remaining trajectories (i.e., VILLAGES for the permanently cultivated trajectory and ROADS for crop–fallow-cycle). SOC, with an averaging ranking of 4, is the most important among the variables, whereas TENURE and DOMINANCE, each with an average ranking of 9.9, are the least important.

SOC, ROADS, ALTITUDE, and VILLAGES, spatial determinants of land rent with overall ranking of 1–4 (last column of Table 5), are the most important across the trajectories. SOC as an index of soil quality also measures the effect of land use on the soil. Its decrease along the continuum of land use supports the neo-Malthusian concerns about the effects of population growth on land degradation. CLAY, PH, PD84, and MARKET, with overall ranking of 5–8, are the next important variables. Low population density in 1984 is an important predictor of trajectories (noncultivated, abandoned cropland, recent crop–fallow cycle and recent cropland), where the change process is agricultural extensification. The low 1984 population densities in these areas (8–45 persons/km$^2$; Table 3) permitted the *filling up* of available open access land by farmers. The decrease in clay content and pH of the soils again tend to support a Malthusian response to land-use change, whereas distance to market further reinforces the role of accessibility in the land-use system. PD00-84, ECEC, TENURE, and DOMINANCE, with overall ranking of 9–11, are the least important. That change in population density generally has a small effect on land-use change further confirms the increasing commercialization of agriculture in northern Ghana. The small effect of land tenure on the other hand, might be due to the absence of the relevant data that categorizes land ownership patterns in the customary land management sector.

To assess the variable importance for specific trajectories, the rankings of the variables were further classified into three *essentiality* classes, where the first class (*most essential*) comprises variables with ranks 1–4, the second class (*moderately essential*) consists of variables with ranks 5–8, and the third class (*least essential*) is composed of variables with ranks 9–12 for each trajectory. Table 6 shows that the composition of variables in the *essentiality* classes differs among the trajectories. For trajectories with relatively low land-use intensity (i.e., the noncultivated, abandoned cropland, recent crop–fallow-cycle, and recent cropland trajectories; Figure 3) the *most essential* variables include initial population density (PD84). Population density/settlement and accessibility by roads are positively correlated in northern Ghana. As these trajectories are the farthest from roads and market (Figure 3), the effect of population density in 1984 in determining these trajectories appears to be due to the indirect effect of poor access to infrastructure.

Change in population density between 1984 and 2000 (PD00-84) is within the *moderately essential* or *most essential* class for abandoned cropland (2.54%), and recent crop–fallow-cycle (7.38%) and old cropland (9.47%) trajectories. Thus, land change in 19% of the study area appears to support the hypothesis of population-induced intensification. Change in population density occurs in association with MARKET in the *most essential* and *moderately essential* classes respectively for recent crop–fallow cycle and old cropland. The development of abandoned cropland, recent crop–fallow-cycle, and recent cropland trajectories associated with extensification is facilitated by relatively low population densities and large amounts of open access land still available for agricultural expansion.

There is no evidence of population-induced intensification in 31% of the landscape: recent abandonment (1.74%), crop—fallow-cycle (6.13%), recent cropland (11.65%), and permanently cultivated (11.65%) trajectories with greater degree of land-use intensification. Rather, accessibility (MARKET, ROADS, and VILLAGES) has a stronger impact on agricultural change processes within these trajectories. Accessibility to Tamale is important because it is where people buy the needed inputs and also sell their produce. The economic opportunities created by the structural adjustment program, (i.e., increased market orientation of farmers) further contributed to the importance of the variables in the land-use system. Roads provide easy access to farmlands, whereas accessibility to villages is also crucial because the processing and storage of crops take place in the villages before they are sent to the market for sale. It is remarkable that with the exception of recent abandonment, at least one of the accessibility factors (MARKET, ROADS, and VILLAGES) is found in the most essential variable group for all of the trajectories.

The last row of Table 6 shows that, generally, the determinants of agricultural potential and accessibility factors constitute the *most essential* and *moderately essential* determinants of all the trajectories, leading to evidence of Ricardian and von Thünen land change.

### Comparison of Results with Recent Case Studies

The results of this study are similar to those of Mertens and others (2000), who noted that the beginning of economic crises (1986) in Cameroon witnessed high deforestation rates related to increased marketing of food crops, modification of farming systems, and migration of farmers to previously unfarmed areas. However, whereas Mertens and others (2000) observed a strong relationship between agricultural change and population growth, our study, like that of Cropper and others (2001) showed that population growth has little explanatory power on land change processes in northern Ghana. The commercialization of agriculture resulting in expansion of irrigated rice around Tamale in northern Ghana is the underlying cause of this difference. Our results compare with that of Laney (2002) who observed a significant expansion of market tree crops and irrigated rice fields as land pressure increased in the Andapa region of Madagascar.

The salience of MARKET, ROADS, and VILLAGES in our models confirms the role of accessiblity factors in determining agricultural land-use patterns (Chomitz and Gray 1996; Mertens and Lambin 2000; Cropper and others 2001; McConnell and others 2004; Southworth and others 2002; Verburg and others 2004). The extensification or intensification of agriculture requires the ability of contact with sites of economic opportunities (Deichmann 1997). Large amounts of open access land might not be converted to agriculture if they are too remote for farmers. This is because extensification is most likely the least cost response to population pressure from the farmers' perspective, especially when the soil quality is suitable and the land accessible (Pender 1999).

The evidence of neo-Malthusian concern about the effects of population growth on land degradation might be due to the intrinsically low biophysical potential of the soils, the shortening of fallow necessary to rejuvenate soil fertility, and the inability of farmers to initiate the necessary soil management counterbalance measures as a result of prohibitive costs of fertilizers and other inputs. Ali (2004) also observed a significant decline in soil quality as a result of the population-induced agricultural intensification (i.e., changes involving labor-saving technologies) in southwestern Bangladesh. Earlier, Pagiola (1985) had observed the degradation of soil resources and decline in crop yields as farmers intensified agricultural production in some regions in Bangladesh. The failure to use sufficient fertilizers was identified as one of the causes of declining productivity.

## Summary and Conclusions

This study enables us to identify the spatial determinants of the land change trajectories. It also suggests the mechanisms related to land change in northern Ghana as a result of macroeconomic changes. Population growth had little effect on agricultural land change compared to accessibility factors that aid the commercialization of agriculture. Three main inferences can be drawn from the analyses:

- An increase in population density is an important determinant of agricultural change only in areas where the initial population density is low. The change process in these areas is mainly agricultural extensification.
- The major response to increasing population is more intensive cultivation of land around the market. Market and road infrastructure serve as incentives to human settlement, conversion of natural vegetation to farmland, and sale of agricultural produce.
- An increase in cultivation frequency is related to relatively lower soil organic matter, clay content, and nutrient holding capacity. Devaluation and subsidy removal increased the vulnerability of the farmers who already had little or no access to credit for agricultural inputs. This phenomenon appears to be directing agricultural intensification into the involution path. Such involution manifests in soil nutrient depletion.

We do not have the relevant data on the various categories of landholders under the customary land management sector to analyze the mediative roles of these institutions in shaping the agricultural land change trajectories. Future studies should acquire the necessary data and assess the relative impact of land ownerships on the trajectories.

This study shows that agricultural change is highly sensitive to accessibility by roads. It is instructive for planners who might want to evaluate the environmental consequences of infrastructure development in Ghana. New roads are likely to stimulate the clearing of natural vegetation for crop production, given the general open access condition that prevails in northern Ghana. However, the economic returns to the new roads should be weighed against the costs of soil nutrient depletion that will result from intensive crop production. Furthermore, this research suggests the need for policies to mitigate the impact of road expansion on land degradation. If tax policies encourage the holding of agricultural land as a speculative asset, the price of existing arable lands will be artificially inflated and encroachment of woodlands or forests might be reduced (Barbier 1997).

The decrease in soil quality along the continuum of land-use intensity also has vital implications for the sustainability of the agricultural system. It calls for measures to restore soil fertility. The use of improved fallows and the practice of agroforestry might be useful. Furthermore, the development of production systems that integrate livestock production with cropping systems will enable nutrient cycling in the production systems. There is also the need for improvements in policies such that the pricing of fertilizers and other farm inputs provide the appropriate incentives for farmers.

The method of this article could be of value for modelers interested in developing land-use models and decision-support systems for policy formulation in Ghana. It provides a platform for selecting variables and identifying functional relationships in dynamic, process-based models of land change. This then leads to improved model specification between land-use change and the underlying driving forces.

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