This Draft: July 2, 2009

Reaching Far into the Woods: Impact of Roads on Forest Structure in China

Karen Sullivan, Ph.D. Candidate
Emi Uchida*, Assistant Professor
Department of Environmental and Natural Resource Economics, University of Rhode Island

Xiangzheng Deng, Senior Research Fellow
Jikun Huang, Director
Center for Chinese Agricultural Policy, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences

Scott Rozelle, Helen F. Farnsworth Senior Fellow
Freeman Spogli Institute for International Studies, Stanford University

John Gibson
Department of Economics, University of Waikato

Selected Paper prepared for presentation at the Agricultural & Applied Economics Association 2010 AAEA,CAES, & WAEA Joint Annual Meeting, Denver, Colorado, July 25-27, 2010

*Corresponding author. Address: 216 Coastal Institute, 1 Greenhouse Road, Kingston, RI, USA 02881. Email: emi@uri.edu. Karen Sullivan and Emi Uchida share senior authorship. The authors would like to thank seminar participants at IGSNRR, University of Connecticut and University of Rhode Island for their valuable comments and suggestions. This project was supported in part by NSF IGERT grant DGE-0504103 to the University of Rhode Island Coastal Institute and the URI Undergraduate and Graduate Research Grant Program. Emi Uchida acknowledges the support from the Chinese Academy of Sciences International Young Scholars Fellowship and the Rhode Island Agricultural Extension Service (AES# 5168).

The declining quality of forests is a global concern because of impacts on ecosystem services (World Resources Institute 2005). Closed-canopy forests—mature forests with high canopy cover—play an important role in providing several key global and local ecosystem services including the preservation of biodiversity and wildlife habitats. It is in part because of the high value of closed-canopy forests that concerns remain about the world's forest resources (FAO 2005). In fact, when all forests are combined—including closed-canopy forests, shrub-covered forests, open-canopy forests and other forests—deforestation in the 2000s is proceeding slower than in the 1990s. However, the pace of deforestation varies by forest type and is faster among primary and modified natural forests (FAO 2005; Loffeir and Brayer 2005). Much of these natural forests are what we call closed-canopy forests. For example, of the 13 million hectares of forests lost since 1990, nearly half of the loss was among primary forests. This trend suggests that forests that provide key ecosystem services are declining disproportionately faster than other types of forests.

This study examines whether or not either constructing or upgrading roads plays a key role in this trend, i.e., whether roads have a varying impact on forests depending on the forest type. This question is not straightforward to study since there is disagreement even when examining the effect of roads on forests, in general. In many instances roads are found to lead to deforestation (e.g., Pfaff et al. 2007). When a road enters an area, or is upgraded, forest areas may become easier targets to be converted to farming. If this happens, forest cover would fall. Roads also may increase the capacity to transport firewood, timber and other forest products.[1]

Several empirical studies find that roads are associated with deforestation in the Amazon (Pfaff 1998; Lawrence and Foster 2004; Pfaff et al. 2007), Belize (Chomitz and Gray 1996), the Philippines (Liu et al. 1993), Honduras (Ludeke et al. 1990), Cameroon (Mertens and Lambin 1997) and Costa Rica (Sader and Joyce 1988).

On the other hand, roads may also reduce the pressure on forests. As more and more roads are built, the non-resource sectors—industry and services—may expand. When new or better roads reach a region, they create a focal point for local development and promote activities that reduce the focus that populations have traditionally had on the forest. In addition, roads also provide new and more convenient linkages to markets and create new opportunities in the non-farm employment sector. Road accessibility has been related to changes in income sources (Binswanger et al., 1993). Elsewhere, rehabilitated roads have been shown to reduce the time that individuals residing in rural villages take to go to key markets (Jacoby 2000; Escobal and Ponce 2002). Improved public transportation services, which are known to accompany road construction, also enhance non-agricultural income opportunities. In fact, several empirical studies support this view (Deininger and Minten 1997; Qiao and Rozelle 1998; Andersen et al. 2002). In a recent study in the context of China, Deng et al. (2009) found that roads have no impact on forest cover, or at best are associated with a slight *increase* in total forest cover between the years 1995 and 2000.

Despite increasing empirical research studying the impact of roads on forests, less attention has been paid to how the impact differs depending on the types of forests. To the best of our knowledge, all of these studies grouped forests as one aggregated category and did not examine how the impact of roads varies across different types of forests. Such undifferentiated studies could be a problem if the impact of roads on forests varies according to the type of the forest. It will also matter if different types of forests have different ecological values. Moreover, with the exception of a few studies (e.g., Pfaff et al., 2007), most studies also do not take into account the quality of roads and instead treat all roads as a single type. Depending on the quality of the road (e.g., its size; transportivity; and the nature of its design—e.g., is it controlled access/toll), roads may have different impacts on forests. If some types of roads lead to the deforestation of only some types of forests, policymakers might have more scope to intervene strategically to manage the quality of forests.

There are reasons why we might expect the impact of roads to differ with the type of the forest into which the road is penetrating. New or better roads may reduce the cost of hauling timber, making harvesting of remote, closed-canopy forests more economical. However, roads may introduce other forces. For example, at the same time roads also may reduce the cost of reforestation and afforestation resulting in an increase in young forests. Roads also may create market demand for the products of other types of forests for cash income generation, for example, tea gardens, orchards and nurseries. Combined, the composition (and hence the quality) of a forest may change while its total area stays constant.

The impact of roads on forests also may vary depending on the type of road.

Large roads, such as expressways and highways, connect remote forests more directly up to national markets and may facilitate timber harvesting in remote areas. Timber production often involves large fixed investment in equipment so to take advantage of economies of scale , timber companies may harvest timber in remote areas (with no roads or with just village roads) if the forests in these area are higher-valued, closed-canopy forests. Alternatively, if harvest costs were a function of the current stock of forest resources such that the marginal cost decreases with a higher stock of the forest resource, timber companies would also have incentives to operate in areas with more forests that contain denser and higher-valued resource stocks. In this case, after the penetration of an expressway or a highway, timber production may shift to areas that are more remote, hence leading to a faster depletion of the closed-forest in unroaded areas compared to areas with larger roads.

To examine how the impacts of different types of roads vary depending on the type of the forest, this study utilizes data from Jiangxi province in China. Jiangxi is a highly forested province with an area approximately that of the U.S. state of Wisconsin and an extensive road network that includes more than 2,200 kilometers of roads. Because of this it is an ideal setting for this type of research. However, it also is a complex province that is undergoing a number of different changes, all of which could affect the impact of roads on the forest. Forests are both economically and environmentally important; the province is part of a traditional timber-producing region that formerly was one of the largest timber producers in China. Jiangxi's temperate weather provides excellent conditions for forest growth, making it one of the provinces in China with a potential for rapid forest development (Zhang et al. 2006). Jiangxi's forests also provide itself as well as the provinces downstream from Jiangxi with critical ecosystem services, such as protection from flooding, etc. However, forest quality is said to have degenerated over the past few decades. For example, Zhang et al. (2000) claims natural forests have been gradually transformed into plantation forests in Jiangxi.

Forests also have been useful sources of energy and employment for Jiangxi's large rural population. Firewood has been one of the major cooking resources for rural households in the mountainous regions (Chen et al. 2006). Moreover, the timber industry has traditionally provided employment in these regions. At the same time, since Jiangxi is a province adjacent to China's fastest growing economic regions, its urban areas are expanding fast. Rural farmers and loggers are finding an increasing number of opportunities to escape poverty through off-farm jobs in Jiangxi's cities and in the nearby coastal provinces. The exit of large numbers of laborers and their families from the rural regions might reduce the pressure on forests. In sum, Jiangxi is experiencing factors that might both simultaneously increase and reduce pressure on forests.

The key feature of this paper is the spatially-detailed data which are available for different types of roads and for the changes in forest cover for several types of forests. Specifically, we use remote sensing data to test whether the existence and the size of roads in 1995 affected the level of forest cover in 1995 and the rate of change between 1995 and 2000. We measure four types of roads: expressways, provincial highways, tertiary roads and village roads. We test the effect of these roads on four different forest types (closed-canopy forests, shrub-covered forests, open-canopy forests and other types of forests). Moreover, unlike many previous studies (e.g., Pfaff et al. 2007) that classify each pixel to a single land use class (or category of forest type), our measure of forests is the percentage of each pixel that is accounted for by each forest type (and other land uses). This way of using spatial data is almost certainly a more accurate way of measuring land use than if the analyst only uses a binary indicator.

We also have an innovative way to analyze the data in order to overcome potential statistical problems in previous studies of roads and forests. For example, we seek to account for the confounding effects of unmeasured but relevant variables (e.g., variables such as the growth potential of certain areas). When such unobserved heterogeneity exists, it potentially biases estimates of treatment effects since the treatment (whether or not there is a road in this case) is not randomly assigned. But the covariate matching techniques that we use can help to deal with potentially biased estimates of treatment effects due to the endogenous placement of roads, if this placement is due to observable factors included amongst our covariates..

Using these data and our approach we build on results in Deng et al. (2009), who find that roads have neutral or slightly positive impact on overall forest cover in Jiangxi. We go further, however, and break down the impact of roads by forest type and find different patterns of impacts depending on the forest type. Specifically, regions with larger roads have less closed-canopy forests remaining but deforestation of closed-canopy forests slows down in regions with larger roads compared to regions with smaller or no roads. In other words, in the long run, larger roads lead to less stock of closed-canopy forests; in the short run, larger roads lead to a slowdown of deforestation of closed-canopy forests (conversely, smaller roads or no roads lead to faster deforestation.)

The rest of the manuscript is organized as follows. In the next section we describe the data we use and the definitions of the key variables in our analysis. We then use descriptive statistics to describe the relationship between roads and the forest in our study area. The third section lays out the econometric approach. The fourth section reports the results of the quantitative analysis and discusses the findings and the final section concludes.

II. Data, Definitions and Simple Descriptive Relationships

In this section we describe the sources of the data, how they were collected and some of their important characteristics . Descriptive statistics of the dependent variable, the explanatory variable of interest and the control variables are shown in Appendix Table 1.

Forests

One of the strengths of this study is the quality of data that we use to estimate the changes in the quantity of forested area by forest type during a five-year period, between 1995 and 2000. For our purposes, we believe that measurements based on satellite remote sensing digital images are the most suitable for detecting and monitoring land use change at the regional scales (Turner et al. 1993; Fresco et al. 1996). The database was developed by the Chinese Academy of Sciences (CAS). Satellite remote sensing data provided by the US Landsat TM/ETM images have a spatial resolution of 30 by 30 meters (Vogelmann et al. 2001). These 30 by 30 meter images have been aggregated by CAS into one kilometer by one kilometer picture elements ('pixels') and these are the observations used in this study. The basic unit of observation in our study is the one kilometer square pixel, of which there are 166,932 in Jiangxi. The database includes panel data for two time periods: a.) the mid-1990s, including Landsat TM scenes from 1995 and 1996 (henceforth, 1995); and b.) the late 1990s, including Landsat TM scenes from 1999 and 2000 (henceforth, 2000).[2] The data team from CAS also spent considerable time and effort to validate the interpretation of TM images and land-cover classifications against extensive field surveys (Liu et al. 2003).[3] A hierarchical classification system of 25 land-cover classes was originally applied to the data. In this study we use information from the data set on forests (primarily as our dependent variable), cultivated land and built-up area (as covariates).

Using the data on forest land use, we can classify forests in different ways and to different degrees of specificity. One such way is to classify forest according to the extent of the forest cover. Some forests have dense canopies and a high share of the ground area that is covered (i.e., high forest cover). Some forests have low forest cover. Another distinction is the height of the trees, which is one indication of maturity of the trees. In this study we classify forested area based on both the extent of forest cover and the height of the trees. Forests are classified into four different types of forests: a.) natural or planted forests with canopy cover greater than 30 percent (hereafter *closed-canopy forest)*; b.) land covered by trees less than 2 meters high, with a canopy cover greater than 40 percent (*shrub-covered forests)*; c.) land covered by trees with a canopy cover between 10 to 30 percent (*open-canopy forests*); and d.)

other forested land, including land used for tea-gardens, orchards, nurseries and other forested area (*other forest*). Appendix A provides a more complete description of how the remote sensing data were interpreted to classify forested area into these four different types.[4]

Using the data, Figure 1 illustrates the forest cover in each 1 by 1 km pixel in Jiangxi Province in the year 2000 for each forest type. By comparing the four maps, it is apparent that closed-canopy forests have the largest area. The second most common type of forest in Jiangxi is open-canopy forest. Both closed- and open-canopy forests occupy many regions in the province except for flat, rice-growing and more urbanized areas in the central-north part of the province.

Spatial scale issues

There is likely to be spatial correlation amongst the pixels in our data, which reflects the fact that values of forest cover (or the residuals from regression models of cover) are similar for nearby pixels, violating assumptions about independently distributed disturbances. In fact, when we use spatial analytical techniques to measure for spatial correlation, we can see that there is a high correlation in forest cover among neighboring pixels.[5] At the very least, this spatial correlation can lead to inefficiency and invalid hypothesis testing procedures (Anselin 1995).

To deal with the spatial correlation problem, and also to ease the computational burden , we take a 1-in-25 sample by choosing only the pixels at the vertices of a five kilometer by five kilometer grid. As a result, the pixels used in the analysis cannot be adjacent neighbors. This approach, which is used in some econometric studies of deforestation (Nelson and Hellerstein. 1997), greatly reduces the spatial autocorrelation.[6]

Forests in Jiangxi Province

Jiangxi is a highly forested province. Based on the data, its forest cover was 56.28 percent in 1995 and 56.23 percent in 2000. While the total area of forested land did not change much in the aggregate, when we look across space, we can see that there is deforestation and reforestation/afforestation occurring at the same time. Figure 2, which maps the changes in forested area in each 1 by 1 kilometer pixel between 1995 and 2000, shows this simultaneous deforestation and reforestation/afforestation. Furthermore, the changes in composition of total forest cover reveal that between 1995 and 2000 the proportion of closed-canopy forest decreased (-0.6%), while the proportion of shrub-covered forests, open-canopy forests and other forest has increased slightly (Table 1).

To further understand transitions among forest types, we formed a matrix that shows the direct conversion among the four forest types (within-forest conversion) at the pixel level between 1995 and 2000 for the sample data set (Table 2). In our sample of 6666 km^2 (that is, 166,000/25), the most significant change uncovered by this conversion matrix is the direct conversion of a large proportion of closed-canopy forest to other forests (199 km^2). In net total, closed-canopy forests declined by 211 km^2. In contrast, the other forests category experienced a total net increase of 205 km^2. Shrub-covered forests and open-canopy forests also experienced a net gain during this time period. With less closed-canopy forests and more of other types of forests, these figures suggest that the quality of the forests may be declining in Jiangxi during this time period. The focus of this paper is whether or not these trends are being driven by roads.

Roads

The basic data for our roads variable comes from provincial, county and local maps which were made available through the CAS Data Center (Figure 4). The maps are up to date through 1995. The information from the hard copies of the maps was digitized by a working group based in the Institute of Geographical Sciences and Natural Resource Research in 1999 and 2000. The roads are classified into four types based on their size: *expressways* (which are multilane, controlled access highways); *provincial highways* (which are major roads which are typically not controlled access, but which are usually relatively well maintained since the province's highway bureau is charged with their maintenance); county and township roads (hereafter called *tertiary roads*) and *village roads* (which are all smaller village-level roads—not shown on Figure 4 for clarity). To the best of our knowledge, this study is the first paper to include village roads in a study of the impact of roads on forests (or any other land use pattern) in China.[7]

Using these data on roads, we measure accessibility to roads by constructing two sets of measures. The first measure of access to roads is a discrete, pixel-specific measure. This means that a pixel is labeled as having access to a certain kind of road according the size of the largest type of road that actually runs through the pixel. We will call this our *pixel-based road measure*. While the pixel-based road measure captures the effect of roads that run through the pixel, forest harvesting decisions in a pixel may also be affected by roads that are in the vicinity of the pixel but do not run through the pixel. We therefore construct a second measure of access to roads based on the characteristics of the watershed within which a pixel is located. This second measure takes the digitized road map of the province and turns it into a discrete, pixel-specific measure of the largest road that penetrates through any part of the watershed in which the pixel is located. We call this our *watershed-based road measure*.

Constructing the watershed-based road measure requires three steps. The first step uses a GIS map of Jiangxi Province and a watershed delineation function included in ArcGIS to divide the area of the province into distinct, non-overlapping watersheds. This process was accomplished using information on elevation and the formation of the landscape.[8] Figure 3 shows a map that divides Jiangxi into 1474 watersheds. In step two the digitized road map and the digitized watershed map were merged.[9] Finally, in step three we assign watersheds into "treated" watersheds and "control" watersheds according to *the size of the largest type of road that runs through the watershed.* Since the treatment is here defined at the watershed level, all pixels in a treated watersheds are treated pixels and vice versa. For example, when we want to define expressways as a treatment, all pixels in watersheds with an expressway would be classified as a treated pixel, while all pixels in watersheds that do not have an expressway would be classified as a control pixel.

Both pixel-based and the watershed-based road measures have their advantages. The pixel-based road measure is useful for at least two reasons. First, it provides a measure of direct access to forest resources from the closest road. For example, a pixel in the expressway treatment group when using the watershed-based road measure could be many kilometers away from the road whereas for an expressway pixel using the pixel-based road measure, the road would never be any more than 1 kilometer away from any part of the pixel. Second, while watershed-based measures allow us to estimate the impact of roads that are nearby (but not necessarily going through the pixel), they do not allow the testing of several hypotheses related to village roads. This is because all the watersheds in Jiangxi province have at least one village road going through them. Because of this, if we want to test the proposition that regions with a village road (treated) will experience more or less deforestation than a region without a village road (control), we would not be able to do so with our watershed-based road measure since we would have no controls. Testing the impact of these smaller roads is important because researchers have been concerned that smaller roads (such as forest roads) accelerate deforestation (e.g., Contreras-Hermosilla 2001). In contrast, the key advantage of the watershed-based road measure is that the estimates of impact of roads should be more robust to neighboring effects of roads, i.e., the effects of roads that do not necessarily go through the pixel but are in the same general vicinity of the pixel (which in this case means that the road is at least within the same watershed).

Other control variables

In addition to information on forested area and roads, other data are used to create control variables for other factors that determine forest area. The empirical literature on the determinants of forest cover considers four broad categories of variables. Cropper, Griffiths et al (2001), Chomitz and Gray (1996) and others include a number of geographic and climatic variables. These same authors plus Cropper, Griffiths et al. (1996) also use several demographic and economic variables. Other authors (e.g., Cropper et al., 1997) include measures of distance from the forested plots to different geographical features (such as distance to the nearest city). There also are other factors that are used by different authors (such as whether or not the pixel is in a protected area). In order to make our analysis as consistent as possible with the rest of the literature, we have collected information on four sets of variables: geographic and climatic factors (rainfall, elevation, terrain slope and soil characteristics), demographic and economic factors (gross domestic product per capita and population), measures of distance (distance to provincial capital and urban core) and an indicator for protected area. These factors have been consistently found to causally affect deforestation in a review paper by Pfaff and Sanchez (2004). In sum, we include 13 control variables in our regression which will help us more effectively isolate the impact of roads on forest cover change. Appendix B provides more information on the data sources and variable definitions.

Correlations between Structure of Forests and Roads

As a preview to more rigorous estimates of treatment effects, we present a figure and cross-tabulations that seek to illustrate the relationship between the pixel-based and watershed-based road measures and forest cover in 1995 and 2000 (Figure 5, Tables 3a and 3b). Figure 5 is a map of the province that overlays the top three tiers of roads (expressways, provincial highways and tertiary roads) and changes in closed-canopy forests between 1995 and 2000. It appears clear from the map that there are more forest cover changes near larger roads. However, these changes are both positive and negative and from casual observation it is not clear in which direction the change is on average.

The cross-tabulations, which are more disaggregated, between the roads and forest cover show a clearer trend (Table 3a and 3b). When dividing all of the pixels in our analysis by the largest road that penetrates each pixel (Table 3a) or watershed (Table 3b) (expressway pixels; provincial highway pixels; tertiary road pixels and village road pixels—rows 1 to 4) and pixels with no roads (row 5), the *level* of closed-canopy forests appear to be negatively associated with access to larger roads. For example, in 1995 a pixel with an expressway going through it had, on average, 25% cover of closed-canopy forest, whereas a pixel with no roads had 41% cover of closed-canopy forests (Table 3a, column 1). The trend is even clearer when we examine the watershed-based road measures (Table 3b, column 1). The same trend can be seen for 2000 for both types of road measures (Tables 3a and 3b, column 5).

Interestingly, when we examine the <u>changes</u> in closed-canopy forests between 1995 and 2000, we see the opposite trend. In general, if a *larger* road goes through a pixel, there is a *smaller* decline of closed-canopy forests (Tables 3a and 3b, column 9). In other words, deforestation of closed-canopy forests slows down when there is a larger road. The trend is clearer when we define access to roads using the watershed-based road measure (Table 3b) in which extreme changes are evened out. Depending on the road type, some of the decline in closed-canopy forest is accompanied by an increase in open-canopy forests and other forests (columns 11 and 12). Given these descriptive statistics, it appears possible that changes in the forest cover of Jiangxi are being affected by roads differently depending on the forest type and the road type.

III. Approach to Estimate the Effect of Access to Roads on Forest Structure

The basic relationship that we are interested in is:

(1) $$Forest\ Area_{ikt} = \alpha_0 + \alpha_{1k}\ (Access\ to\ Roads_{it\text{-}j}) + \varepsilon_{ikt}$$

where $Forest\ Area_{ikt}$ is the area of forest type *k* in pixel *i* in year *t*; $Access\ to\ Roads_{it\text{-}j}$ is a binary treatment variable that measures the nature of the largest road that ran through the watershed (or the pixel) in year t-j; and α_1 is our coefficient of interest. Controlling for access to roads for periods before the year of the forest area variable helps reduce some of the endogeneity problem.

Since we are interested in the impact of different types of road (expressway, provincial highway, tertiary roads and village roads), we define the variable $Access\ to\ Roads_{it\text{-}j}$ in eight different ways (Table 4). First we define the variable $Access\ to\ Roads_{it\text{-}j}$ in five ways (models 1.1-1.5) using pixel-based road measures and utilize the new data on village roads. We then define it in three more ways (models 2.1-2.3) when the variable is defined by watershed-based road measures. Models 2.1-2.3 are identical to the treatments tested in Deng et al. (2009), although their paper did not disaggregate forests by forest type.

In model 1.1, we include in our sample only the expressway and provincial highway pixels defined by the pixel-based road measures. $Access\ to\ Roads_{1.1it\text{-}j}$ equals 1 if the largest road that goes through the pixel is an expressway and equals 0 if the largest road is a provincial highway.[10] In the estimation of model 1.1, $\alpha_{1.1}$ will measure the effect on the forest area of building an expressway through a pixel that only had a provincial highway. In model 1.2, *Access* *to Roads*$_{1.2it-j}$ will equal 1 if the largest road going through the pixel is an expressway or a provincial highway and will equal 0 if the largest road is a tertiary road. In the estimation of model 1.2, $\alpha_{1.2}$ is measuring the effect on the forest area of building an expressway or a provincial highway through a pixel that originally only had a tertiary road.

Model 1.3 is similar to model 1.2 except that we include as the control pixels pixels with either tertiary roads or village roads or no roads. The interpretation of $\alpha_{1.3}$ then becomes the effect on the forest area of building a provincial highway or an expressway through a pixel that was roadless or with some village or tertiary road.

In model 1.4 we define *Access to Road*$_{1.4it-j}$ = 1 if there is any type of road going through the pixel, including village roads, and set the measure to 0 if there is no road in the pixel. The interpretation of $\alpha_{1.4}$ becomes the effect on the forest area of building any type of road into a previously roadless pixel.

Finally, in model 1.5 we include in our sample only the pixels with village roads (as treated) and roadless pixels (as controls). *Access to Roads*$_{1.5it-j}$ equals 1 if the largest road that goes through the pixel is a village road and equals 0 if there is no road in the pixel. In the estimation of model 1.5, $\alpha_{1.5}$ will measure the effect on the forest area of building a village road into a previously roadless pixel. It is important to note when estimating model 1.5, we drop all of the pixels that have an expressway, provincial highway or tertiary road running through them.

Models 2.1, 2.2 and 2.3 are similar to models 1.1, 1.2 and 1.3, respectively, except that in models 2.1-2.3 we define *Access to Roads* using watershed-based road measures rather than pixel-based measures. When using watershed-based measure, the analysis captures the effect on forest area of the nature of the road network inside each watershed. For example, in model 2.1 we define *Access to Road*$_{2.1it\text{-}j}$ = 1 if there is an expressway going through the watershed, and 0 if provincial highway is the largest road going through that watershed. The interpretation of $\alpha_{2.1}$ becomes the effect on the forest area of changing a watershed's highway system from a provincial highway to an expressway.[11]

We estimate all nine models (1.1-1.5 and 2.1-2.3) for two types of dependent variables: a.) forest cover in 1995 and b.) change in forest cover between 1995 and 2000 (forest cover 2000 – forest cover 1995). The first set of models captures the impact of roads on the level of forest, whereas the second set captures the impact of roads on changes in forest cover.[12] Moreover, we estimate the models with two types of dependent variables for each of the four types of forests (closed-canopy forests, shrub-covered forests, open-canopy forests and other forests.)

Identification problems

Producing an unbiased estimate of the coefficient of interest, a_1, using equation (1) is challenging for several reasons. Watersheds with expressways are likely to differ systematically from those without any roads (or with only smaller roads). They may be located in areas with less severe topography. The soils may be more productive. There also may be a number of unobserved locational advantages, since richer areas (or areas with more development potential) are more likely to attract investment in roads. These systematic differences may be even starker when we make the comparisons at the pixel level. Hence, applying Ordinary Least Squares (OLS) to equation (1) may produce biased treatment effects estimates of what happens to the forest cover when a previously roadless watershed has new roads introduced. Indeed, as discussed above, previous studies suggest many other factors that might affect forest area and since some are likely to be correlated with both forest area and access to roads, we can reduce omitted variable bias by controlling for as many covariates as possible.

In this study we use a matching approach as a further way to reduce estimator bias caused by the potentially endogenous placement of roads. Matching is an increasingly popular quasi-experimental evaluation method that offers a way of structuring non-experimental data to look like experimental data. Specifically, for every subject in the "treated" group, the researcher finds comparable subjects in the "control" group. It is a way to examine the impact of a treatment (in our context, the existence of particular types of roads) on an outcome (in our case a particular type of forested area) when selection takes place on observable characteristics (Pfaff 1998). Measuring the effect of roads on forest cover without bias using the matching method assumes that the outcome in the base state (forested area if the pixel was not in a watershed with a particular type of road) is independent of the treatment (in watershed without such roads), conditional on observed covariates. If this assumption holds, we can say that given the observable covariates, the forest cover of the control pixels is what the forest cover of the treated pixels would have been, had they not had their particular types of roads.

To take advantage of these features, we follow the recent literature and match every treated pixel with a control pixel using covariate matching (Rubin 1980). Covariate matching matches directly on covariates.[13] In our analysis, we choose to match the two nearest neighbors with similar covariates (Z) using an inverse variance weighting scheme to measure the closeness of two observations, which is an often-used metric.[14] Once we have a matched sample, we compare the forested area of the treated pixels with the forested area of the control pixels. We report the estimated coefficients that use the post-matching bias correction factor (Abadie and Imbens 2006). This correction factor is needed to correct for the conditional bias in finite samples when there are three or more continuous variables.

The variables used to match the pixels include seven measures of geographic and climatic variables (*rainfall*, *temperature*, *elevation*, *terrain slope*, *nitrogen*, *available phosphorous* and *soil pH value*); two measures of demographic and economic variables (*population in 1995*; *GDP in 1995*); three measures of distance variables (*distance to the provincial capital*, *distance to the nearest urban core in 1995*); one variable that indicates protected area (*protected_area*); and finally, *forest area of respective type in 1995*.

IV. Results

Pixel-based Measures of Roads

When the road treatments are defined using the pixel-based measures of roads, we find that the effect of access to roads on the aggregate, cross-sectional forest cover differs depending on the size of the road (Table 5, row 1). When comparing pixels with larger roads with those that already have provincial or tertiary roads, the effect is neutral (models 1.1 and 1.2); however, when comparing pixels with larger roads with those that have smaller or no roads the effects are strongly negative (models 1.3-1.5). For example, in model 1.3., pixels with expressways or provincial highways have 11.8% less forest cover in 1995 compared to pixels with only tertiary, village roads or no roads. Results also indicate that pixels with any type of road have 4.3% less forest cover compared to pixels that have no roads (model 1.4). Finally, pixels with only village roads have 2.5% less forest cover compared to those with no roads (model 1.5).

Importantly, however, when we decompose the effect of roads by the type of the forest (closed-canopy forests, shrub-covered forests, open-canopy forests and other forests) we see that the effect of roads differs depending on the type of the forest. We find consistently that the strong negative association between roads and forest cover in 1995 is reflecting the negative relationship of roads with closed-canopy forests (models 1.3-1.5, row 2). For example, pixels with any type of roads have nearly 4% less cover of closed-canopy forest compared to those with no roads (model 1.4, row 2). On the contrary, this negative association between larger roads and forests does not hold consistently for other types of roads. Larger roads seem to have a positive relationship with the cover of shrub-covered forests (models 1.4 and 1.5, row 3); a negative relationship with the cover of open-canopy forests (model 1.3, row 4); and no significant relationship with other forests (row 5).

Interestingly, the negative relationship between access to roads and forests does not carry over when the dependent variable is the change in forests between the five years (Table 6). When larger roads penetrate through a pixel that only had a smaller road or no road, forest cover either increases (or declines more slowly) or remains neutral for the model with aggregate forest cover (row 1) and for all forest types (rows 2-5). For example, when some type of road penetrates through a previous roadless pixel, the overall effect on the forest is neutral (model 1.4, row 1). However, when we examine the effect by forest type, we find that roads lead to an increase in closed-canopy forests (model 1.4, row 2, 0.209%), whereas other forest types remain neutral (rows 3-5). We find a similar finding when a village road penetrates into a previously roadless pixel (model 1.5). While the effect of building a village road is neutral for aggregate forest cover (row 1) as well as for shrub-covered forests, open-canopy forests and other forests (rows 3-5), it leads to an increase (or a slower decline) in closed-canopy forests (row 2, 0.227%).

Watershed-based Measures of Roads

When the road treatments are defined using the watershed-based measures of roads, the effects of roads on forest cover differ compared to the results using the pixel-based measures. The impact of roads—defined using the watershed-based measures--on aggregate forest cover in 1995 and the change in forest cover between 1995 and 2000 is neutral or slightly positive (Tables 7 and 8, row 1).[15] Based on the cross-sectional models which estimate the impact of the road network in the watershed on forest cover in 1995, the only significant coefficient was in model 2.1 (Table 7, row 1). The coefficient can be interpreted that there is 2.7% more forest cover (of any type) in watersheds with an expressway compared to those with only a provincial highway.

None of the coefficients were significant for the total forest when the dependent variable was the change in forests between the five years, suggesting that roads lead to neither an increase or decrease in aggregate forest cover.

When the total forest is decomposed into different types of forests, we find that the impact of roads on forests differs depending on the type of the forest (Tables 7 and 8, rows 2 through 5). For example, in model 2.1, there is 1.4% less cover in shrub-covered forests in watersheds with an expressway compared to those with only a provincial highway, whereas there are 2.9% more open-canopy forests. In fact, we consistently find that when watersheds have larger roads, such as expressways or provincial highways, there are more open-canopy forests than watersheds without those larger roads (Table 7, row 4). Importantly, the effect of roads on closed-canopy forest in 1995 is neutral across all models (row 2).

The effects of access to roads on changes in forest cover also differ depending on the types of the forest (Table 8). While most effects of roads are neutral, in model 2.3 we find that building larger roads (expressways or provincial highways) leads to an *increase* (or a slower decline) in closed-canopy forests but a *decrease* in shrub-covered forests (Table 8, rows 2 and 3). Building these larger roads in a watershed that previously had only village roads slows down deforestation of closed-canopy forests by 0.262%. From an inspection of the average change in forest cover (Table 4), this coefficient should be interpreted that the deforestation rate of mature forests is 0.3% slower when a watershed changes from a roadless watershed to a watershed with some type of a road. In contrast, the same change in roads accelerates deforestation of shrub-covered forests by 0.112% (row 3).

V. Conclusion

This study demonstrates that examining the effect of roads on measures of forests that aggregate across all forest types masks the effect on the overall quality of the forests. Our major finding is that roads have different effects on forests depending on the type of the forest. Although some estimates are statistically only weakly significant, when we examine the relationship between roads and forests using cross-sectional data, we find that the aggregate forest cover is smaller in areas with larger roads, and importantly, that this reflects the smaller areas in closed-canopy forests . On the contrary, when we examine the effect of roads on changes in forest cover between 1995 and 2000, larger roads are associated with a slowdown in the decline in the cover of closed-canopy forests. This result holds even for village roads, the building of which has been a concern for forest managers. In other words, in the Jiangxi case roads appear to be slowing down the deforestation of mature forests; conversely, forests are declining faster in roadless areas. This result is not surprising if we interpret the cross-sectional results as estimates for long-run results and the differenced models as short-run results. Depletion of mature, closed-canopy forests is the fastest in roadless areas but the depletion rate slows down as more and larger roads get built; but in the long run the regions that become more developed end up with less coverage of mature forests.

We conjecture that this perhaps counter-intuitive trend is driven by a combination of several factors. Our finding is consistent with the hypothesis that as larger road networks are constructed and other non-agricultural sectors develop, people depend less on the forest sector as a source of income. It is also consistent with the hypothesis that when timber companies decide where to harvest, they may want to take advantage of economies of scale and choose to harvest timber in areas where there are more abundant resources. With the penetration of larger roads, timber companies may shift their production to areas with more abundant forests if there is a large fixed cost associated with harvesting timber. Alternatively, if the marginal cost of harvesting trees is decreasing in resource stock, timber companies would also have incentives to operate in areas with more resource stock. So where are forests more abundant? In the case of China the areas with larger roads already have been "settled" (sometimes for thousands of years!). Not surprisingly, in Jiangxi Province we found that there is a lower forest cover of closed-canopy forests where larger roads, such as expressways and provincial highways, have penetrated. Areas with village roads or no roads have disproportionately more abundant closed-canopy forests. If our conjecture is correct, we should expect that timber companies would choose areas with only village roads or no roads to harvest the timber. Moreover, if this is so, then this would drive a faster deforestation rate in those areas. In our matching models, we matched each treated pixel with a control pixel using forest area in 1995. However, to capture the economies of scale (or the decreasing marginal costs) we need information on the abundance of forest resource at the regional scale. Examining the association between forest resources at a larger geographical scale and the harvesting activities at the micro scale is one potential topic for future research.

Finally, do our results mean that China does not need to be worried about the impact of building more roads on forest quality? Even though we found that roads are associated with slower deforestation of closed-canopy forests, their forest cover is still declining. Without an understanding of when this downward trend in forest cover will halt (or reverse), policymakers still need to be concerned about the effects of building roads on forest quality. This is especially true if critical ecosystem services rely on better quality forests, such as mature forests.

[1] Blackman et al. (2008) provides an interesting case in which managed forests (e.g., coffee trees) are less likely to be cleared in areas that have better transportivity to larger cities. The study argues that the proximity to urban centers reduces the cost of transporting inputs and outputs associated with nontimber agroforestry, a factor that would encourage the preservation of tree cover. However, this type of association between transportivity and forest cover is not a focus of our study. We deal with four different forest types, and managed forests for non-timber goods constitute only a small portion of the forests in the study area (less than 1% in 2000.)

[2] A TM/ETM scene is the unit of area of coverage of digital images that are made by Landsat satellites. In the original Landsat material, which was configured by NASA before they provided the material to CAS, it took about 500 scenes to completely cover all of China's territory. Because we only have roads data for the mid-1990s, we are unable to use the 1988 information on forest use. In the rest of the paper, then, we use only the 1995 and 2000 images for our analysis.

[3] Additional details about the methodology, which we used to generate the databases of land cover from Landsat TM, are documented in Deng et al. (2002) and Deng et al. (2008).

[4] See Liu et al. (2002) for a literature review on using remote sensing data to measure forested land in China and elsewhere.

[5] The Moran *I* statistic is 0.73 for the dependent variable and 0.49 for the residuals. Intuitively, this statistic is equivalent to the slope coefficient of a linear regression of the weighted average

value of forest cover (residuals) for the pixels surrounding the *i*th pixel on the forest cover (residual) in pixel *i*.

[6] After sampling, the Moran *I* statistic falls to 0.47 for the dependent variable and 0.13 for the residuals.

[7] Despite the fine scale of our road data, there are several caveats. It is well established that satellite imagery is effective in tracking the development of major disturbances such as roads and large clear cut operations (Contreras-Hermosilla 2001). However, satellite imagery may not capture forest roads if there is a canopy closure over roads at the time of satellite imagery. Moreover, if the logging operation is small scale or selective, it may leave behind a mosaic of intact forest with tree fall gaps, truck loading areas and damaged trees along with primary and secondary roads. In that case, it would be challenging for an automatic classification procedure to classify land use with precision (Stone and Lefebvre 1998; de Wasseige Pierre Defourny). However, in our study (as will be seen below) this should not be a problem since, despite this problem, there will not be any watershed in which the entire road is unobservable.

[8] In our study (as in most GIS-based watershed analyses) a watershed is defined as a set of spatially contiguous pixels, where if two drops of water were to fall on any two arbitrary pixels and if the drops were allowed to flow out of the watershed, they would both leave the watershed through the same point (or through the same outlet pixel).

[9] The maps were drawn so that a given segment of road could not, simultaneously, be in two watersheds at once.

[10] The county / township road pixels and no road pixels are excluded from the analysis when we use *Access to Roads*1.1it-j.

[11] We do not estimate models for watershed-based road measures that are equivalent to models 1.4 and 1.5 because there are only five watersheds which have no roads of any type and hence we do not have enough controls to do meaningful analyses.

[12] An additional advantage of using the change in forest cover is that it avoids the purely mechanical effect of roads. If an expressway is 20 meters wide (2 lanes each way plus median strip) and transverses a pixel, then that is 20,000 sq meters out of 1 million in the pixel taken up by roadway; therefore there would already be 2% less forest cover even if the road stimulates no behavioral impacts of further clearance. Since there are no new roads in 2000 in our data set, the pure mechanical effect of roads get differenced out. The watershed-based road variables also have a similar advantage because the fraction of a watershed taken up by roadway is much less and thus this mechanical effect would not show up in the treatment effects.

[13] Another common matching method is the propensity score matching method, where the pixels are matched based on the probability of treatment. Although there is no dominance between covariate matching and propensity score, Zhao (2004) demonstrates that covariate matching is robust under a number of different settings. Zhao (2004) also shows that covariate matching is preferable when the sample size is small and when the correlation between covariates and the participation indicator is not high. Since the sample size is not large in all models, and since the

correlation between the covariates in the models and the treatment is not high based on logit models, we restrict our analysis to covariate matching method.

[14] Under the inverse variance weighting scheme, we match the treated and the control pixels using the k x k diagonal matrix of the inverse of the sample standard errors of the 13 variables in the model.

[15] The results shown in Tables 7 and 8, row 1 are consistent with Deng et al. (2008) which examined the impact of access to roads on aggregate forest cover.

Bibliography

Abadie, A. and G. W. Imbens (2006). "On the Failure of the Bootstrap for Matching Estimators." NBER Technical Working Papers 0325.

Andersen, L. E., C. W. J. Granger, E. J. Reis, D. Weinhold and S. Wunder (2002). The Dynamics of Deforestation and Economic Growth in the Brazilian Amazon. Cambridge, Cambridge University Press,.

Anselin, L. (1995). "Local Indicators of Spatial Association." Geographical Analysis **27**: 93-115.

Binswanger, H. P., S. R. Khandker and M. R. Rosenzweig (1993). "How infrastructure and financial institutions affect agricultural output and investment in India." Journal of Development Economics **41**: 337-366.

Blackman, A., H. J. Albers, B. Avalos-Sartorio and L. C. Murphy (2008). "Land cover in a managed forest ecosystem " American Journal of Agricultural Economics **90**(1): 216-231.

Chen, L., N. Heerink and M. van den Berg (2006). "Energy consumption in rural China: A household model for three villages in Jiangxi Province." Ecological Economics **58**(2): 407-420.

Chomitz, K. M. and D. A. Gray (1996). "Roads, Land Use, and Deforestation: A Spatial Model Applied to Belize." World Bank Economic Review **10**(3): 487-512.

Contreras-Hermosilla, A. (2001). Forest Law Compliance--An Overview, CIFOR.

Cropper, M., J. Puri and C. Griffiths (2001). "Predicting the location of deforestation: the role of roads and protected areas in North Thailand." Land Economics 77(2): 172-186.

Cropper, M. L., C. W. Griffiths and M. Mani (1997) "Roads, Population Pressures, and Deforestation in Thailand, 1976-89." World Bank Policy Research Working Paper No. 1726.:

de Wasseige, C. (Pierre Defourny). "Remote sensing of selective logging impact for tropical forest management." Forest Ecology and Management **188**(1-3): 161-173.

Deininger, K. and B. Minten (1997). "Determinants of forest cover and the economics of protection: An application to Mexico." American Journal of Agricultural Economics **84**(4): 943 - 960.

Deng, X., J. Liu and D. Zhuang (2002). "Modeling the relationship of land use change and some geophysical indicators: a case study in the ecotone between agriculture and pasturing in Northern China." Journal of Geographical Sciences **12**(4): 397-404.

Deng, X., H. Su and J. Zhan (2008). "Integration of Multiple Data Sources to Simulate the Dynamics of Land Systems." Sensors **8**: 620-634.

Deng, X., J. Huang, E. Uchida, S. Rozelle, and J. Gibson (2009). "Pressure Cookers or Pressure Valves: Do Roads Lead to Deforestation in China?" Working Paper. Center for Chinese Agricultural Policy, Beijing, China.

Doll, C. N. H., J. P. Muller and J. G. Morley (2006). "Mapping regional economic activity from night-time light satellite imagery." Ecological Economics **57**(1): 75 - 92.

Escobal, J. and C. Ponce (2002). The benefits of rural roads: Enhancing income opportunities for the rural poor. GRADE Working Paper. Lima, Peru, Grupo de Analisis para el Desarrollo.

FAO (2005). Forest Resource Assessment 2005, Food and Agriculture Organization of the United Nations.

Fresco, L. O., R. Leemans, Turner II, B.L.,, D. Skole, A. G. v. Zeijl-Rozema and V. Haarmann, Eds. (1996). Land use and cover change (LUCC) Open Science Meeting Proceedings. LUCC Report Series No. 1. Barcelona International Project Office, LUCC, Institut Carogràfic de Catalunya,.

Hartkamp, A. D., K. De Beurs, A. Stein and J.W. White. (1999). "Interpolation Techniques for Climate Variables." NRG-GIS Series 99-01.

Jacoby, H. C. (2000). "Access to markets and the benefits of rural roads." Economic Journal **110**(465): 713-737.

Kaimowitz, D. and A. Angelsen (1998). Economic models of tropical deforestation: A review. Indonesia, Center for International Forestry Research.

Kravchenko, A. and D. G. Bullock (1999). "A comparative study of interpolation methods for mapping soil properties." Journal of Agronomy **91**: 393–400.

Lawrence, D. and D. R. Foster (2004). Recovery of nutrient cycling and ecosystem properties following shifting cultivation: regional and stand-level constraints. Integrated Land-Change Science and Tropical Deforestation in the Southern Yucatán: Final Frontiers. B.L. Turner II, J. Geoghegan and D. Foster. Oxford, Clarendon Press of Oxford University Press: 81-104.

Liu, D. S., L. R. Iverson and S. Brown (1993). "Rates and patterns of deforestation in the Philippines: applications of Geographic Information System analysis." Forest Ecology and Management **57**: 1-16.

Liu, G. B., M. X. Xu and C. Ritsema (2003). "A study of soil surface characteristics in a small watershed in the hilly, gullied area on the Chinese Loess Plateau." Catena **54**(1-2): 31-44.

Liu, S. L., B. J. Fu, Y. H. Lu and L. D. Chen (2002). "Effects of reforestation and deforestation on soil properties in humid mountainous areas: a case study in Wolong Nature Reserve, Sichuan province, China." Soil Use and Management **18**(4): 376-380.

Loffeir, M. E. and J. Brayer (2005). The changing objectives of FAO forest resource evaluation. Beyond Tropical Deforestation: From Tropical Deforestation to Forest Cover Dynamics and Forest Development (Mand and the Biosphere). D. Babin. Paris, UNESCO and CIRAD.

Ludeke, A. K., R. C. Maggio and L. M. Reid (1990). "An analysis of anthropogenic deforestation using logistic regression and GIS." Journal of Environmental Management **31**: 247-259.

Mertens, B. and E. F. Lambin (1997). "Spatial modelling of deforestation in Southern Cameroon: spatial disaggregation of diverse deforestation processes." Applied Geography **17**: 143-68.

Ministry of Public Security of China (various years). China counties and cities' population yearbook. Beijing, Chinese Public Security University Press.

NBSC (2001). China social-economic statistical yearbooks for China's counties and cities. Beijing, China Statistics Press.

Nelson, G. C. and D. Hellerstein. (1997). "Do Roads Cause Deforestation? Using Satellite Images in Econometric Analysis of Land Use." American Journal of Agricultural Economics **79**(1): 80-88.

Pfaff, A. (1998). "What Drives Deforestation in the Brazilian Amazon? Evidence from Satellite and Socioeconomic Data." Journal of Environmental Economics and Management **37**(26-43).

Pfaff, A. and A. Sanchez (2004). "Deforestation Pressure and Biological Reserve Planning: A Conceptual Approach & An Illustrative Application For Costa Rica." Resource & Energy Economics **26**: 237-254.

Pfaff, A., J. A. Robalino, R. Walker, E. J. Reis, S. Perz, C. Bohrer, S. Aldrich, E. Arima, M. Caldas, W. Laurance and K. Kirby (2007). "Road Investments, Spatial Intensification and Deforestation in the Brazilian Amazon Journal of Regional Science." Journal of Regional Science **47**: 109-123.

Qiao, F. and S. Rozelle (1998). "Tenure of Forest Land and the Development of Forestry Sector." Problems of Agricultural Economy 7(5): 23-29.

Rubin, D. B. (1980). "Bias reduction using Mahalanobis-metric matching." Biometrics **36**(March): 249-264.

Sader, S. A. and A. T. Joyce (1988). "Deforestation rates and trends in Costa Rica." Biotropica **20**: 11-19.

Stone, T. A. and P. Lefebvre (1998). "Using multi-temporal satellite data to evaluate selective logging in Para, Brazil." International Journal of Remote Sensing **19**(13): 2517-2516.

Turner, B. L., R. H. Moss and Skole D. L., Eds. (1993). Relating land use and global land-cover change: A proposal for an IGBP-HDP core project. Land-Use/Land-Cover Change, IGBP-HDP Working Group.

Vogelmann, J. E., Helder, Dennis, Morfitt, Ron, Choate, Michael J., Merchant, James W., Bulley and Henry (2001). "Effects of Landsat 5 Thematic Mapper and Landsat 7 Enhanced Thematic Mapper Plus radiometric and geometric calibrations and corrections on landscape characterization." Remote Sensing of Environment **78**: 55 - 70.

World Resources Institute (2005). Millennium Ecosystem Assessment, 2005. Ecosystems and Human Well-being: Synthesis. Washington, D.C., Island Press.

Zhang, Y., S. Tachibana and S. Nagata (2006). "Impact of socio-economic factors on the changes in forest areas in China." Forest Policy and Economics **9**(1): 63-76.

Zhao, Z. (2004). "Using matching to estimate treatment effects: Data requirements, matching metrics, and Monte Carlo evidence." The Review of Economics and Statistics **86**(1): 91-107.

Table 1. Changes in Composition of Total Forest Area in Jiangxi Province between 1995 and 2000

Forest type	Fraction of total forest area in Jiangxi Province		Change
	1995	**2000**	**2000-1995**
Closed-canopy forest	73.0%	72.4%	-0.6%
Shrub-covered forests	4.7%	4.9%	+0.2%
Open-canopy forest	21.7%	21.9%	+0.1%
Other Forest	0.5%	0.8%	+0.3%
Total Forest	100%	100%	

Source: Author's data

Note: The total forest cover in Jiangxi Province is 56%. All pixels (before sampling) in Jiangxi province were used to calculate the numbers.

Table 2. Direct Conversion between Forest Types at the Pixel Level using Sample Data Set, between 1995 and 2000 (km^2)

Forest type	**To:**	Closed-canopy forest	Shrub-covered forests	Open-canopy forest	Other forest	Total loss
From:						
Closed-canopy forest			7.96	22.7	199.02	-229.67
Shrub-covered forests		0.19		3.65	15.09	-18.93
Open-canopy forests		3.63	0.11		29.18	-32.92
Other forest		13.75	11.59	12.93		-38.27
Total gain		+17.75	+19.65	+39.28	+243.28	

Source: Author's data.

Note: The total area in the sample data set is $6666km^2$.

Table 3a. Levels and Changes of Mean Forest Cover in the Sampled Data Set, by Largest Road Type Going through Each Pixel, Jiangxi Province, 1995 and 2000 (%)

	1995				2000				2000-1995			
Largest type of road going through pixel	Closed-canopy forest	Shrub-covered forests	Open-canopy forest	Other forests	Closed-canopy forest	Shrub-covered forests	Open-canopy forest	Other forests	Closed-canopy forest	Shrub-covered forests	Open-canopy forest	Other forests
Expressway (n=138)	24.70	1.14	10.31	0.09	24.61	1.10	11.54	0.70	-0.09	-0.04	+1.24	+0.61
Provincial highway (n=130)	22.37	2.98	13.69	0.87	22.80	2.90	13.88	0.59	+0.43	-0.08	+0.19	-0.28
Tertiary roads (n= 128)	28.79	2.32	11.19	0.13	28.14	2.34	11.19	0.29	-0.64	+0.02	+0.21	+0.16
Village roads (n=1893)	43.45	2.85	12.98	0.34	43.24	2.88	13.00	0.49	-0.21	+0.03	+0.02	+0.13
No road (n=4377)	41.36	2.81	11.88	0.30	40.92	2.88	12.00	0.44	-0.45	+0.07	+0.12	+0.14
Overall	41.00	2.78	12.18	0.32	40.64	2.83	12.30	0.46	-0.34	+0.05	+0.12	+0.14

Notes: n indicates the number of pixels. Tertiary roads include county and township roads.

Source: Authors' data.

Table 3b. Levels and Changes of Mean Forest Cover in the Sampled Data Set, by Largest Road Type Going through Watershed, Jiangxi Province, 1995 and 2000 (%)

	1995				2000				2000-1995			
Largest type of road going through watershed	Closed-canopy forest	Shrub-covered forests	Open-canopy forest	Other forests	Closed-canopy forest	Shrub-covered forests	Open-canopy forest	Other forests	Closed-canopy forest	Shrub-covered forests	Open-canopy forest	Other forests
Expressway (n=2430)	34.83	2.01	12.58	0.38	34.62	2.00	12.83	0.55	-0.22	-0.01	+0.26	+0.17
Provincial highway (n=1652)	38.53	3.75	12.08	0.20	38.27	3.81	11.94	0.33	-0.26	+0.06	-0.14	+0.13
Tertiary roads (n=986)	45.77	2.68	12.19	0.39	45.37	2.67	12.43	0.45	-0.40	-0.00	+0.24	+0.06
Village roads (n=1593)	49.94	3.02	11.69	0.33	49.28	3.18	11.79	0.47	-0.66	+0.16	+0.09	+0.15
No road (n=5)	65.35	4.76	5.88	0.00	64.80	4.76	5.84	0.00	-0.55	+0.00	-0.05	0.00
Overall	41.00	2.78	12.18	0.32	40.64	2.83	12.30	0.46	-0.34	+0.05	+0.12	+0.14

Note: n indicates the number of pixels in watersheds where the specified road type is the largest road. Tertiary roads include county and township roads.

Source: Authors' data.

Table 4. Definition of Treatments and Controls

Treatment The largest type of road is:	Model: Largest type of road going through: Pixel	Watershed	Express-ways	Province-level Highways	Tertiary roads	Village roads	No roads
Expressways vs. provincial highways	1.1	2.1	T	C			
Expressways / provincial highways vs. tertiary roads	1.2	2.2	T	T	C		
Expressways /provincial highways vs. tertiary roads / village roads / no roads	1.3	2.3	T	T	C	C	C
Any road vs. no roads	1.4		T	T	T	T	C
Village roads vs. no roads	1.5					T	C

Notes: T = Treated; C=Control. Tertiary roads include township roads. Treatments defined in models 2.1 through 2.3 are identical to Deng et al. (2009).

Table 5. Effect of Roads on Forest Cover 1995 Using Covariate Matching Method, Access to Roads Defined at the Pixel Level.

	Dependent Variable: Forest cover in 1995				
Model:	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**
Treatment:	Expressways	Expressways or provincial highways	Expressways or provincial highways	Any road	Village roads
Control:	Provincial highways	Tertiary roads	Tertiary roads, village roads or no road	No road	No road
Total forest	2.415	-0.206	-11.824***	-4.283***	-2.517**
	(0.44)	(0.05)	(6.03)	(5.62)	(3.14)
Closed-canopy forest	7.976*	-4.109	-8.602***	-3.968***	-2.827**
	(1.94)	(1.18)	(4.28)	(4.58)	(3.03)
Shrub-covered forests	-0.832	-0.630	-0.028	0.374**	0.392**
	(1.34)	(0.79)	(0.08)	(2.20)	(2.11)
Open-canopy forests	-3.792	4.032	-3.551**	-0.772	-0.160
	(0.93)	(1.57)	(2.33)	(1.25)	(0.24)
Other forest	-0.937	0.502	0.356*	0.083	0.079
	(1.31)	(1.42)	(1.65)	(0.81)	(0.71)
N treated	138	268	268	2289	1893
N controls	130	128	6398	4377	4377

Notes: The models control for forest cover in 1995. 5 by 5 km sampling dataset with 1474 watersheds. Tertiary roads include township roads. Absolute value of z statistics in parentheses. Calipers restrict matches to units within 0.5 standard deviations of each covariate.

***=significant at 1% level, **=significant at 5% level, and *=significant at 10% level

Table 6. Effect of Roads on Changes in Forest Cover between 1995 and 2000 Using Covariate Matching Method, Access to Roads Defined at the Pixel Level.

	Dependent Variable: Forest cover in 2000- Forest cover in 1995				
Model:	**1.1**	**1.2**	**1.3**	**1.4**	**1.5**
Treatment:	Expressways	Expressways or provincial highways	Expressways or provincial highways†	Any road†	Village road†
Control:	Provincial highways	Tertiary roads	Tertiary roads, village roads or no road	No road	No road
Total forest	2.351*	0.028	1.060*	0.214	0.158
	(1.69)	(0.03)	(1.81)	(1.31)	(0.97)
Closed-canopy forest	0.430	0.536	0.307	0.209*	0.227*
	(0.80)	(1.19)	(0.87)	(1.64)	(1.65)
Shrub-covered forests	0.100	-0.085	-0.255	-0.025	0.000
	(0.35)	(0.40)	(1.62)	(0.50)	(0.99)
Open-canopy forests	1.218	-0.112	0.958*	0.078	-0.050
	(0.94)	(0.14)	(1.95)	(0.52)	(0.31)
Other forest	0.610	0.058	-0.088	-0.002	0.046
	(0.81)	(0.12)	(0.26)	(0.02)	(0.54)
N treated	138	268	268	2289	1893
N controls	130	128	6398	4377	4377

Notes: † Not comparable to treatments in Deng et al. (2009) since data for village roads were not available at that time. The models control for forest cover in 1995. 5 by 5 km sampling dataset with 1474 watersheds. Tertiary roads include county and township roads. Absolute value of z statistics in parentheses. Calipers restrict matches to units within 0.5 standard deviations of each covariate. ***=significant at 1% level, **=significant at 5% level, and *=significant at 10% level.

Table 7. Effect of Roads on Forest Cover in 1995 Using Covariate Matching Method, Access to Roads Defined at the Watershed Level

Dependent Variable: Forest cover in 1995			
Model:	**2.1**	**2.2**	**2.3**
Treatment:	Expressways	Expressways or province–level highways	Expressways or provincial highways†
Control:	Provincial highways	Tertiary roads	Tertiary roads, village roads or no road
Total forest	2.739*	0.608	0.219
	(1.76)	(0.38)	(0.24)
Closed-canopy forest	1.259	-1.596	-1.359
	(0.85)	(0.89)	(1.33)
Shrub-covered forests	-1.435***	-0.095	0.187
	(4.34)	(0.28)	(0.92)
Open-canopy forest	2.915*	2.134*	1.297*
	(1.75)	(1.87)	(1.86)
Other forest	-0.000	0.166	0.094
	(0.00)	(1.11)	(0.87)
N treated	2430	4081	4082
N controls	1651	995	2584

Notes: † Not comparable to treatments in Deng et al. (2009) since data for village roads were not available at that time. The models control for forest cover in 1995. 5 by 5 km sampling dataset with 1474 watersheds. Tertiary roads include county and township roads. Absolute value of z statistics are reported in parentheses. Calipers restrict matches to units within 0.5 standard deviations of each covariate. ***=significant at 1% level, **=significant at 5% level, and *=significant at 10% level

Table 8. Effect of Roads on Changes in Forest Cover between 1995 and 2000 Using Covariate Matching Method, Access to Roads Defined at the Watershed Level

Dependent Variable: Forest cover in 2000-Forest cover in 1995			
Model:	**2.1**	**2.2**	**2.3**
Treatment:	Expressways	Expressways or province–level highways	Expressways or provincial highways
Control:	Provincial highways	Tertiary roads	Tertiary roads, village roads or no road
Total forest	0.235	-0.124	0.194
	(0.78)	(0.31)	(1.01)
Closed-canopy forest	0.104	0.164	0.262*
	(0.47)	(0.70)	(1.69)
Shrub-covered forests	-0.003	0.018	-0.112*
	(0.03)	(0.19)	(1.73)
Open-canopy forest	0.305	-0.333	-0.048
	(1.16)	(1.12)	(0.27)
Other forest	0.113	0.094	0.070
	(0.88)	(0.70)	(0.76)
N treated	2430	4081	4082
N controls	1651	995	2584

Notes: † Not comparable to treatments in Deng et al. (2009) since data for village roads were not available at that time. The models control for forest cover in 1995. 5 by 5 km sampling dataset with 1474 watersheds. Tertiary roads include county and township roads. Absolute value of z statistics are reported in parentheses. Calipers restrict matches to units within 0.5 standard deviations of each covariate. ***=significant at 1% level, **=significant at 5% level, and *=significant at 10% level

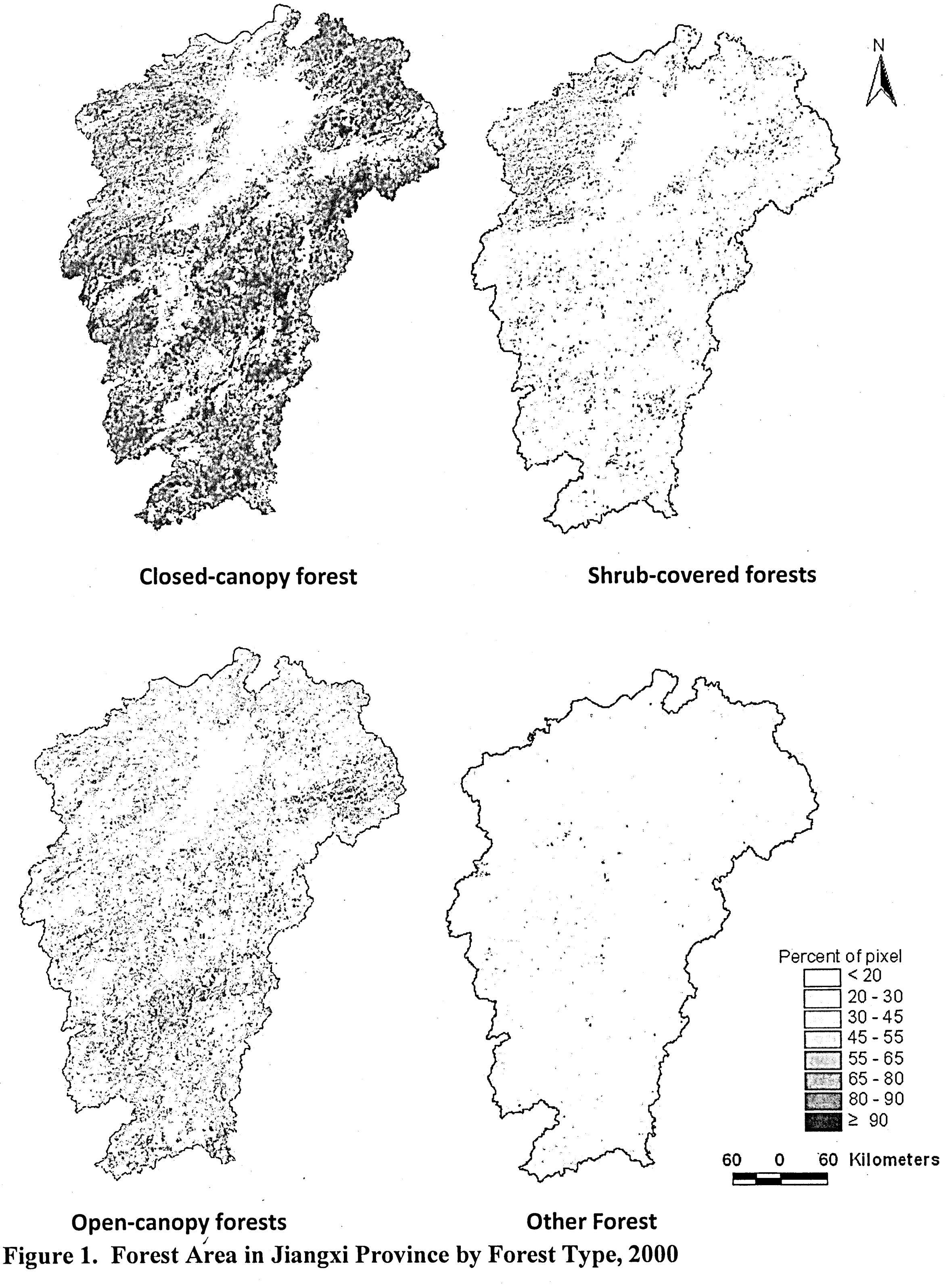
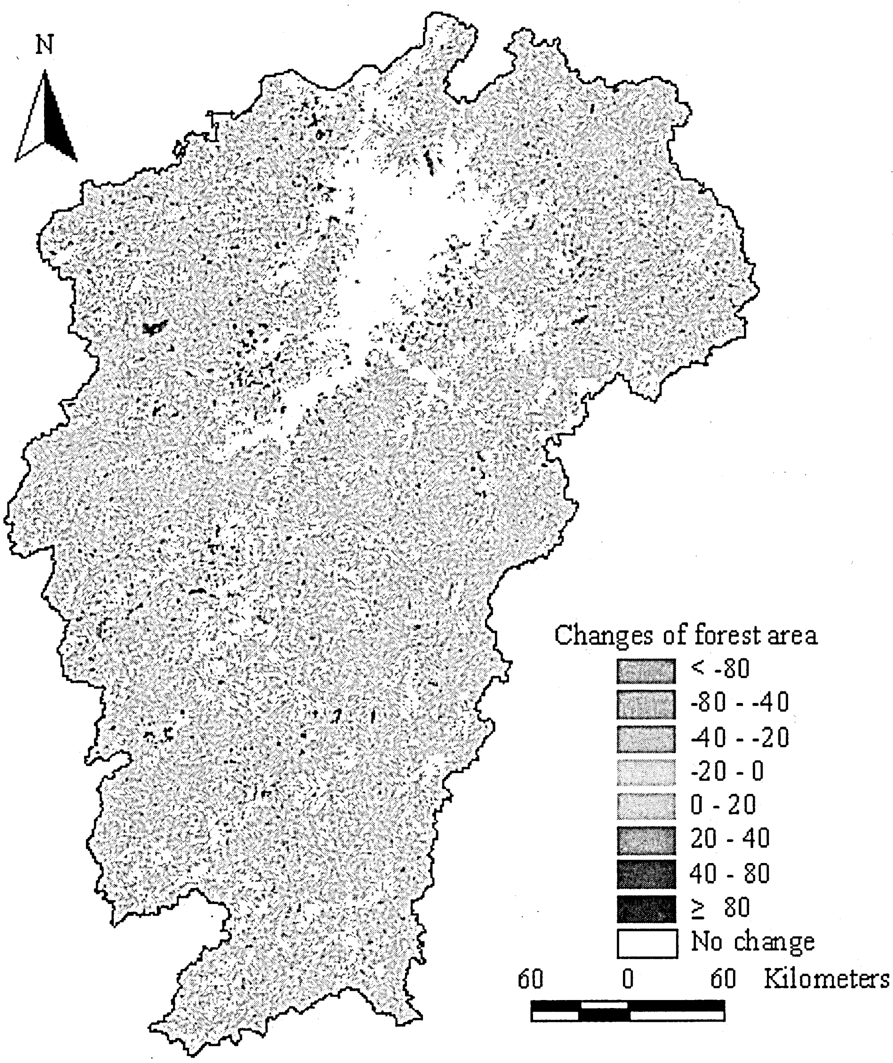
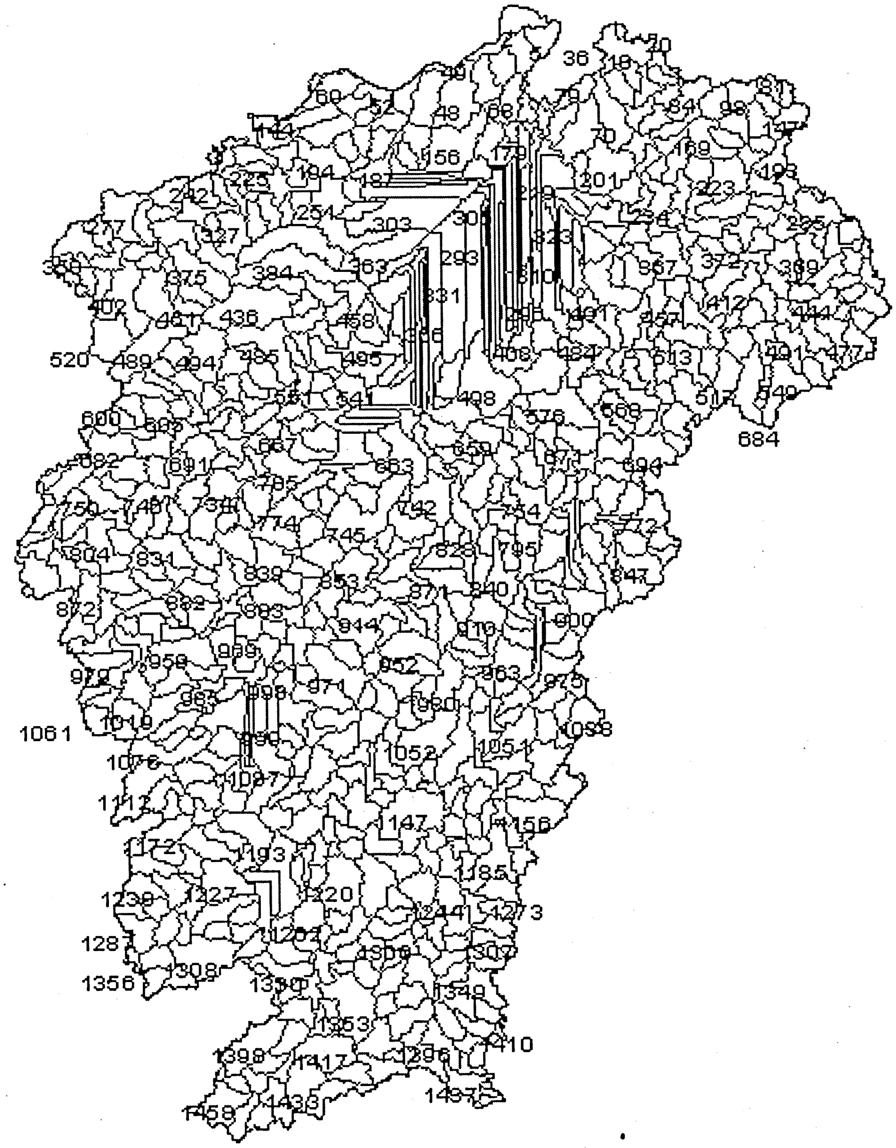


Figure 1. Forest Area in Jiangxi Province by Forest Type, 2000



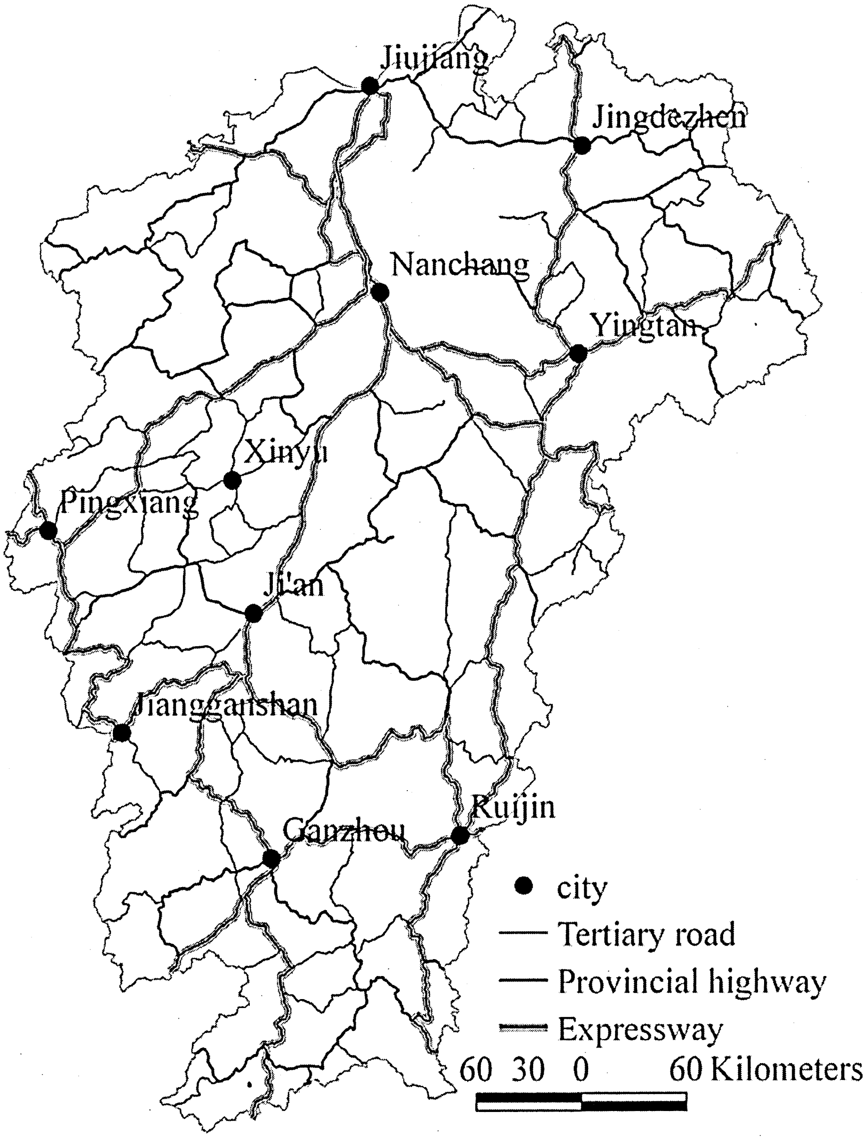
Data: Authors' data.

Figure 2. Changes in Total Forest Cover, 1995 to 2000.



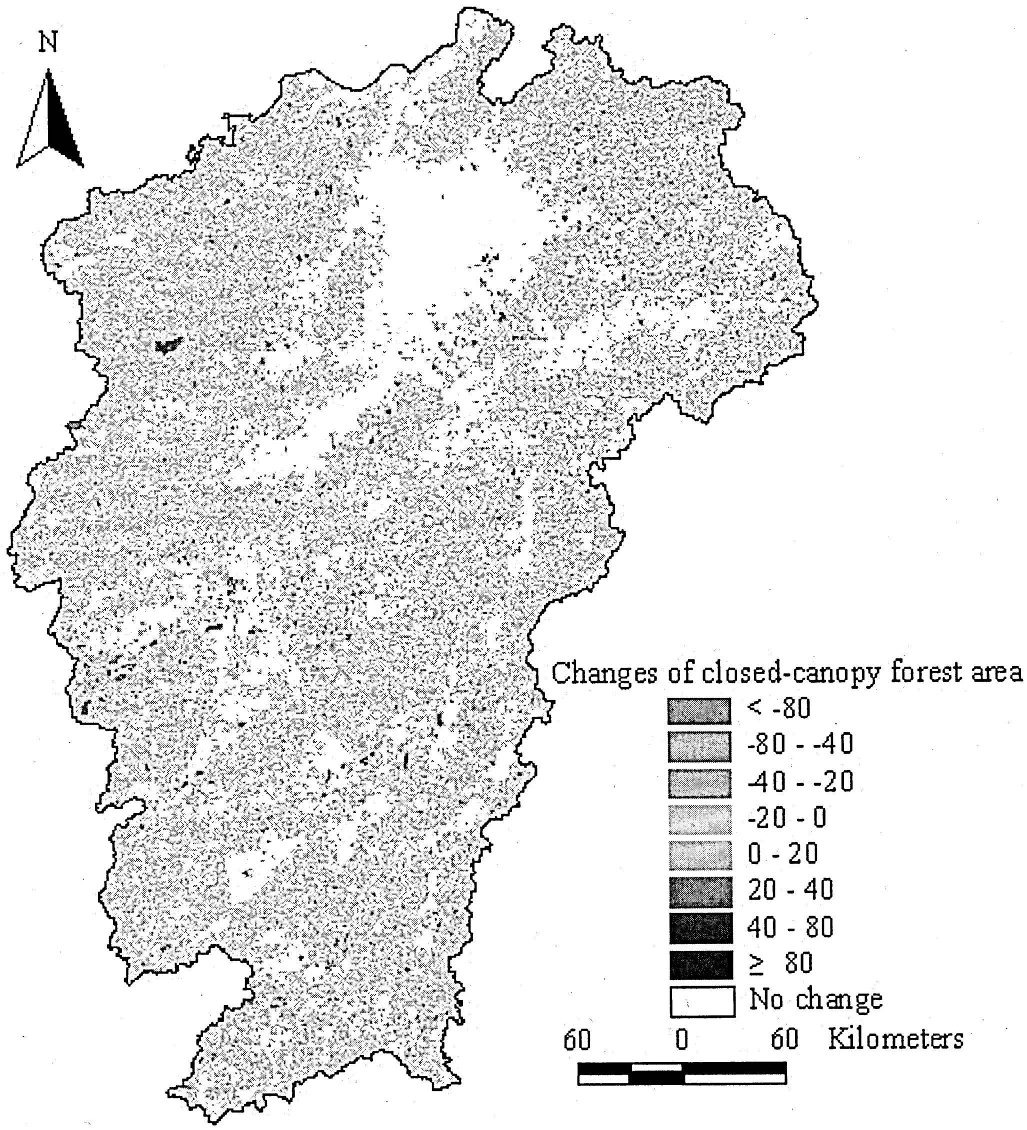
Data: Authors' data.

Figure 3. Boundaries of Watersheds in Jiangxi Province When Divided into 1474 Watersheds



Source: Authors' data.
Note: This map shows expressways, provincial highways, and tertiary roads. It does not show village roads for clarity.

Figure 4. Illustration of Road Network of Jiangxi Province



Source: Author's data

Note: White area indicates pixels with zero changes in forest cover.

Figure 5. Changes in Closed-canopy Forest in Jiangxi Province, 1995-2000

Appendix A. Interpretation of satellite images.

Interpreting forest area using satellite images is an analytical process which involves investigating the photographic images, detecting and determining of forest categories, and quantifying biometric indicators of forest stands (Deng et al. 2008). To interpret the photographic images, we first identify the contour (polygons) of the forest area. To do this, we first read the images, determine and draw the borders of the forest categories and primary units of inventory, and identify the exact locations of objects (Deng et al. 2008).

Using the satellite images, we identify and decode four kinds of polygons of forest cover for this study: close forest, shrub-covered forests, open-canopy forests and other forest. To do so, we conduct visual interpretation of three features of the satellite images: photometric, morphological and spectral. The photometric feature refer to the tone (black and white) and the color (spectrazonal and multispectral) of the images to identify the boundaries of forest cover. The morphological feature describes the structure and canopy layer of stands, the size of crowns and the gaps between them, the characteristics of unforested areas and landscaping features that reflect existing regularities in a location of forest objects such as the types of site conditions and dominant species connected to landscape structures. Lastly, the following spectral features are identified and used to identify the boundaries of four kinds of forest cover.

Closed-canopy forests: Patch or belt pattern; board-leaf forest with bright red color, conifer forest with dark red color, even and lighter tone; clear boundary with grassland or cropland; ambiguous boundary with shrub-covered forests, but distinguished by an even texture while shrub-covered forests are recognized by a rough texture; shelter-belt has a regular grid pattern, located in the cropland along the water or coastlines.

Shrub-covered forests: Light red color, with dispersed bright red spots for some cases because of the existence of scattered trees; rough texture. Along the northern aspect (shadow effect) the texture is referred to distinguish shrub-covered forests from grasslands: grasslands are identified by a smooth texture, while shrub-covered forests have a rough texture.

Open-canopy forests: Light red color with dispersed bright red spots. Different from closed-canopy forest by its uneven and dark tone; different from grassland by its rough texture whereas grasslands have light tone.

Other forests: Orchard with bright red color, scattered in the cropland or around residential areas. Regenerated land of other forests with cyan or grey color, mixed with shrub-covered forests or open-canopy forests.

Our experience suggests that desirable results on decoding the boundary of forest cover can be achieved if the operator and computer work in an interactive mode. That is, the operator provides stratification and contour decoding of the images identifying the information on forest cover while the delimitation of the boundary of four kinds of forest cover was performed automatically by the computer. The operator controls the analytic process and can interrupt it to change its direction or make corrections. Then, algorithms are used for geometric and photometric transformations of images, filtration and statistical processing, and identification and parameters estimation. A research team at the Chinese Academy of Sciences developed a technical framework of interactive image processing and used it to decode the information of forest cover.

The interpretation of TM images and forest cover information were validated against extensive field surveys (Liu et al. 2003). The research team conducted ground checks for more than 75,000 kilometers of transects across China, with more than 8,000 photos taken using cameras equipped with global position system (GPS). The average accuracy of interpretation for the four kinds of forest cover is around 95.2% for 1995 data and 96.1% for 2000.

Appendix B: Data sources and definitions

The data for measuring *rainfall* (measured in millimeters per year) and *temperature* (measured in accumulated degrees centigrade per year) are from the CAS data center but were initially collected and organized by the Meteorological Observation Bureau of China from more than 600 national climatic and meteorological data centers. For use in our study, we take the point data from the 15 climate stations in Jiangxi and interpolate them into surface data using an approach called the *thin plate smoothing spline* method (Kaimowitz and Angelsen 1998). The *elevation* and *terrain slope* variables, which measure the nature of the terrain of each county, are generated from China's digital elevation model data set that are part of the basic CAS database. Information on the properties of soil also is part of our set of geographic and climatic variables from the CAS data center. Originally collected by a special nationwide research and documentation project (the *Second Round of China's National Soil Survey*) organized by the State Council and run by a consortium of universities, research institutes and soils extension centers, we use the data to specify three variables: the nitrogen content of the soil (*nitrogen*—measured in percent); *available phosphorous* in the top soil (measured in ppm); and *soil pH value*. By using a conventional kriging algorithm (Hartkamp et al. 1999), we are able to interpolate the soil information into surface data to get more disaggregated information on the property of the soil over space for each pixel.

Two demographic and economic variables, *population* and the level of gross domestic product per capita (*GDP/capita*), are included in our modeling work. The demographic data for

1995 and 2000 are from the *Population Statistical Yearbook for China's Counties* (Kravchenko and Bullock 1999). Information on GDP for each county for 1995 and 2000 are from the *Socioeconomic Statistical Yearbook for China's Counties* (Ministry of Public Security of China various years). When there are missing data in the yearbook, the information is supplemented by each province's annual statistical yearbook for 1995 and 2000. In order to get pixel-specific measures of the demographic variables we use an approach called the Surface Modeling of Population Distribution framework (NBSC 2001) to interpolate the data across space (measured as persons/kilometer square). The level of GDP (GDP per capita per kilometer square) is also interpolated across space using commonly available GIS algorithms (Doll et al. 2006; Deng et al. 2008).

We also created several measures of distance (all of which are measured in kilometers). These variables are defined separately for each pixel in our sample. *Distance to the provincial capital* is measured as the distance (by the shortest road route) from each pixel to Nanchang, Jiangxi's provincial capital. We also generated a variable, *distance to the nearest urban core*, by measuring the distance by shortest road route from each pixel to the nearest county seat or other major urban center.

We also include a dummy variable that is equal to one if the pixel is in a county that contains a protected area and zero otherwise (*protected_area*). The information on whether or not a county contains a protected area or not is from a survey that we conducted of the Environmental Protection Bureaus of all of the counties in Jiangxi.

Appendix Table 1. Descriptive statistics of variables at the pixel level

Variable	Units	Obs	Mean	Std. Dev.
Dependent variables				
Total forest area:				
Total Forest Area 2000	ha	6666	56.20	35.40
Change in Total Forest Area (2000-1995)	ha	6666	-0.05	5.54
Forest area by forest type:				
Closed-canopy Forest Area 2000	ha	6666	40.64	37.01
Shrub-covered Forests Area 2000	ha	6666	2.83	6.30
Open-canopy Forests Area 2000	ha	6666	12.30	20.83
Other Forest Area 2000	ha	6666	0.46	3.64
Change in Closed-canopy Forest Area (2000-1995)	ha	6666	-0.36	4.63
Change in Shrub-covered Forests Area (2000-1995)	ha	6666	0.05	1.72
Change in Open-canopy Forests Area (2000-1995)	ha	6666	0.12	5.20
Change in Other Forest Area (2000-1995)	ha	6666	0.14	2.64
Geographic and climatic factors				
Elevation	meter	6666	251.70	230.00
Terrain slope	degree	6666	2.70	3.00
Nitrogen	%	6666	0.20	0.00
Available phosphorous	ppm	6666	0.80	2.70
Soil pH	–	6666	4.70	0.80
Temperature	degree centigrade	6666	16.90	1.30
Rainfall	mm	6666	1625.20	110.00
Demographic and economic factors				
Population	persons per km^2	6666	241.10	259.70
GDP	10000 Yuan	6666	46.10	187.00
Measures of distance				
Distance to provincial capitals	km	6666	134.00	70.70
Distance to the near urban core	km	6666	110.20	74.90
Other factors				
Total Forest Area in 1995	ha	6666	56.30	35.80
Protected area	–	6666	0.20	0.40

Source: Authors' data.