Working Paper

Trees on Farm:

Analysis of Global Extent and Geographical Patterns of Agroforestry

Robert J. Zomer, Antonio Trabucco, Richard Coe and Frank Place

World Agroforestry Centre
TRANSFORMING LIVES AND LANDSCAPES

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Abstract

Agroforestry, the inclusion of woody perennials within farming systems, has been both a traditional landuse approach developed by subsistence farmers throughout the tropics, and a livelihood option promoted by landuse managers and international development efforts. Agroforestry systems range from subsistence livestock and pastoral systems to home gardens, alley intercropping, and biomass plantations with a wide diversity of biophysical conditions and socio-ecological characteristics. The extent of its practice has never been quantified leading to widely varied estimates about its importance. This paper is the first attempt to quantify the extent of agroforestry at the global level.

A geospatial analysis of remote sensing derived global datasets investigated the correspondence and relationship of tree cover, population density and climatic conditions within agricultural land at 1 km resolution. Among the key results are that agroforestry is a significant feature of agriculture in all regions, that its extent varies significantly across different regions (e.g. more significant in Central America and less in East Asia), that tree cover is strongly positively related to humidity, and that there are mixed relationships between tree cover and population density depending on the region. This first analysis suggests that patterns of tree cover are influenced by a range of factors we were not able to examine at the global scale and a number of follow up analyses are recommended.

Keywords: land use / spatial modeling / trees / agroforestry

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1. Introduction

Agroforestry, the inclusion of trees within farming systems, has been a traditional landuse developed by subsistence farmers throughout most of the world. In the last 40 years it has also become a subject for systematic study and improvement, and a livelihood option promoted by landuse managers and international development efforts. It has come to the attention of global analysts and policy makers, for example UNFCCC (2008) and MEA (Hassan et al 2005), and has been recognized in regional and national development plans (NEPAD 2003) and is an obvious component of many farming systems.

Agroforestry systems range from subsistence livestock silvo-pastoral systems to home gardens, on-farm timber production, tree crops of all types integrated with other crops and biomass plantations within a wide diversity of biophysical conditions and socio-ecological characteristics. The term has come to include the role of trees in landscape level interactions, such as nutrient flows from forest to farm, or community reliance on fuel, timber, or biomass available within the agricultural landscape.

Despite its ubiquity and apparent importance, is hard to find data on the actual extent of agroforestry around the world. The lack of data and more fundamental misconceptions of what agroforestry is, has led to an assumption that it is globally of little importance, even by people who should know better: “During preparation of the IAAST report, USA referees said that everyone knew there were only 50,000 ha of agroforestry in the world and that they were a failure” (Roger Leakey, personal communication). Such misunderstandings lead to suboptimal policy decisions, and can best be reversed by providing objective, data-based measures of the extent of agroforestry.

Understanding the extent and distribution of trees on agricultural land, at the landscape level, including the numbers and characteristics of farmers and farming communities within those landscapes, can help to assess the importance and role of agroforestry both to the livelihood of farming communities as well as to overall global

agricultural production. Further, understanding the geographic, ecological, and demographic distribution of agroforestry related land uses can also highlight those areas where increased tree densities could make a greater contribution to livelihoods or landscapes.

We set out with the aim of answering the basic question:

1. How much agroforestry land is there and where is it?

Once we had a viable method, described below, we realized it would provide much richer data that could answer further questions:

2. How many people are associated with agroforestry ?
3. What patterns can be seen in the density of people in agroforestry land? What patterns of tree cover can be seen across different densities of people?
4. How are the patterns of tree cover, population density, and their interactions affected by climate and basic ecology?

2. Measuring agroforestry extent

For many years the term 'agroforestry' was applied to particular arrangements of trees in crop and animal production systems. This view was summarised as follows:

> 'Agroforestry is a collective name for land-use systems and technologies, where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land management unit as agricultural crops and/or animals, either in some form of spatial arrangement or temporal sequence. In agroforestry systems there are both ecological and economical interactions between the different components'. (ICRAF, 1993).

Based on this view, several authors have produced estimates of the extent of particular systems. IAASTD (2008) listed those in Table 1. Nair and Nair (2003) estimated the extent of alleycropping, silvopasture, windbreaks, and riparian buffers in the USA as 235.2 M ha. Kumar (2006) estimated the area of homegardens in South- and

southeast Asian homegardens as 8.0 M ha, and Reisner et al (2007) estimated European silvoarable systems to cover 65.2 M ha.

Table 1. Examples of land areas under agroforestry (IAASTD 2008)

Country	**Area** (hectares)	**Specific information**	**Reference**
Indonesia	2.8 million	Jungle rubber agroforests‡	Wibawa et al., 2006
Indonesia	3.5 million	All multistrata agroforests†	van Noordwijk (pers. com.)[1]
India	7.4 million	National estimate	Zomer et al., 2007.
Niger	5 to 6 million	Recently planted	Gray Tappan (pers. com.)[2]
Mali	5.1 million	90% of agricultural land	Cissé, M.I. 1995; Boffa, 1999.
C. America*	9.2 million	Silvopastural systems	Beer et al., 2000
C. America*	0.77 million	Coffee agroforests	Beer et al., 2000
Spain/Portugal	6 million	Dehasa agroforestry	Gaspar et al., 2007
Worldwide	7.8 million♠	Cocoa agroforests	van Grinsven[3] (pers. com.)

‡ = 80% of Indonesian rubber = approximately 24% of world production
† = Including jungle rubber (above), durian, benzoin, cinnamon, dammar, and others.
* = Costa Rica, Nicaragua, Honduras, El Salvador and Guatemala.
♠ = 5.9 million ha in West and Central Africa, 1.2 million ha in Asia and 0.7 million ha in South and Central America
[1] = Meine van Noordwijk, World Agroforestry Centre, Bogor, Indonesia.
[2] = Gray Tappan, Science Applications International Corp. (SAIC), USGS Center for Earth Resources Observation and Science, Sioux Falls, SD 57198, USA.
[3] = Peter van Grinsven, Masterfoods BV, Veghel, The Netherlands.

The problem with trying to produce a more encompassing estimate of the extent of agroforestry systems was summarized by Nair et al (2009):

> A major difficulty in estimating the area under agroforestry is lack of proper procedures for delineating the area influenced by trees in a mixed stand of trees and crops. In simultaneous systems, the entire area occupied by multistrata systems such as homegardens and shaded perennial systems and intensive tree-intercropping situations can be listed as agroforestry. However, most of the agroforestry systems are rather extensive, where the components, especially trees, are not planted at regular spacing or density; for example, the

> parkland system and extensive silvopastures. The problem is more difficult in the case of practices such as windbreaks and boundary planting where although the trees are planted at wide distances between rows (windbreaks) or around agricultural or pastoral parcels (boundary planting), because the influence of trees extends over a larger than easily perceivable extent of areas…. The problem has a different dimension of difficulty when it comes to sequential tropical systems such as improved fallows and shifting cultivation. In such situations, the beneficial effect of trees and other woody vegetation (in the fallow phase) on the crops that follow them (in the cropping phase) is believed to last for a variable length of time (years).

Nair et al (2009) go on to make an estimate of 823 M ha globally under agroforestry and silvo-pastoral systems. Of these, 307 M ha are agroforestry. However their estimate comes from taking the FAO estimate of agriculture land multiplied by an estimate of 20% covered by agroforestry. The value of 20% is not based on any objectively measured data. Another estimate of global agroforestry extent which is widely quoted is Dixon (1995), who suggests 585–1215 M ha of agrosilvopastoral and agroforestry systems in Africa, Asia, and the Americas. However, this is an estimate of the area they judge technically suitable for these systems, not occupied by them.

The current view of agroforestry is not as a collection of technologies, but of trees included in agricultural landscapes. For example, Schroth and Sinclair (2003) note that agroforestry is increasingly recognized for its ecological and economic interactions at the landscape scale.

This changes the measurement problem considerably, for we have global databases which can be combined and interpreted to generate relevant information. Three data sources are used:

1. Global land use. Spatial data layers exist which classify any pixel as agricultural or some other land use.
2. Global tree cover. Remotely sensed data has been interpreted to give estimates of % tree cover in a pixel.

3. Global population. Spatially disaggregated population layers are available which give an estimate of population in any pixel and can be used to measure the extent of agroforestry in terms of population.

Details of the data sources are give in the Methods section and Appendix 1. 'Landscape scale' is not precisely defined. However, each of the above data sources is available at 1km x 1km resolution. This corresponds roughly to a common notion of 'landscape scale'. Thus we look at the 1 km x 1km pixels that are classified as 'agriculture' and find the percent tree cover in each. This varies from 0%, clearly not agroforestry, up to close to 100%, though most pixels with high tree cover have not been classified as agricultural. It is not necessary to choose a cut off value for tree cover below which we do not consider the landscape as being an agroforestry landscape. Most results can be presented as a continuum of patterns from low to high tree cover, a continuum which represents reality better than any arbitrary cut off.

We can then assume the population estimated as living in the 1 km x 1 km pixel is in some sense 'connected with' that agricultural landscape and its trees. While we do not know the extent to which those people depend on the agroforestry landscape, it is reasonable to assume that at the 1km scale they are influenced by and influence that landscape.

The limitations of this approach are numerous, with the major ones being outlined in the Discussion. However, it appears to be a step forward compared with other estimates to date, particularly when it is understood as a global assessment. We do not expect the results of every pixel to closely match an observation on the ground, but expect the broad patterns to be revealing

3. Methods

3.1. Geodatasets

The global geospatial analysis combined tree cover, with landuse classification, population density, a delineation of rural extent and an aridity index. The spatial modeling procedure was developed and implemented in ArcGIS (ESRI Inc.) using ArcAML programming language. All datasets used for the analyses have been re-projected into two coordinate systems, sinusoidal and geographic. The sinusoidal projection has been used to calculate zonal statistics and carry out areal computations as it represents area extent accurately across latitudes (i.e. equal-area projection). The cell size for analyses in sinusoidal projection is 1 km. The dataset in geographic coordinates is used for map presentation purposes.

The geodatasets used in this analysis are listed below, and described more fully and mapped in Appendix 1:

- VMAP 0 - Country Boundaries (NIMA 1997)
- MOD44B MODIS Vegetation Continuous Field Coll. 3– Tree Cover (Hansen et al. 2003)
- Global Land Cover 2000 database (GLC, 2000)
- Global Rural-Urban Mapping Population (GRUMP v. 1) (CIESIN 2004)
- Aridity Index (Zomer et al. 2007)

Since the land extent of the above global geodatasets were delineated from different landform masks, complicating cross-thematic correlations over coastal areas, we derived a final harmonized set of grids defining valid thematic values from any dataset within a common landform mask that we used as landform template. All the geodatasets were systematically clipped in GRID with the SELECTMASK command using the landform reference grid as mask; subsequently pixels for any dataset with NODATA values over land, as defined by the landform reference grid, were filled with the NIBBLE command to replace NODATA values with the values of the nearest neighbor’s pixel.

3.1.1. Land Cover Categories

Three agricultural land use types from the Global Land Cover Class scheme used for the Global Land Cover 2000 database were selected as relevant for the specific objectives of this work: *Cultivated and managed areas* (Agriculture – intensive), *Cropland / Other natural vegetation* (non-trees) (Mosaic agriculture / degraded vegetation) and *Cropland / Tree Cover Mosaic* (agriculture / degraded forest)

Although at first the "Cropland / Tree Cover Mosaic" type seems to identify agroforestry systems, we recognize that the mix of forest and agriculture does not occur at discrete intervals, but is a gradient where the two components of the landscape level agroforestry mix within the landscape. The mix of tree cover over agriculture land is depicted along a continuous gradient by the MODIS VCF tree cover dataset, within the relevant GLC2000 land cover type. Tree cover shows the percentage of the 1 km^2 grid cell occupied by trees, therefore at this resolution of 1000 meters, tree cover percentage can be expressed as hectares (ha) of tree cover per km^2. At 100% tree cover the whole grid cell is occupied, i.e. 100 ha / km^2.

3.1.2. Aridity Index

A global model of aridity (Zomer et al. 2006, 2007). was used to stratify ecological conditions based upon climatic and agroecological charactistics. Aridity is expressed as a function of precipitation, temperature and potential evapotranspiration (*PET*). Based upon an attempt to classify climatic zones by moisture regime, the Aridity Index (*AI*) quantifies precipitation deficit over atmospheric water demand as:

$$\text{Aridity Index } (AI) = MAP / MAE \qquad [1]$$

where:

MAP = mean annual precipitation

MAE = mean annual evapotranspiration.

3.2. Processing and presenting results

All the geodatasets have been masked to exclude areas which are either non agricultural land use types or urban areas. Successively, the agricultural land extent has been stratified for each tree canopy cover value (0 to 100), 20 population density classes, 20 aridity index classes and 13 subcontinents (North America, Central America, South America, Europe, North Africa, West and Central Africa, Eastern and Southern Africa, Western Asia, Northern and Central Asia, South Asia, East Asia, SouthEast Asia, Australian Area). Within each stratum, or within specific aggregation of strata, zonal statistic values (mean, sum, total area, percentiles, areal distribution, etc) were summarized to describe those factors of interest for this study: tree canopy cover (percentage), total population and population density. Only results from developing countries are highlighted in this report, although the analysis is complete for the total global extent of the datasets.

In the first stage, cumulative agricultural area and cumulative population is presented at decreasing tree canopy cover to infer at global and subcontinent scales the total population and area engaged above any and specific tree canopy cover values. In a second stage, the same cumulative distribution of population and total agricultural land in function of tree canopy cover has been disaggregated for five different aridity classes (AI < 0.45 or arid, 0.45 < AI < 0.6 or semi-arid, 0.6 < AI < 0.8 or sub-humid, 0.8 < AI < 1.0 or humid, AI > 1.0 or very humid), to show how climate regimes might differentiate specific patterns of interdependence between tree canopy cover with population pressure (total population and average population density) and land surface available for different geographical areas.

More specific analyses describe two typologies of bivariate distributions, shown graphically as surfaces. In the first typology the total surface in km^2 is shown within matrices representing variations across 20 by 20 classes of tree canopy cover and population density. These surfaces reflect specifically conditions for any of the 5 aridity index ranges mentioned above, at global and subcontinent scales. Since some of the strata in these surfaces can easily be under-represented, because of low number of observations, we present surfaces, which have been smoothed by splining functions on a 5x5 cells neighborhood around any stratum to derive more generic patterns.

In the second typology average tree canopy cover is inferred and smoothed within any combination of the 20 by 20 classes of population density and aridity index. Beside average tree canopy cover percentage, also tree canopy cover distribution was extracted within each stratum to compare average to other percentiles values of tree canopy cover, to measure the lagging of tree canopy cover for similar conditions of climate and population density.

An estimate of ‘potential tree cover’ is found by assuming that for a given region, aridity and population density, the distribution of tree cover in agricultural land represents feasible or viable systems. While the maximum tree cover that occurs in those conditions could be taken as a potential, this is rather unrealistic, as the maximum probably occurs in a very small area and represents some unusual set of circumstances. Therefore we take the 80% point of the distribution as presenting potential. That is, the potential tree cover of a region, conditional on aridity and population density, is the tree cover that only 20% of the agricultural area exceeds. Once a potential cover is found, differences from potential are calculated and mapped. Of course, using this definition, 20% of the area has ‘above potential’ tree cover.

4. Results and discussion

The characteristics, assumptions and limitations of the data layers and methods condition all the results. These are discussed in Section 5. The results should not be used or quoted without understanding these limitations.

4.1. Tree canopy cover in agricultural land

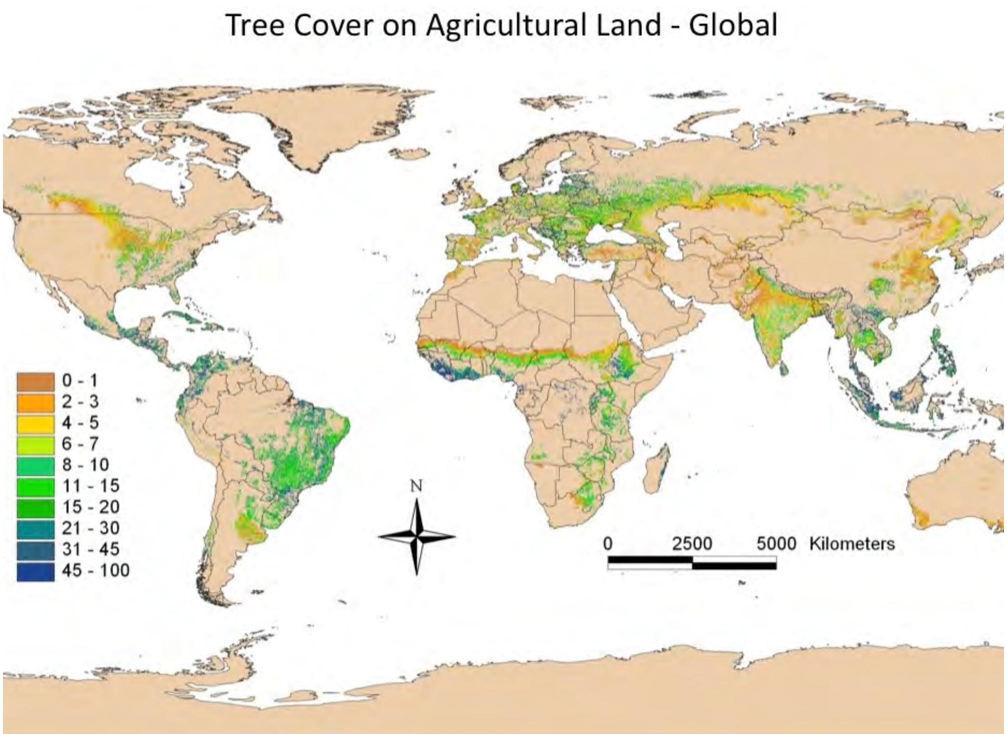


Figure 1. Tree cover on agricultural land.

Tree canopy cover on agricultural land is mapped out at the global level in Figure 1. Tree cover varies from 0% to 100%. However, about 7% of land classified as agricultural has more than 50% tree cover. Some lands with tree crops are undoubtedly classed as forest. The global variation broadly follows climate zones with high tree cover (> 45%) found in the more humid regions such as southeast Asia, Central America, eastern South America and coastal west Africa. Moderate levels of between 10% to 30% cover describe the majority of agricultural areas in south Asia, sub-humid Africa, central and western Europe, Amazonian South America, and

midwestern North America. At the other extreme are agricultural areas with relatively low (<10%) tree cover such as eastern China, northwestern India and the Punjab, west Asia, the southern border of the Sahara, the northern prairies of North America and the southwest of Australia. Not surprisingly, in general the tree canopy cover follows a pattern influenced by precipitation regimes, shown as Aridity Index in Figure 2. Specific divergences of tree canopy cover from climate influence are stronger where population density (Figure 3) or human activities are higher (e.g. China, India). These patterns are explored below.

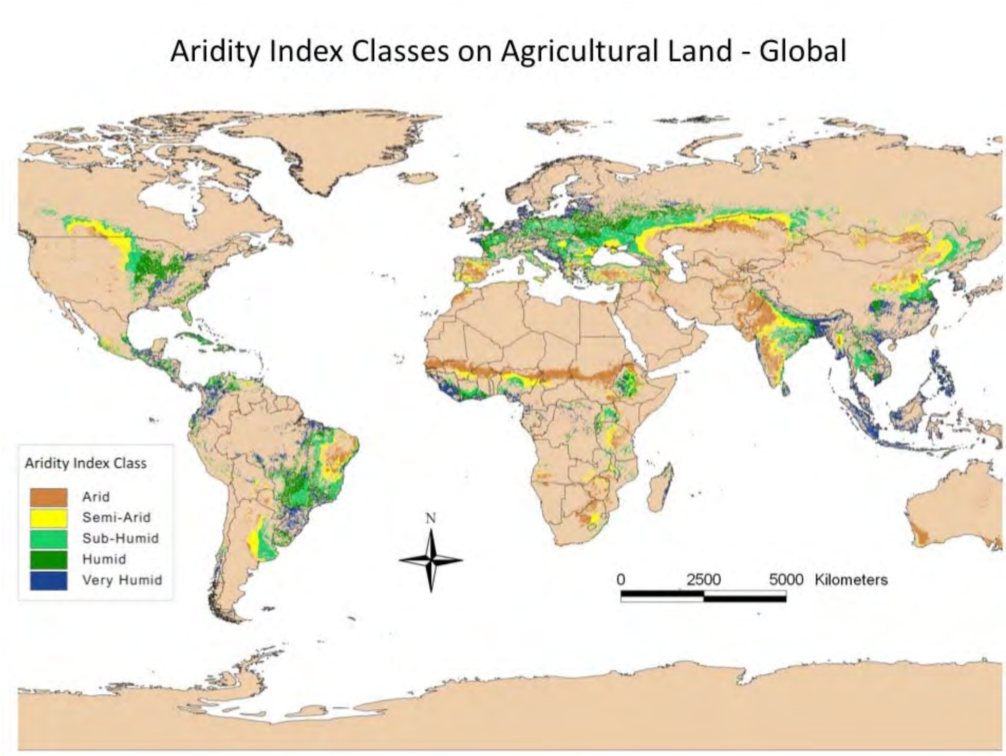


Figure 2. Aridity index classes on agricultural land.

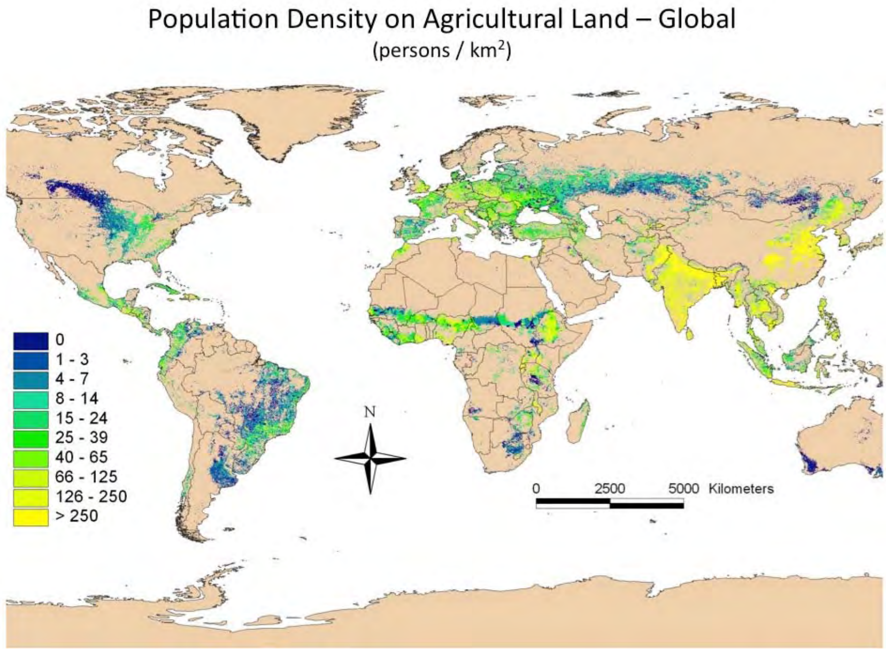


Figure 3. Population on agricultural land (persons/km^2).

4.2. Estimates of the Extent of Agroforestry

4.2.1. By area

The total global area classified as agricultural in our database is 22,183,204 km^2. Figure 4 shows the global cumulative agricultural area as tree canopy cover increases. Thus 10,120,000 km^2 (46% of agriculture land) have more than 10% tree cover, 5,960,000 km^2 (27% of agricultural land) have more than 20% tree cover and only 1,670,000 km^2 (7.5%) have more than 50% tree cover. It is not helpful to label some minimum tree cover percentage as representing 'agroforestry', as the reality is a continuum of tree cover fractions from zero to high. The way trees are integrated into the farming landscape and used in agriculture vary across the world and there are prominent and economically important agroforestry systems which nonetheless have low tree canopy cover on landscapes. Examples are the parkland systems in the Sahel and the poplar-wheat/barley agroforestry systems of northern India.

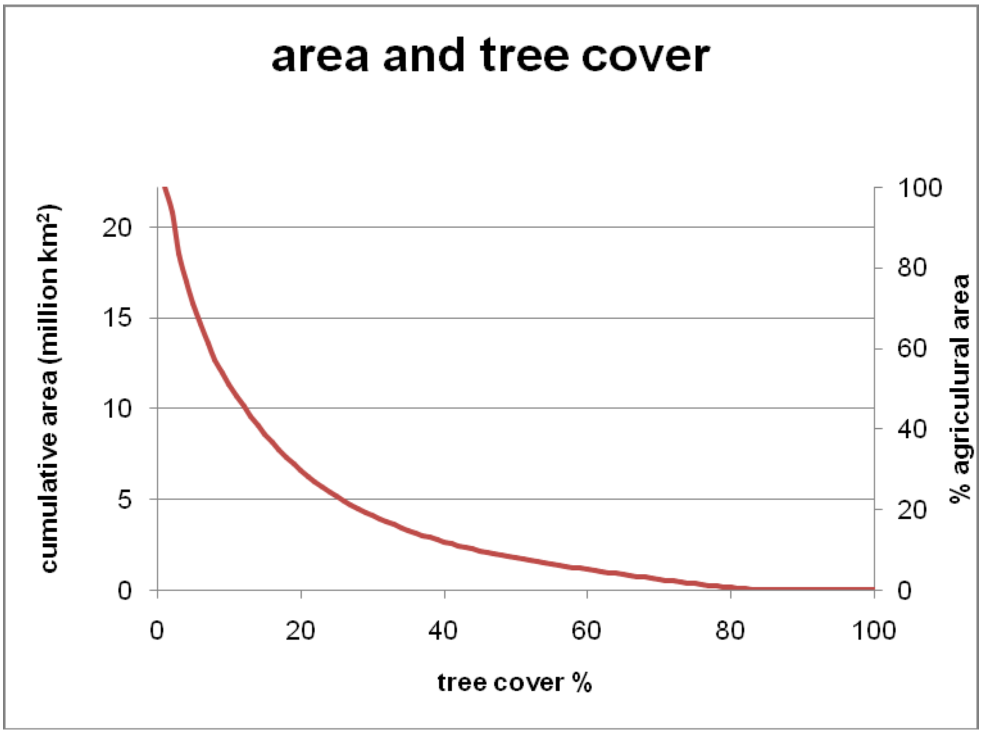
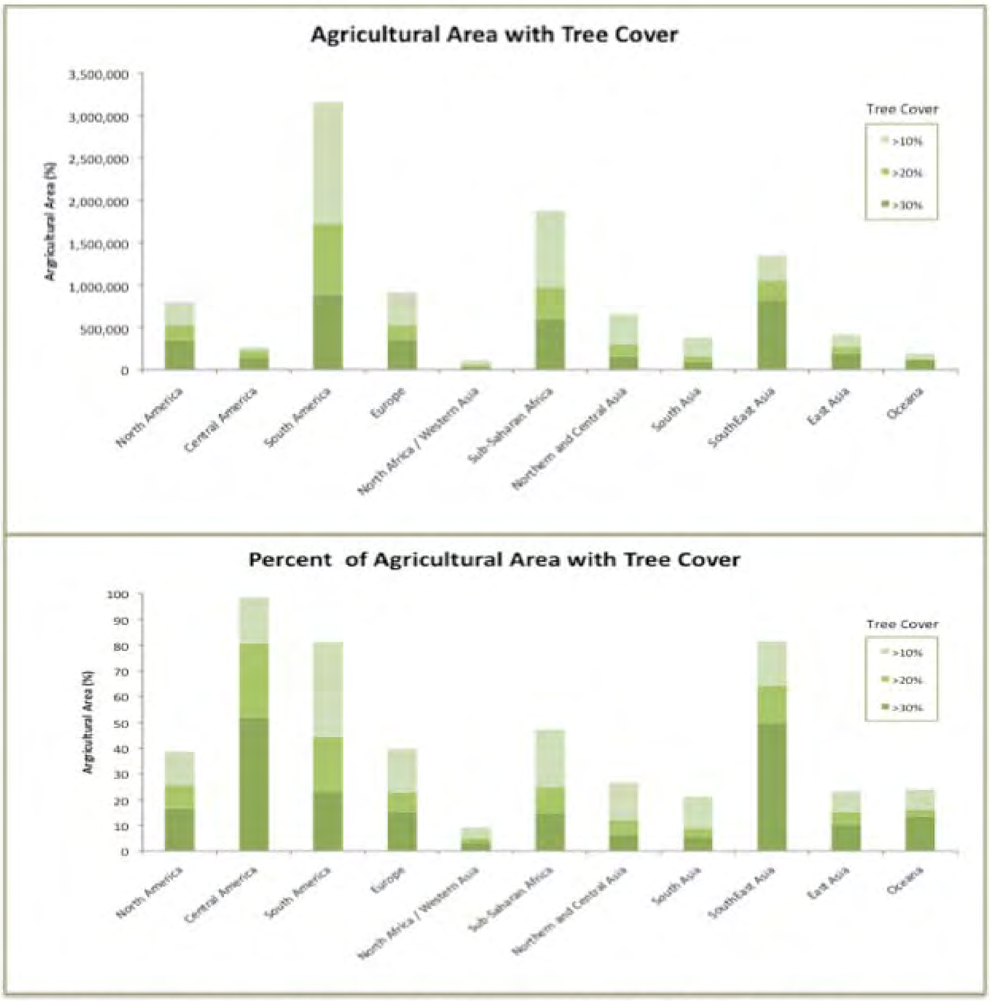


Figure 4. Global cumulative agricultural area by tree canopy cover.

However, for the purpose of presenting numerical tables we show results for 10, 20 and 30% tree cover. Figure 5 shows in graphical and tabular format the agricultural areas under tree cover by each major region. The numbers presented are cumulative such that , for example, the area under tree cover of greater than 20% is inclusive of the area shown under tree cover of greater than 30%. The percentage of land under each level of tree cover is also given, calculated using the total agricultural land area in the last column.



Agricultural Area with Tree Cover Greater than 10 to 30 Percent (km2 and % of all agricultural area)

Tree Cover	>10%		>20%		>30%		Agriculture (>0%)
	km^2	%	km^2	%	km^2	%	km^2
Region							
North America	800,632	*39*	528,745	*26*	346,194	*17*	2,073,352
Central America	265,057	*98*	217,731	*81*	140,165	*52*	269,503
South America	3,159,991	*81*	1,726,431	*44*	887,714	*23*	3,888,963
Europe	914,122	*40*	529,438	*23*	354,654	*15*	2,301,062
North Africa / Western Asia	105,298	*9*	58,598	*5*	38,956	*3*	1,138,842
Sub-Saharan Africa	1,875,543	*47*	974,333	*25*	595,834	*15*	3,964,972
Northern and Central Asia	657,008	*27*	299,563	*12*	160,946	*7*	2,473,698
South Asia	389,056	*21*	161,463	*9*	97,160	*5*	1,828,926
SouthEast Asia	1,346,888	*82*	1,059,471	*64*	826,577	*50*	1,652,548
East Asia	417,273	*23*	273,466	*15*	188,112	*10*	1,800,443
Oceana	190,466	*24*	128,487	*16*	108,202	*14*	790,875
Global Total	10,121,334	*46*	5,957,726	*27*	3,744,514	*17*	22,183,184

Figure 5. Agricultural area with tree cover at different thresholds (10%, 20%, 30%) by major regions.

Globally, a cautious estimate of agricultural land that involves agroforestry is 17% (>30% tree cover), with a more realistic one being 46% (>10% tree cover). Using our definition of agricultural land (covering 22.2 million square kilometers) and a 10% tree cover threshold for agroforestry, there are slightly over 10 million km^2 of

agricultural land which is also under agroforestry. Large areas of agroforestry are found in South America (3.2 million km^2), in sub-Saharan Africa (1.9 million km^2), and southeast Asia (1.3 million km^2). Europe and North America also have significant absolute areas of agroforestry, despite having large commercial agricultural sectors.

Trees are an integral part of the agricultural landscape in *all* regions except North Africa/West Asia. Virtually all of Central America agriculture has > 10% tree cover, as does 82% of southeast Asian agriculture and 81% of South American agriculture. Significant proportions of land under agroforestry are found in sub-Saharan Africa, Europe, North America, each above 39% of area with all the remaining regions apart from North and West Africa registering proportions of between .21 and .27 of agroforestry.

The percentage of agricultural land with substantial tree cover (>30%), is remarkably high in some regions – over 50% in Central America and southeast Asia. In these areas, which have substantial cover of tree crops and ‘agroforests’ (probably often omitted from our agricultural land analysis), the wider agricultural landscapes are also well stocked with trees. In all regions, however, the contribution of high tree cover agroforestry (>30%) to total agroforestry (>10%) is significant, the lowest being in south Asia where the proportion is .25. Nonetheless, the prominence of sparser tree cover (between 10 and 20 percent tree cover) in relation to tree cover greater than 20 percent is high in some regions such as South America, sub-Saharan Africa, northern and central Asia, south Asia, and Europe.

4.2.2. By population

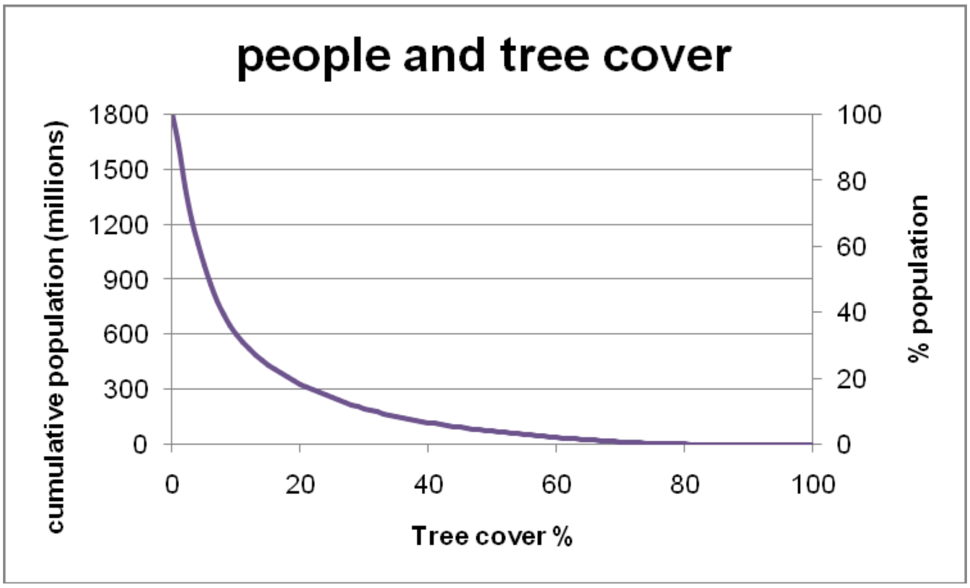
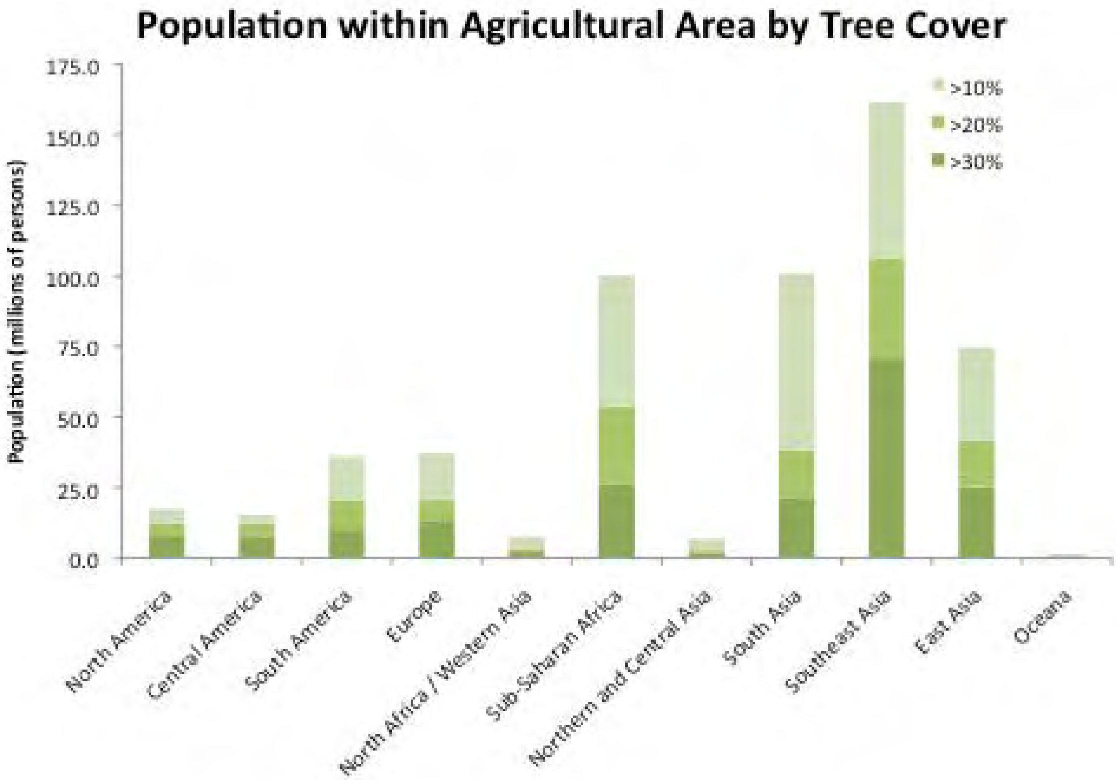


Figure 6. Global cumulative population in agricultural areas by tree canopy cover.

The analysis of area under agroforestry in 4.2.1. is repeated in this section, but using population rather than area as the basis for assessing the extent of agroforestry. Figure 6 shows the overall global distribution of population in agricultural lands by tree cover. Our database has 1.8 billion people living in agricultural lands. Of these, 558 million (31%) live in landscapes with greater than 10% tree cover. This drops to 187 million (10%) on land with greater than 30% tree cover and 71 million (4%) on land with greater than 50% tree cover. Figure 7 shows that there are at least 100 million people living in landscapes with more than 10% tree cover in each of sub-Saharan Africa, South Asia and South East Asia.

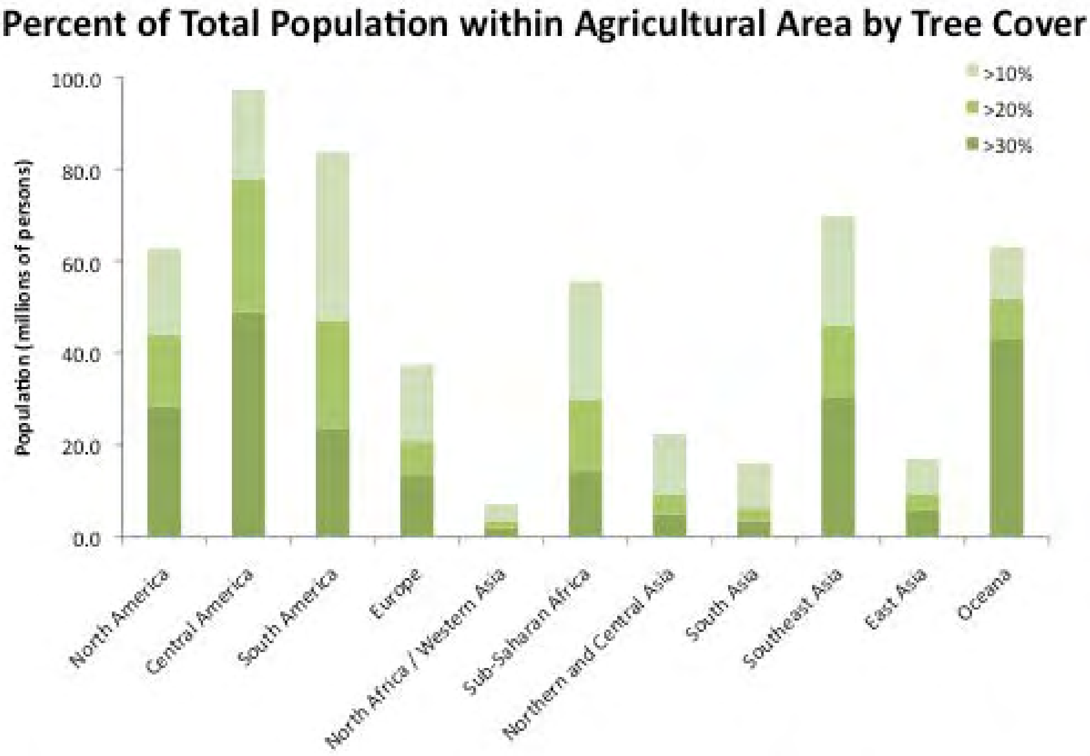
(a)



Population within Agricultural Area by Tree Cover

Tree Cover	>10%	>20%	>30%	Total Agriculture (>0%)
		millions of persons		
Region				
North America	17.4	12.2	7.8	27.66
Central America	15.2	12.1	7.6	15.59
South America	36.1	20.3	10.2	43.07
Europe	37.2	20.7	13.4	99.47
North Africa / Western Asia	7.5	3.5	2.1	106.24
Sub-Saharan Africa	100.2	54.1	26.0	180.37
Northern and Central Asia	6.7	2.8	1.5	30.05
South Asia	100.8	38.5	21.6	628.43
Southeast Asia	161.6	106.3	70.8	231.48
East Asia	74.5	41.4	25.2	439.89
Oceana	1.0	0.8	0.7	1.60
Global Total	558.2	312.7	186.9	1,803.85

(b)



Percent of Total Population within Agricultural Area by Tree Cover

Tree Cover	>10%	>20%	>30%
		(%)	
Region			
North America	62.8	44.0	28.3
Central America	97.4	77.8	49.1
South America	83.7	47.2	23.7
Europe	37.4	20.8	13.5
North Africa / Western Asia	7.1	3.2	2.0
Sub-Saharan Africa	55.5	30.0	14.4
Northern and Central Asia	22.4	9.4	4.9
South Asia	16.0	6.1	3.4
Southeast Asia	69.8	45.9	30.6
East Asia	16.9	9.4	5.7
Oceana	63.1	51.8	43.3
Global Total	30.9	17.3	10.4

Figure 7. Population in agricultural areas with tree cover at different thresholds (10%, 20%, 30%) by major regions. (a) Absolute population (b) Relative population.

The results are different from those based on area because of the variation in population density across the different regions. In comparison to the percent area under agroforestry, those for population are lower (e.g. 46% vs 30%). The reason for this is that agricultural populations are largest in south Asia and east Asia (together representing 60% of the global agricultural population) and both have significant agricultural areas characterized by both very high population densities and few trees;

irrigated rice systems are the most obvious example of this. A similar explanation can be made in the case of southeast Asia, which actually has the largest discrepancy between the percent of area under more than 10% tree cover (82%) and the percent of population living in areas with more than 10% tree cover (70%).

In terms of patterns observed across regions, the proportion of the agricultural population in agroforestry areas (where tree canopy cover > 10%) is highest in Central America and South America – with over 80%, followed by southeast Asia, Oceana, and North America, -- each over 60%. But there are also significant proportions of rural populations living in agroforestry landscapes in sub-Saharan Africa and Europe.

Thus, the extent of agroforestry, as measured either by area or population is very significant in absolute and relative (compared to overall extent in agriculture) terms. Further, this is not due to dominance by certain regions but rather because it is practiced commonly across many regions.

4.3. Agroforestry and aridity

Tree cover can be expected to be strongly dependent on climate, here characterized by the aridity index (Figure 2). Globally, agricultural areas in each aridity class are roughly equal, as class boundaries were selected to make this the case. However, there is wide variation across regions, with arid and semi arid areas becoming disproportional in north Africa/west Asia, sub-Saharan Africa, northern and central Asia, and South Asia. On the other hand, humid areas predominate landscapes in Central America, southeast Asia, and South America. The average tree cover within agricultural land can be calculated as a function of aridity (Figure 8) for different geographical areas, by normalizing the population distribution. These show similar trends for each region, but with curves shifted vertically (i.e. indicating different tree cover for given aridity class), with Central America being highest and East Asia lowest, with a difference between the two of about 20% tree cover for any given aridity class.

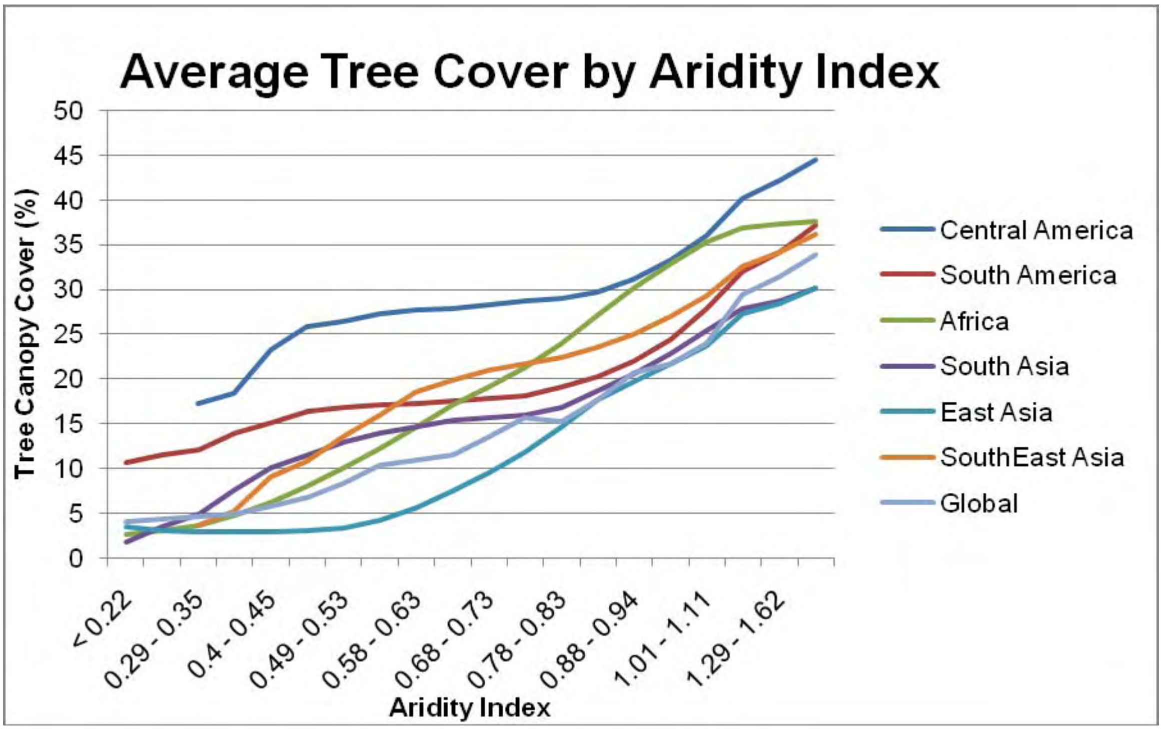
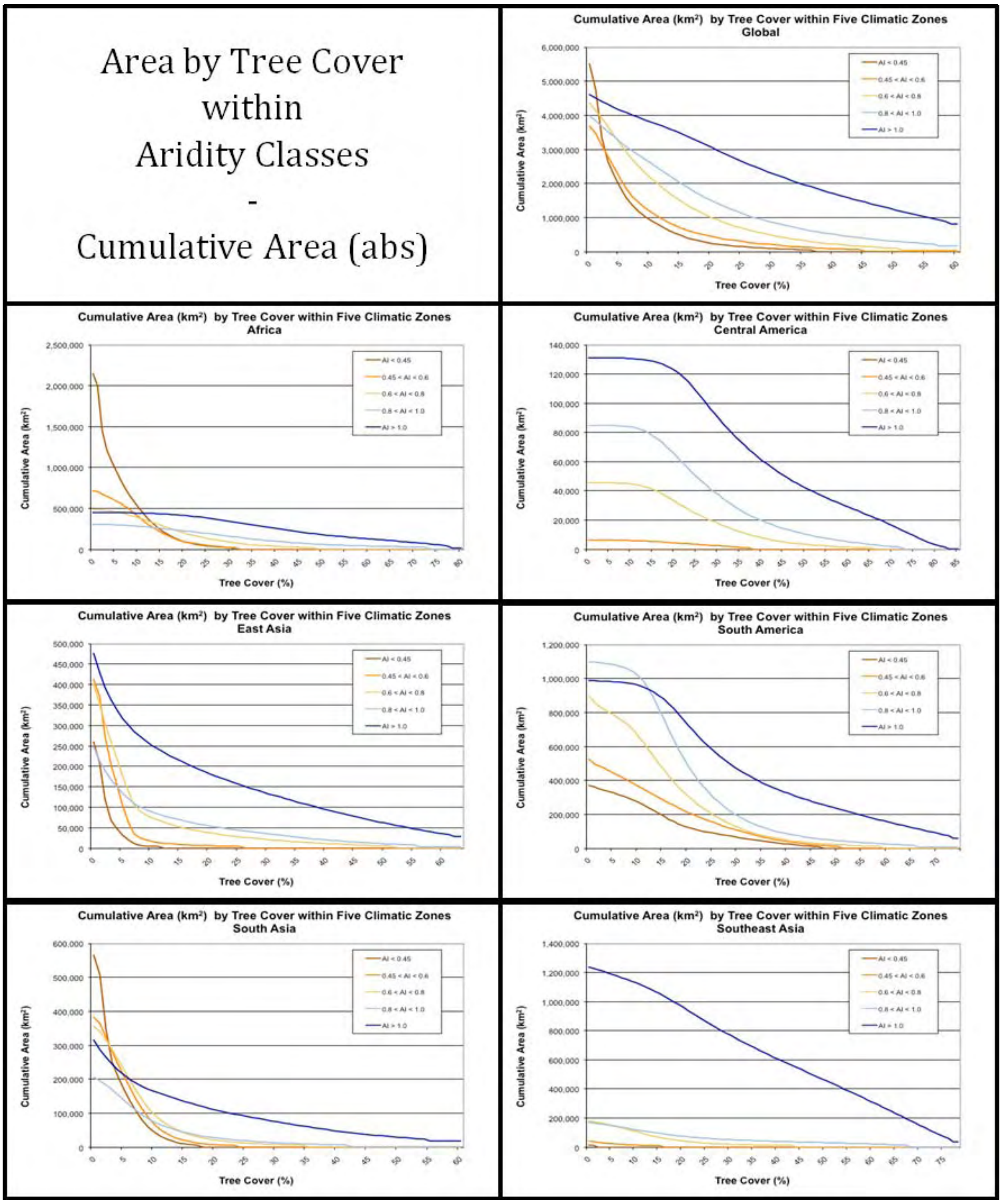


Figure 8. Average tree cover density by aridity for each region.

Figure 9a shows distributions of cumulative areas at different tree canopy cover levels for different climate conditions rather than just means. Unlike figure 8, figure 9 is affected by the actual population density levels encountered in each climate zone. Whichever tree cover threshold is used, the global area of agroforestry is highest in wetter zones and least in the drier zones. Since the total area is a reflection of the global distribution of agricultural land, we standardize this to look at the relative proportion of tree cover within each aridity class (Figure 9b). Now the global pattern is really remarkably 'regular'. In dry areas there is very little (5%) agricultural land with over 20% tree cover. This increases steadily to nearly 70% in humid areas. More 'sparse' agroforestry andscapes, with 10% tree cover, are clearly viable in all climate zones suitable for agriculture, as even in the driest agricultural areas at least 20% of agricultural land has this level of tree cover.

(a)


Area by Tree Cover within Aridity Classes - Cumulative Area (abs)
Cumulative Area (km²) by Tree Cover within Five Climatic Zones Global
Cumulative Area (km²) by Tree Cover within Five Climatic Zones Africa
Cumulative Area (km²) by Tree Cover within Five Climatic Zones Central America
Cumulative Area (km²) by Tree Cover within Five Climatic Zones East Asia
Cumulative Area (km²) by Tree Cover within Five Climatic Zones South America
Cumulative Area (km²) by Tree Cover within Five Climatic Zones South Asia
Cumulative Area (km²) by Tree Cover within Five Climatic Zones Southeast Asia
AI < 0.45
0.45 < AI < 0.6
0.6 < AI < 0.8
0.8 < AI < 1.0
AI > 1.0
Cumulative Area (km²)
Tree Cover (%)

(b)

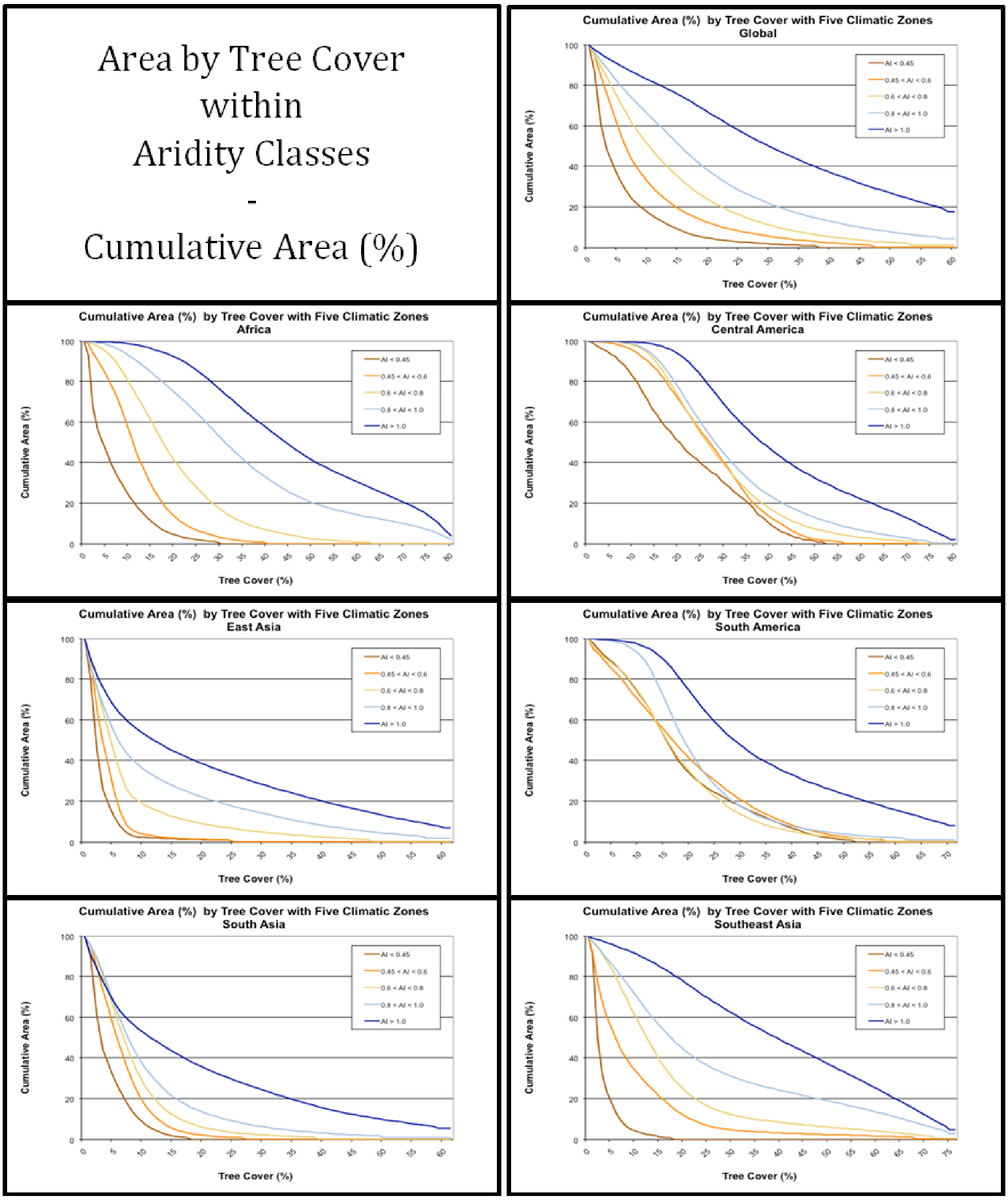


Figure 9. Cumulative agricultural area for increasing levels of tree cover by region and aridity class (a) absolute areas (b) percent.

However, climate (or aridity) is not the only determinant of the pattern of trees in agricultural land. The graphs for each region are very different:

- Africa shows the largest difference between aridity zones. In the very humid areas, almost all agricultural land has at least 20% tree cover, with at least half the land having >45% cover. In the driest agricultural areas, at least half the area has less than 5% tree cover.
- South East Asia has the next highest contrast between climate zones, but note there is very little area in the drier zones.
- Central and South America are characterized by little difference in tree cover distribution in different zones. The humid areas have slightly lower tree cover than comparable areas in Africa, and a similar distribution. But the drier areas do not have much less tree cover. Even in the arid areas, the median tree cover is 20%. This may reflect differences in population density (below), but is also determined by different patterns of livelihood and development, such as reliance on wood for fuel.
- South and East Asia show the lowest tree coverage on agricultural land – this despite significant tree growing on Indian farms (Zomer et al. 2007). Note that some well-publicized examples, such as poplars grown for timber in crop fields, are both confined to fairly limited areas and contribute only a small tree crown cover to the landscape. Median tree cover even in the humid areas is about 10%. Much of that land is seasonally flooded rice, with no tradition and maybe little scope for inclusion of trees. However, seasonal flooding *per se* is not a reason for a treeless landscape, as demonstrated in the Amazon.

4.4. Agroforestry and population density

The method we have used has the potential to show patterns of tree cover in agricultural land (agroforestry) and human population. However, presenting and interpreting this can be confusing. It is not clear that one of tree cover or population is a ‘response’, dependant on the other, as explained below. Rather we have a statistical

bivariate distribution of tree cover and population in agricultural land. We have mapped that bivariate distribution globally in Figure 10. Areas of low tree cover and low population densities are shown in lighter shades, while areas with high tree cover and high population are shown in darker colors. Brighter greens show high tree cover with lower population densities, and brighter blues show high populations with relatively lower tree cover. The dark green, blue and gray colors indicate areas with both high tree cover and population density.

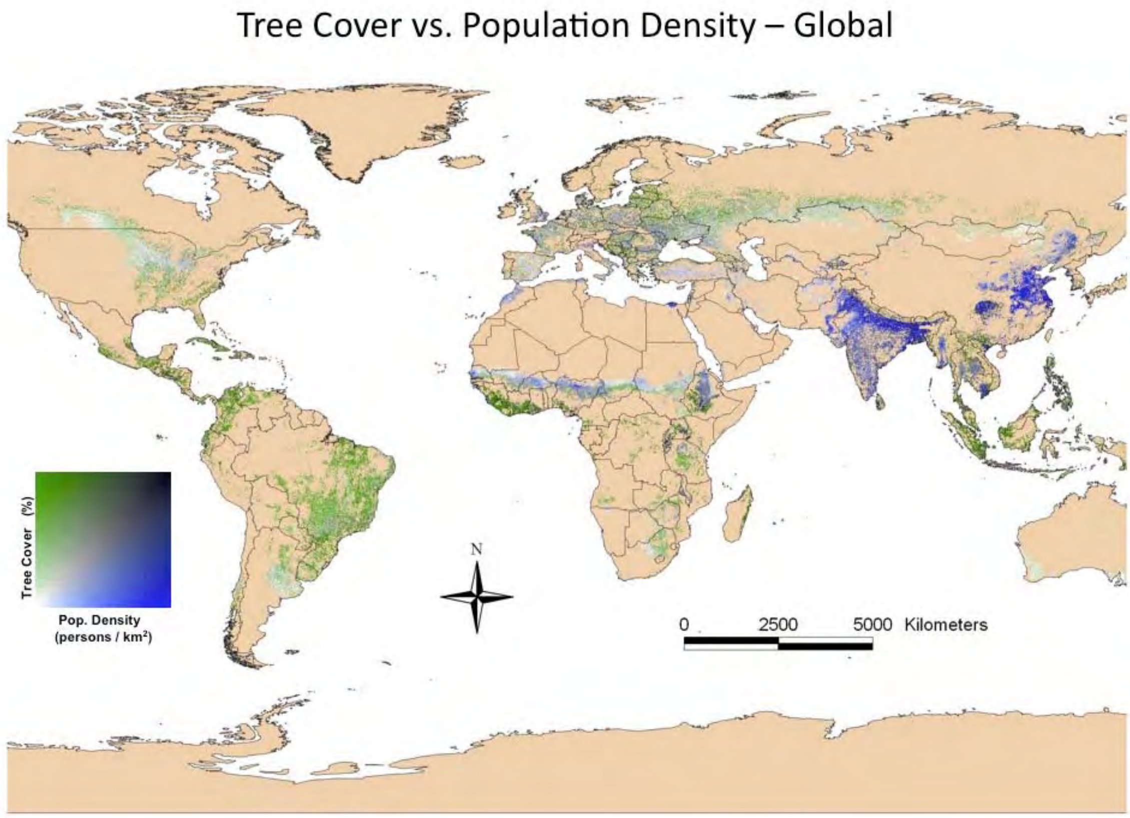


Figure 10. Tree cover and population on agricultural land. Areas of low tree cover and low population densities are shown in lighter shades, while areas with high tree cover and high population are shown in darker colors. Brighter greens show high tree cover with lower population densities, and brighter blues show high populations with relatively lower tree cover.

There are 'obvious' interactions of tree cover with population density. A first thought is simply that there is 'less room' for trees in densely populated areas that depend on agriculture. Throughout history trees have been cleared to create space for agriculture. While agroforestry experience has shown this is not inevitable and there are other options, it still persists. The increase in population in agricultural land or mosaic cropland/natural vegetation can be seen as a model of agricultural development in the area and the tree/population density response is the dynamics itself of land clearing

(especially at low population density). In general at low population density, as agricultural gets established, land clearing and tree removal is almost unavoidable. But we also know that in intensive systems dependent on labour input, trees can increase resource use efficiency and add resilience through diversifying production enterprises. And hence there are documented cases of the time-trajectory of tree cover being U shaped – pioneer farmers remove trees from the landscape, but as intensive systems develope there is an increase in 'useful' trees. At a landscape scale, dynamics of crop-fallow-secondary forest sequences and the way they change with intensification have been described and vary greatly across the world (Lambin and Geist 2006). So what does the global picture look like? Remember we only have cross-section data. Only under rather restricted conditions will the cross-section data reflect the dynamics.

The global picture that emerges is surprising. There at global level there is no obvious correlation between population density and tree density. Every tree cover/ population density combination exists on agricultural land (low/low, low/high, high/low, high, high). The patterns are spatially coherent in the sense that there are 'patches' of different colours, not just random scatterings, suggesting influence of ecology, climate and other factors of influence at meso scale which we have not identified. However, although climate zones clearly are correlated with the patterns, they are only part of the story. For example:

- Looking from east to west across the Sahelian zone of west Africa, the climate is very similar but there is variation in the tree x population patterns, even though most of it is dominantly blue ('more people than trees')
- The whole of South America is green ('more trees than people'). This includes northeast Brazil, with its semiarid climate similar to that of the Sahel. The dry northeast area of Brazil, strikingly distinct in the climate map does not stand out at all in the tree cover/population map
- South Asia has a strong east-west trend in aridity but no similar trend in the tree/people pattern.
- The striking difference between Java, Sumatra and Philippines (all humid forest areas, but with very different patterns of trees/people in agricultural land)

- The differences between western Kenya and central Kenya (two subhumid areas with settled farming originating from about the same time)

It is likely that regional or local historical and recent development pathways are as important in determining tree x population density patterns as global patterns and trajectories.

However, as we know climate matters, we explore the patterns further while normalizing the existing areal distribution in different aridity classes, which differentiates patterns for different geographical areas. If we condition on population density, then the average tree cover on agricultural land can be calculated (Figure 11). Again these show distinct patterns for each region. Only South East Asia shows any hint of a U shaped trend, with increasing average tree cover at higher population densities.

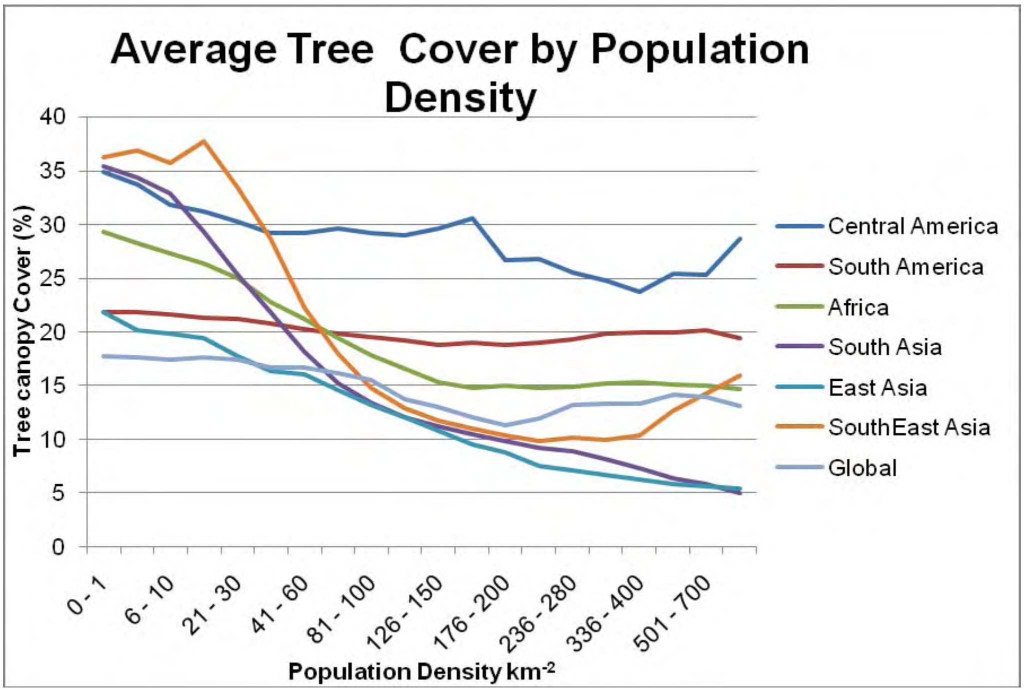


Figure 11. Average tree density on agricultural land by population density for each region.

4.5. Agroforestry, population density, and aridity

To improve the interpretation of the tree cover – population density relationship we now unpack some of the confounding factors by controlling for aridity class. This

helps in the analysis because both tree cover and population density are endogenous variables that respond to the more fixed climate variables like aridity, and thus patterns would be expected to differ across aridity class. We also analyze the relationship in each region to control for other factors that may create distinct patterns.

4.5.1. Global level

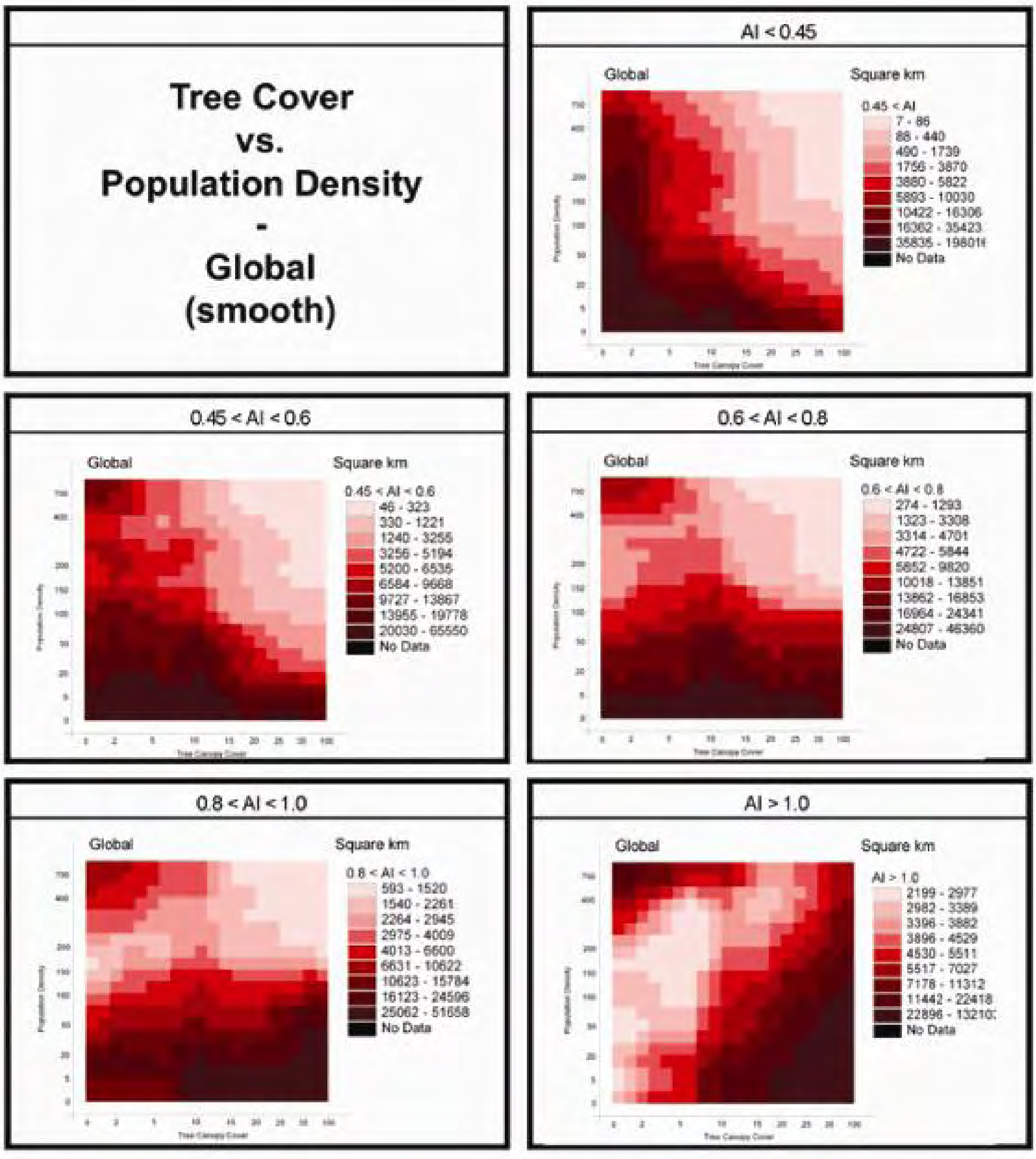


Figure 12. Distribution of tree cover on agricultural land globally in relation to population density. Darker reds indicate class combinations with more area, while lighter colors indicate classes with less area (in km^2).

Figure 12 shows the distribution of area by population density and tree cover , drawn separately for each of the five aridity classes. These figures are bivariate histograms of the joint distribution of tree cover and population density. They show the relative frequency of each tree cover and population density combination. Note that a correlation would appear as a 'ridge' on the surface, show as a dark bar from bottom left to top right (positive correlation) or top left to bottom right (negative correlation). Such correlations do not stand out. From arid to humid zones, it can be observed that very little agricultural land with high population and high tree cover is observed (the light color in the top right corner). It is only in the very humid zone where such an occurrence is common. The dark area, showing where the most common relationships are found, 'moves' with aridity. In the arid areas, the most common relationship is that of low population and low tree cover, but also with high population/low tree cover and low population/high tree cover patterns occurring with frequency. In the semi-arid and sub-humid zones, there is a flattening of the dark spots where the frequency of high population/low tree cover reduces, slowly shifting towards high population densities at the higher tree covers. Then, in humid and very humid zones, the dark area shifts towards the bottom right corner indicating a high tree cover overall, but also an increase in the area under both high population and high tree cover.

If we focus on means rather than the whole distribution, we can plot them as functions of population density or aridity. The global picture (Figure 13) shows the way in which the pattern across regions is dominated by aridity rather than population density. This changes when we break it down by region (below). Figures 14 to 16 show the relationships from a different perspective, looking at cumulative population by tree cover and across different aridity zones. At the global level, the very humid zone stands out as uniquely hosting large numbers of people alongside high tree cover (Figure 14). That combination is rare in the other aridity classes. The same pattern can be observed for the cumulative percentage of the population by tree cover in Figure 15.

At the global level, the mean population density is nearly constant for agricultural land observations having between 15% to 65% tree cover for almost all aridity zones (Figure 14). That implies that within that range, there is not a noticeable tradeoff

between people and trees. For a given tree cover, the mean population density is higher, the more humid the aridity zone, as is expected, though the differences are not always large. Mean population densities increase rapidly with lower tree cover (below 15% cover). Moreover, for very high tree covers (>65%) population densities fall and converge to a similar value for all aridity zones (at 10 persons km^{-2} or less). The overall global picture then is one that confirms that very high agricultural populations and large numbers of trees do not commonly mix.

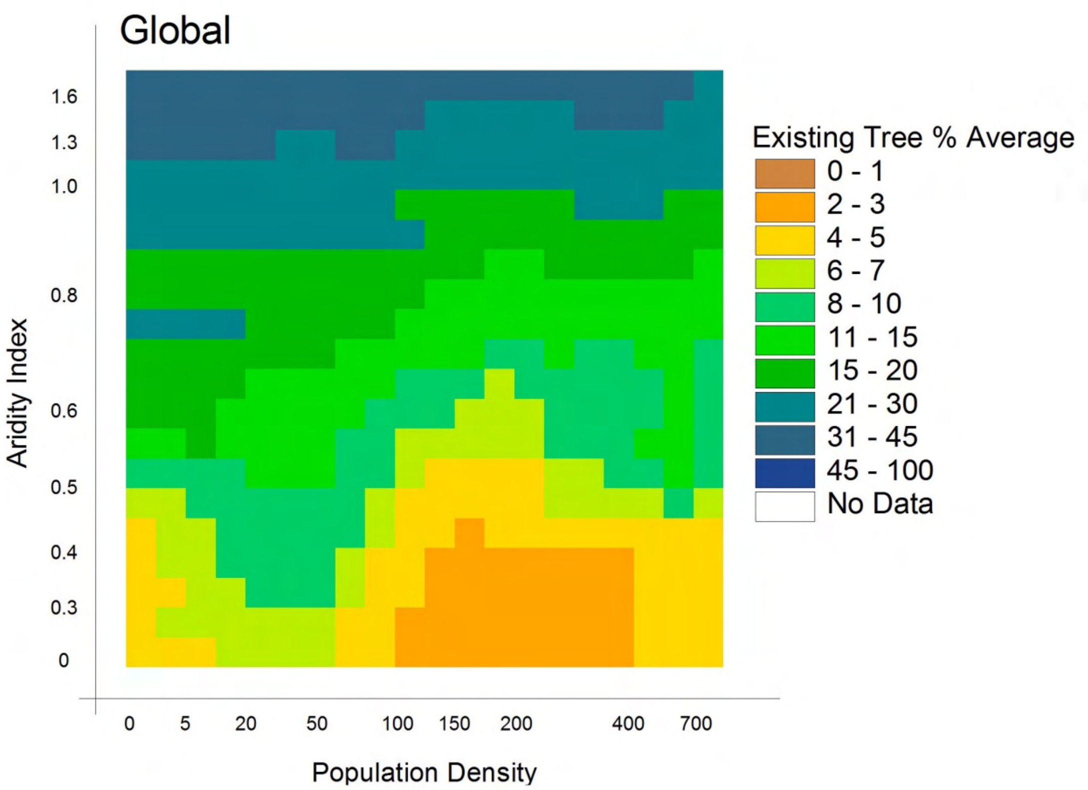


Figure 13. Global average tree cover % on agricultural land as a function of population density and aridity.

4.5.2. Regional level

It is critically important to discuss regional dimensions of the aridity, population, and tree cover nexus because the differences are so stark and patterns uniquely different than the aggregate global pattern. In terms of the mean population density by tree cover analysis, (Figure 14), Southeast Asia and South Asia generally show monotonically negative relationships between mean population density and tree cover for all aridity classes. South America has very flat relationships between the two, for

all aridity classes and Central America is quite similar (apart from some spikes caused by limited number of observations).

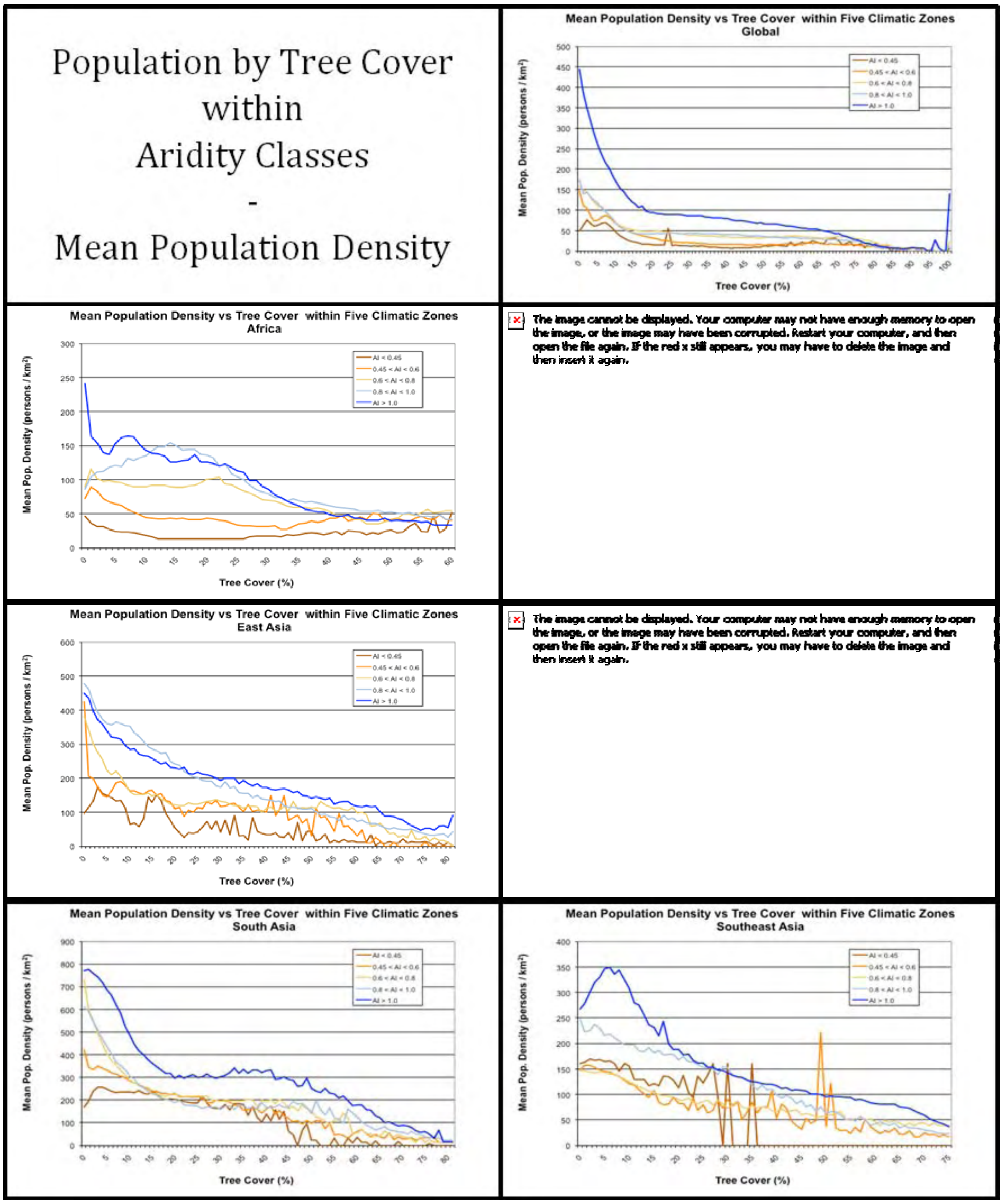


Figure 14. Population by tree cover within aridity classes (mean population density).

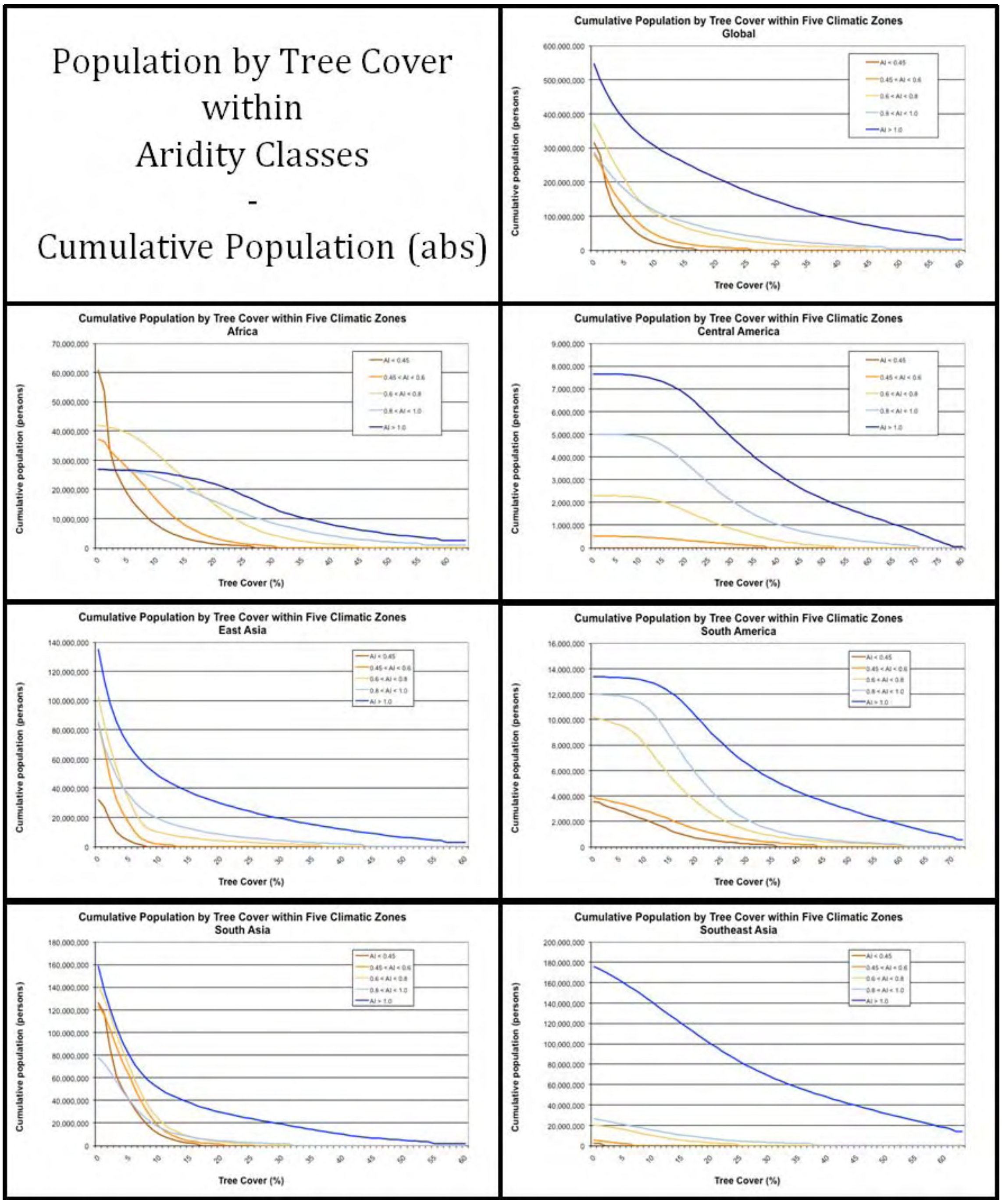


Figure 15. Population by tree cover within aridity classes (cumulative population - abs).

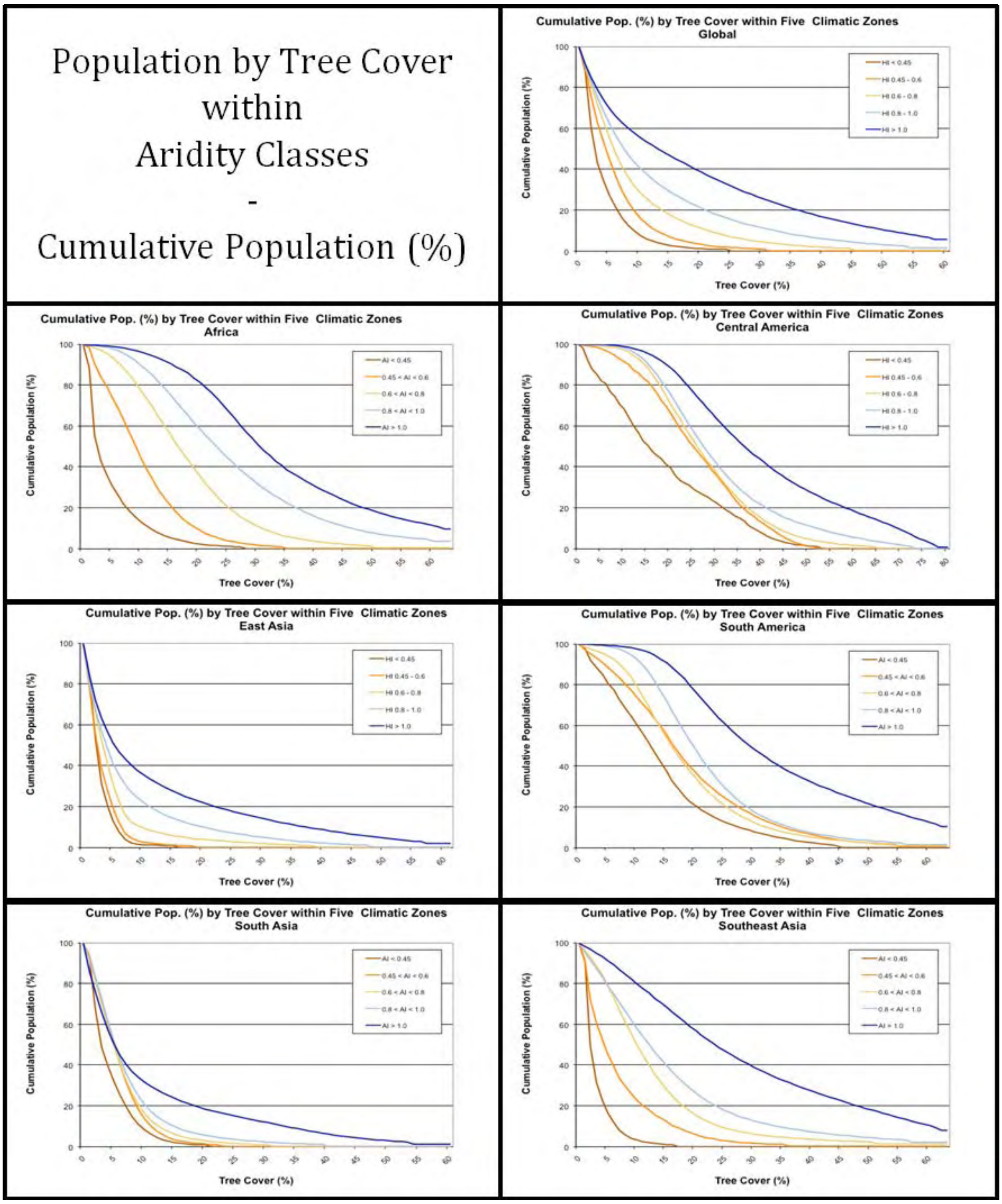


Figure 16. Population by tree cover within aridity classes (cumulative population %).

Africa has perhaps the most variation in population density / tree cover patterns across aridity zones. For the arid and semi-arid zone, Figure 14 shows a slight u-shaped curve indicating that increases in tree cover from low to moderate levels are correlated with lower populations. However, increases from moderate to high levels of cover are associated with higher populations. The sub-humid zone is distinguished by a flat mean population density over tree cover levels up to around 25% after which it drops off. This suggests that increasing tree cover to reasonably high levels does

not necessarily imply tradeoffs with population. The humid area shows yet another pattern, one where mean population density actually increases from low levels of tree cover and peaks at around 15% tree cover, at which point it falls again. This is perhaps indicative of large areas of the densely populated east African highlands where significant tree planting has occurred. Finally, the humid zone shows the most monotonic and negative relationship between people and trees. The tradeoff is less at tree cover levels below 20% and strengthens thereafter.

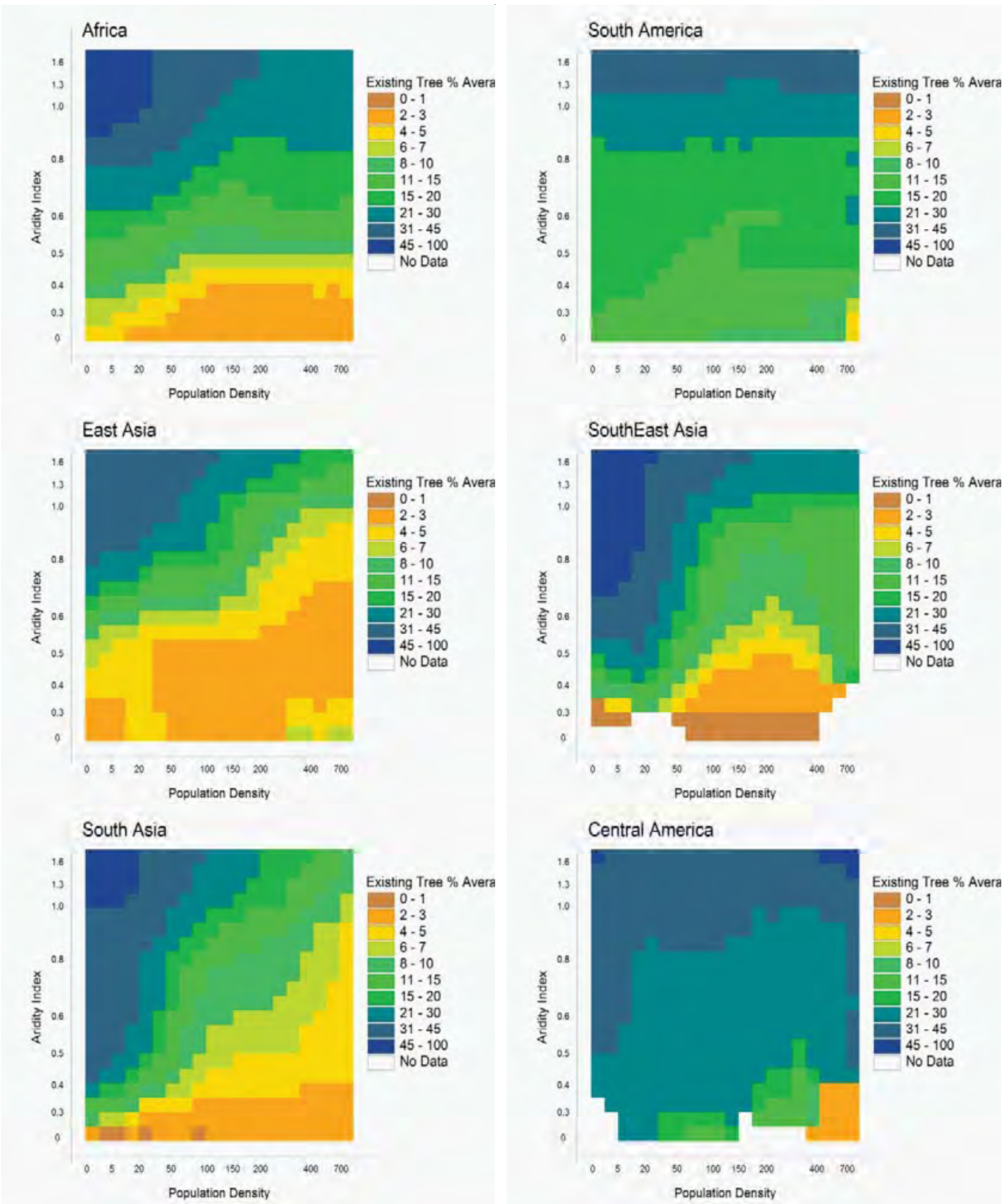


Figure 17. Tree cover by population density and aridity for each region.

Using distribution of area by population density and tree cover (similar to Figure 12), similar analyses were conducted at the regional level and are found in Appendix 2 (Figures A-1 to A-6). The averages are in Figure 17. These again demonstrate the clear differences across region and that the global pattern described above is not replicated in any of the regions. Some key differences are that (i) in Africa and South America, as humidity increases the occurrence of high population and low tree cover reduces quickly, (ii) in Central America, there are overall few cases of low tree cover and thus the largest area is always on the right side of the graph (in the higher tree cover zone), (iii) in east Asia the most frequent occurrences are at very low tree cover from arid to sub-humid areas with a bi-modal relationship emerging in more humid zones covering both a low tree cover and a high tree cover outcome, (iv) in South America, a high frequency of high tree cover is observed in all aridity classes, (v) in south Asia, the most common pattern is that of high population / low tree cover through all but the very humid zone when other patterns also emerge, and (vi) in southeast Asia the most common patterns are not at the corners or edges as in most cases elsewhere but are swathes that indicate common occurrence of a wide range of tree cover for a given band of population density.

Focusing on total population (Figure 15), we again see differences across region with Africa, Central America and South America showing similar patterns in humid and very humid areas, with a strong majority of the population coexisting with high levels of agroforestry. This is not the case at the global level or in the other regions, which show high populations living only in areas with relatively low tree cover.

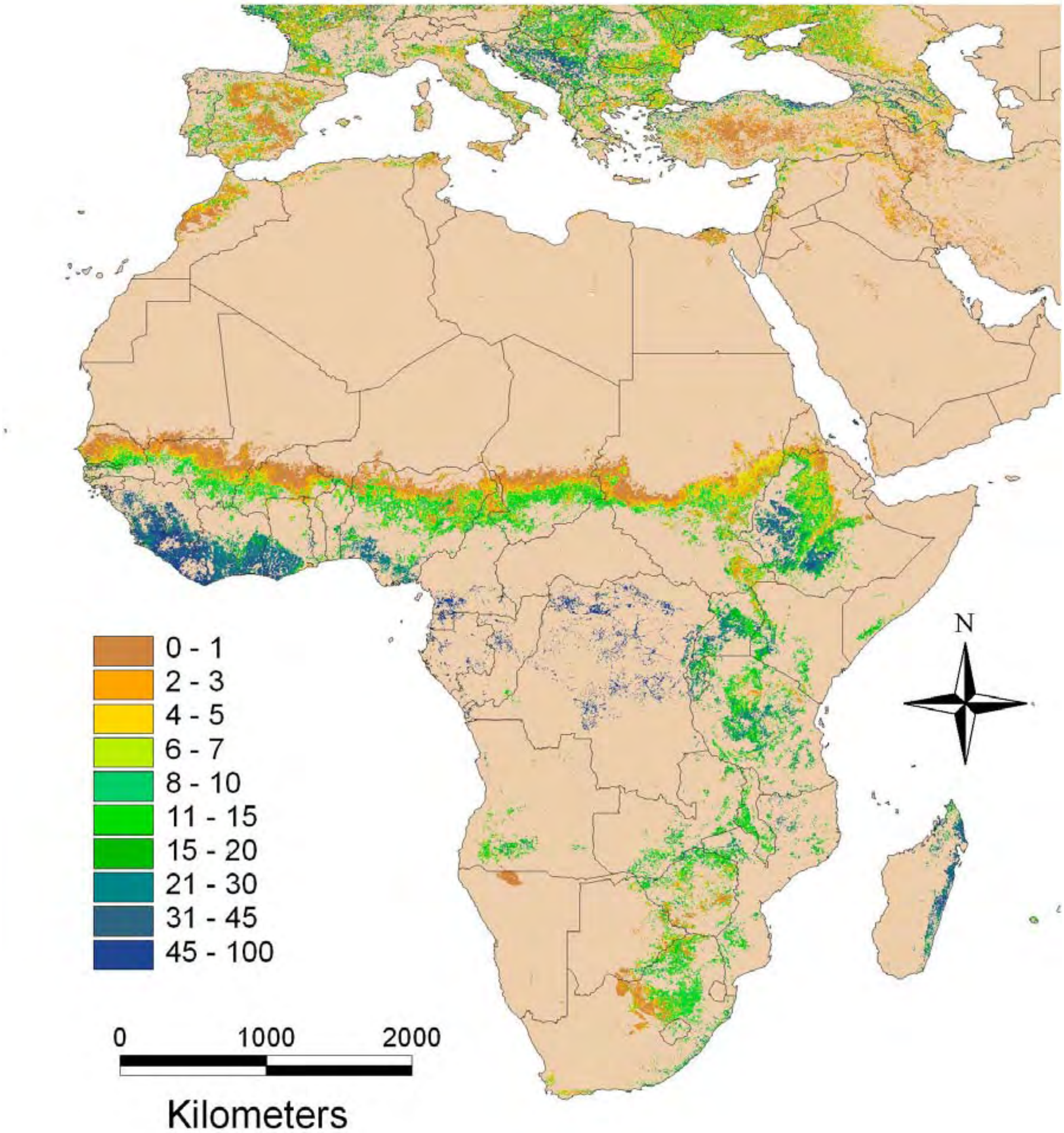
In southeast Asia, the numbers of people in all but the humid zone are negligible. In that zone the cumulative curve is fairly straight showing that up to 60% tree cover, any band of tree cover has about the same overall population. Thus there is no ‘typical’ agricultural landscape and its tree cover: as far as the people go, about as many live in landscapes with 0-10% cover as in landscapes with >45% cover. In humid areas of South and Central America, essentially all people in agricultural areas have at least 20% tree cover (i.e. the curve is flat from 0 to 20% tree cover). This contrasts strongly with the situation in south and east Asia, where even in humid areas, the majority of people have very low (<5%) tree cover.

In Africa, there is a striking contrast between the arid and the very humid zone. In the arid zone practically all inhabitants live in areas with less than 15% tree cover while in the humid zone, almost all inhabitants live in areas with more than 15% tree cover. Population is less skewed in specific tree cover bands in the other aridity zones. Figure A-1 shows very clearly that a greater share of the population coincide with high tree cover the more humid the zone.

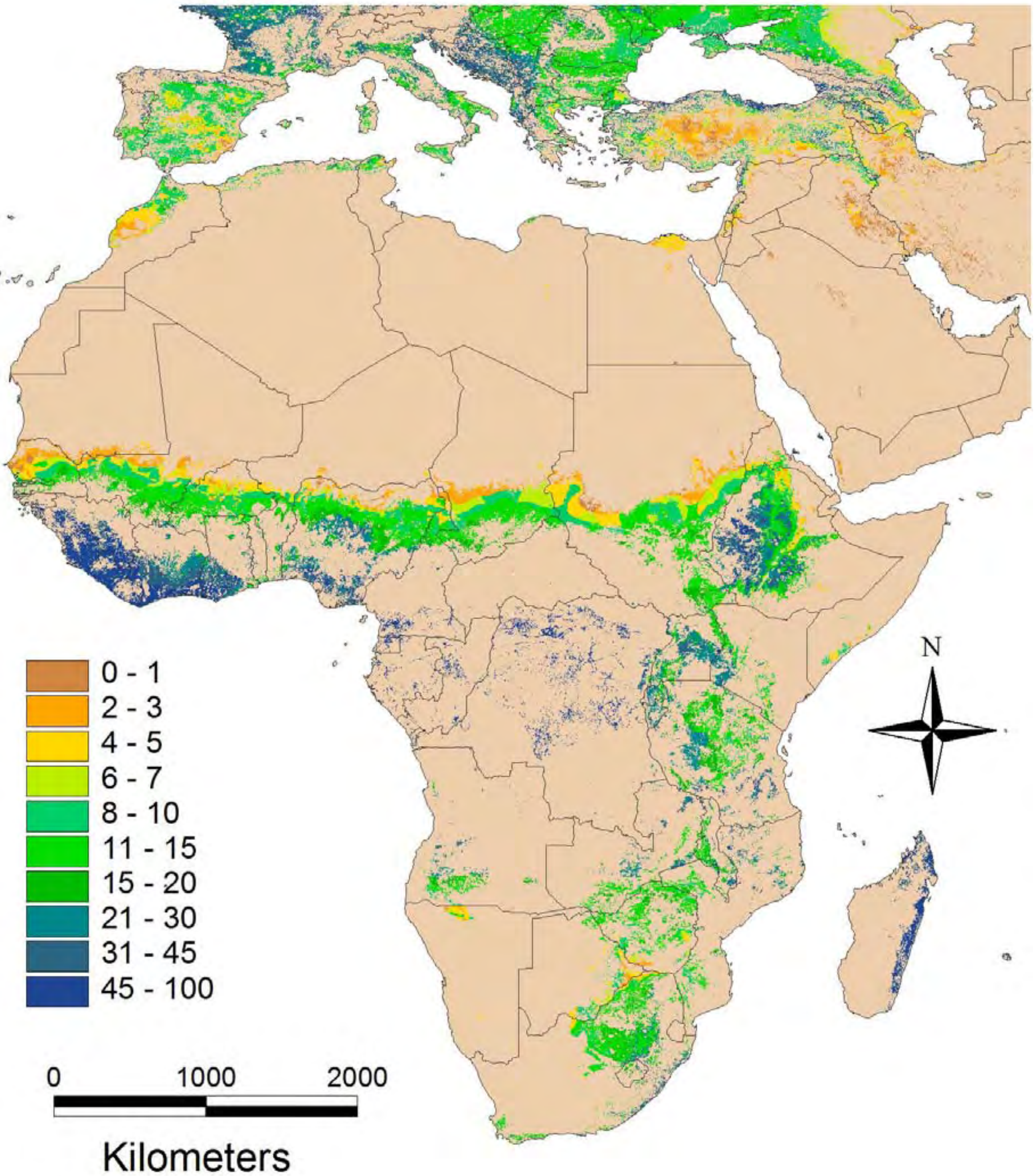
4.6. Estimating actual versus potential tree cover

The difference between actual and potential (see Methods section) tree cover gives an indication of where tree cover is below that which is feasible, based on what is already practiced in similar areas. 'Similar' here means similar on the basis of the variables used in this analysis – region, aridity and population density. We present this analysis for Africa only, as an illustration of what can be learned from such an analysis. For Africa, three figures are presented (Figure 18 a, b, c). Figure 18(a) is the tree cover map for Africa. Figure 18(b) shows the zonal 80 percentile tree cover value – that is the value of tree cover found for the 80^{th} percentile observation (from low to high) from among all those in the same aridity and population density classification. Thus, for most of the pixels the actual will be less than the potential and Figure 18(b) will depict a general increase in tree cover over and above the actual tree cover in Figure 18(a). Figure 18(c) then shows the difference of actual tree cover less potential tree cover and again because of the definition of potential tree cover, indicates more areas of below potential than areas of equivalence or above.

(a)


0 - 1
2 - 3
4 - 5
6 - 7
8 - 10
11 - 15
15 - 20
21 - 30
31 - 45
45 - 100
0
1000
2000
Kilometers
N

(b)


0 - 1
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(c)

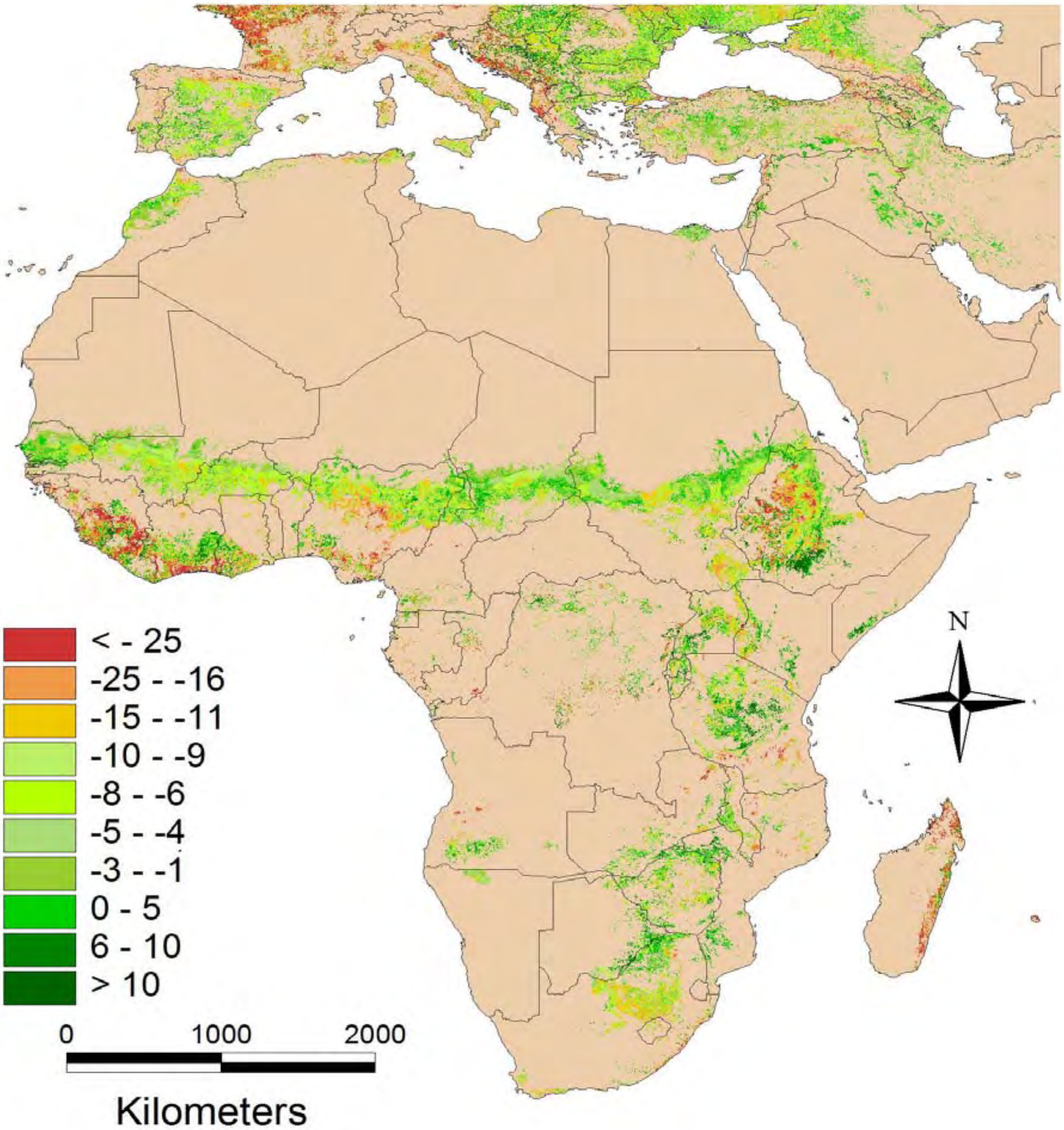

Figure 18. Actual (a) and potential (b) tree cover and their difference (c) in Africa. See methods for details.

Looking first at the potential tree cover (Figure 18(b)), it is worth noting that almost the entire area bordering the Sahara desert has a potential that is above the actual, but is still low (less than 10% tree cover). There is also a significant area in South Africa

which currently has few trees planted but has the potential to increase significantly above the threshold of our definition of agroforestry. Finally, there is quite an expansive area in east Africa in which potential exceeds actual, even though actual tree cover is often quite high.

Turning to Figure 18(c), it is clear that the areas below or above potential follow a spatial pattern at a scale much larger than the pixel – neighbouring pixels tend to be similar in their deviation from potential tree cover. This therefore represents a pattern that is worth trying to understand. The most significant major area of tree cover deficit is the band just south of the Sahara stretching from Senegal to Sudan. However, because the potential tree cover is low, the area can be described as being only moderately in deficit. A second large tree deficit area is in the west African coastal lowlands. That is hard to detect from an inspection of Figures 18(a) and 18(b) because both indicate quite high tree cover. Here the potential is high. While much of the area is well treed, the results show that systems with higher tree cover exist in the same conditions. A third noticeable area with below potential tree cover is a band running northward from central Tanzania to the Kenya/Uganda border and up into southern Sudan. A fourth area is in the northern part of South Africa. For both of these areas, the degree of the deficit is not high – the potential is not too far from actual practice. A fifth area would be pockets in both northern and southern Nigeria, hence in different ecological zones. A sixth area of deficit is along the eastern coast of Madagascar. The last major tree cover deficit area is found in Ethiopia, in particular in the north central section. In some places, the deficit is severe (as shown by the red color).

In fact, Ethiopia is quite the place of contrasts, with highland areas of severe deficit, mild deficit, and surplus, all within relatively short distances of each other. Other regions showing areas consistently at potential include southern Uganda and into Rwanda, some pockets of Tanzania, the humid area along the border of Cote d'Ivoire and Ghana, some areas of the Sahel, especially in Chad and Sudan, and areas in northern Zimbabwe.

For all these locations, the interpretation is not that there is 'potential for further agroforestry'. We know much of the prerequisite conditions for adoption of

agroforestry systems, and those have not been built into this analysis. This analysis does identify areas in which atypical tree cover and population pathways of development have occurred, Understanding these may help change them. The benefits from agroforestry may not be related to tree cover itself (areas under less tree cover may actually benefit more from trees than areas with higher tree cover). Future impacts from increasing agroforestry is not necessarily related to actual levels of tree cover or potential levels of tree cover (there may be more impact from increasing tree cover in areas with already high tree cover, for example)

5. Limitations

The data sets and methods used in this analysis have various limitations, peculiarities and ambiguities. These bound the interpretation of all the results, and hence must be understood before using the results. The major limitations we have identified are listed below.

1. This is a global analysis. We are looking for global averages, trends and large scale patterns. We cannot expect results for an individual pixel (1 km x 1 km) to be close to reality. But averages for large regions should be realistic, with trends and differences between regions reflecting real differences. For example, for each pixel classified as agriculture that actually has a large non-agricultural village in it, there is a pixel classified as urban or some other land use that has a substantial agricultural area.
2. Since the tree cover variable is based on remote sensing, it is an estimate of % crown cover, not tree density *per se*, nor of tree biomass. At landscape scale the correlation between these is probably quite good within broad agroforestry systems and climate zones, but this will not be true globally.
3. The interaction of a given % crown cover with other agricultural activities varies with system, climate and other factors. For example, in the Sahel, 30% crown cover with mature parkland trees will enhance crop productivity relative to no trees; 30% crown cover of young trees will probably reduce crop production close to zero (van Noordwijk and Ong 1999)

4. Agricultural land cover classification from remotely sensed data , particularly for Africa, is weak (Hannerz and Lotsch 2008). Many readers will be able to spot areas which are not included as agricultural but which, in their experience, have a large agricultural component. Much of the disagreement between land cover maps arises from areas of low cropping density, where sparse agriculture tend to be confused with natural vegetation. For example, in Africa, where subsistence agriculture mixed with natural vegetation is a common practice, total agriculture area is quite underestimated. Therefore, our definition of agricultural areas may be biased towards more extensive (and productive) agricultural systems. On the other side, we should stress that in mosaics of agricultural area with natural vegetation, tree inclusion is more likely a natural presence and less "of use" for human needs, as in agroforestry systems.
5. Our 'agricultural land' class does not include areas dominated tree crops. Further, we are not able to include land classified as forest but which we would call 'agroforest' – forest which is managed more or less intensively by small holders producing timber and non-timber products.
6. Discrepancies between the area we found as agricultural and other sources may be further compounded by the difference between *de facto* and *de jure* classifications.
7. The tree cover data is also interpreted from remote sensing data. MODIS VCF is likely to underestimate tree cover in general. Comparisons with ground tree cover databases in southwestern US (FIA and SWRrGAP), Utah Arizona and Colorado, show that VCF Tree canopy cover Collection 3 (the one we use) has slightly positive or nil bias for low tree canopy cover (0-10%), with bias becoming increasingly more negative (underestimates tree canopy cover) as tree canopy cover increases (White et al. 2005). White et al. report in general a bias of -14/-18 % for southern US, concluding that errors are unlikely to be related to habitat fragmentation or variation in canopy height but may be influenced by scaling discontinuities between ground and satellite resolutions. In concordance with this report, a previous study we did showed that while tree canopy cover assessed from MODIS on agroforestry in India was about 8%, on ground tree canopy cover (assessed with high resolution imageries) was about 11% (Zomer et al, 2007). The Collection 3 is an average over the

year, 2000 and uses an algorithm that has been showed could be improved. In fact an assessment for 11 study areas in Africa (Rokhmatuloh et al, 2005) showed an average prediction error of about 12% with VCF Collection 3, while a new method that the same study proposed gave an average prediction error of about 3-4%.. However the VCF Collection 4 (monthly time series of tree canopy cover 2000-2006) is not available globally and has not been fully reviewed.

8. The population layer is a statistical interpolation built from a range of data sources and assumptions and from different levels of resolution in different regions. Population census, available for political regions, as districts or counties, is redistributed spatially based on night imageries of artificial light distribution. Such political boundaries for census data are wider for lower populated areas. However, bias exists in districts with high population with small political boundaries, where strong lighting may be produced from social infrastructure. For instance, lights on highways might infer high populations, indeed few people live adjacent to highways.
9. We have no information on configuration of trees in the landscape. A 1 km x 1 km pixel classified as agricultural land and having 49% tree cover could be:
    a. 51% treeless crop land and 49% dense forest, with a hard boundary
    b. 100% trees and crops fully integrated at the finest scale
    c. Anything in between.
10. We have no information on the nature and level of interaction between the people in a pixel and the assumed agroforestry. A 1 km x 1 km pixel classified as agricultural land with 49% tree cover and 100 people could be any of:
    a. 100 people living in and dependant on an integrated AF system
    b. A 51% treeless cropland with 100 agriculturalists living on it, plus a people-less forest they are prohibited from entering.
    c. 51% treeless crop land with 1 commercial farmer working on it and 99 people living in a forest village and working in a papermill.
11. Readers knowledgeable about specific geographical areas will identify agricultural areas that are omitted from the land cover data available. Many such areas will have been classified as woodlands or forests instead of agriculture. This means our estimates of the extent of agroforestry is

conservative – much, if not all, of the misclassified agricultural area are under agroforestry.

12. In all interpretations and descriptions, we must remember that the analysis is based on cross-sectional data. The climate (and region) is assumed a fixed conditioning variable or explanatory variable (economists exogenous) (ignoring any hypotheses about changing tree cover changing local climate). But both population and tree cover are response variables (endogenous), and evolve through complex interactions with each other. It is tempting but not valid to explain tree cover by conditioning on population (e.g. 'There are few trees here because there are a lot of people) or vice versa ('There are few people here because there are a lot/few trees'). However it is useful to condition on one to detect patterns in the other. For example, if two agricultural areas with the same climate and population have very different tree cover there is something to understand and explain. Likewise if there are two areas with the same climate and tree cover but very different populations.
13. It is important to note that areas of low tree cover and relatively high population do not mean that people are living without the benefits of trees. There may be nearby woodlands / forests or they may be purchasing tree products which are produced elsewhere.

6. Where next?

As noted in the introduction, this global analysis is a first step in understanding the extent and importance of agroforestry and to examine patterns of agroforestry across a relatively few variables (population, climate, region). A number of further analyses can be identified which would either enrich or extend the results found in this study.

The first set of analyses relate to validation of the findings and the importance of comparing them to results from more detailed studies. There is no point trying to validate at a pixel level. But we should be getting realistic results at scales of 100s of km^2. Some possibilities exist now for the whole of India and parts of Indonesia where tree cover and agroforestry systems have been analyzed at high resolution. There are undoubtedly growing opportunities for this.

The second set of analyses relate to enriching the current global level analysis. As noted in the Limitations, there are known gaps in the agroforestry assessment such as the lack of tree crops systems, agroforests, due to difficulties in classifying land use rather than land cover. Likewise, the global tree cover database has gone through several rounds of improvement and will be available at higher resolution in the near terms. The re-running of our analyses with these improved datasets would be useful for establishing a more reliable estimate of agroforestry, especially if this was to be used as a baseline for assessment of change (see below).   The main point is that there will be opportunities to improve results and possibly the techniques based on refined data which is continually available.

A third set of analyses relate to higher resolution analysis. The analysis in this paper is strictly about tree cover, which masks the vast range of agroforestry systems and practices. Though there have been many case studies of particular agroforestry systems or practices in defined geographical areas, the global analysis would be enriched by a collection of agroforestry systems or practices in given population x climate combinations. What do these look like, how did they arise, how do they

benefit livelihoods or environment. This analysis would be vital for assessing the importance of agroforestry.

A fourth most interesting area is to drill down to understand the differing patterns uncovered by our global assessment. Some examples are: (a) within regions, with similar basic ecology – what are the factors which lead to different patterns of tree cover within relatively short distances with similar population and climate; (b) between regions, what are the cultural and historical processes that lead to where we are? For example, are places in Africa and S Asia different points along a common trajectory, or are they very distinct? This could have large scale policy implications; (c) can the patterns found be explained by other driving or conditioning factors for which data are now available, such as market access?

Lastly, this cross-section dataset and analysis may well be thought of as a baseline for investigating ex ante or ex post dynamics in tree cover or agroforestry systems development. Longitudinal data will enable the development of change variables which themselves can then be used to formulate tests of causality (e.g. does population growth lead to increased or reduced tree cover), which we were unable to do in our cross-section analysis. Our assessment on agricultural lands could further be integrated into a comprehensive tree cover dataset, including all land uses which would then be more useful for assessing or predicting global biomass supply and above ground carbon storage, for example. One could also use such a data set to examine relationships between natural woody vegetation and agroforestry systems (e,g. globally does agroforestry reduce pressure on natural forests?)

7. Summary/Conclusions

We believe the following key messages can be gleaned from this analysis.

A. Tree cover is a common feature on agricultural land. It is therefore essential that this is recognized by all involved in agricultural production, planning and policy development.

Agroforestry, if defined by tree cover of greater than 10% on agricultural land, is widespread, found on 46% of all agricultural land area globally, and affecting 30% of rural populations. Based on our datasets, this represents over 1 billion hectares of land and 558 million people. Agroforestry is particularly prevalent in southeast Asia, Central America, and South America with over 80% of area under agroforestry.

B. It is not possible to describe the resulting patterns as ‘good’, ‘bad’, appropriate or inappropriate tree cover. We did not analyse the costs and benefits associated with these agroforestry lands, nor the implications of a change in tree cover. However, the existence of extensive areas of agroforestry even in arid areas shows that such systems are viable in some sense.

C. There is large variation in tree cover in agricultural land. From continental scale down to the smallest detectable in this analysis (1 km^2) there is variation in tree cover in agricultural lands. But some major trends stand out.

D. There is a strong association between aridity and tree cover. The more humid the climate, the higher the level of tree cover. The results from South East Asia, Central America, and South America are examples of this relationship. However, there are still many exceptions to this rule – high tree cover found in more arid zones and low tree cover found in more humid zones - that are thus explained by other factors.

E. There is no general tradeoff in agricultural landscapes between people and trees. Within aridity classes and continents, there are distinct patterns in the relationship between trees and people, but these do not generally correspond to either a negative or positive correlation, except in the very low or high range of tree cover.

F. Large scale tree cover patterns cannot be fully explained by aridity, population density or region. This points towards the importance of other factors like tenure, markets, or other policies and institutions in affecting incentives for tree planting and management, as well as the historical trajectory that has lead to the current pattern.

G. Tree cover patterns and relationships to other variables like aridity or population vary considerably across sub-continent. 'Global' level results are rarely replicated in any specific subcontinent and hence may not be practically applied. Further investigations at finer regional scales are likely therefore to prove even more illuminating in terms of understanding where on the landscape agroforestry is practiced

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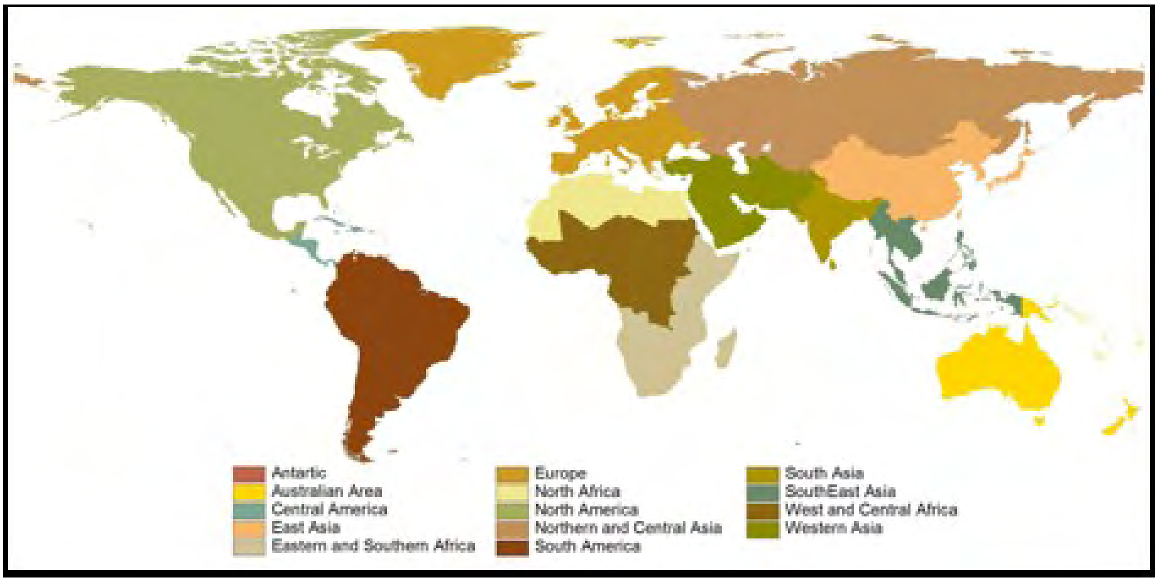
Appendix 1: Geodatasets

1. VMAP0 Political Boundaries

Vector Map level 0 (VMAP) is an updated and improved version from the National Imagery and Mapping Agency of the Digital Chart of the World, which provides a worldwide coverage of vector-based geospatial data. The primary source is the 1:1,000,000 scale Operational Navigation Chart (ONC) series co-produced by the military mapping authorities of Australia, Canada, United Kingdom, and the United States.

The download dataset is available as Vector Product Format (VPF) for 4 different regions of the world: North America, South America-Africa, Europe-North Asia and South Asia-Oceania. The VPF format of the country boundaries for the four regions was converted to shapefiles in ArcGIS. The four regions of the world were merged together and all the different administrative boundaries (sub-country level) were dissolved to create a unique polygon coverage of country boundaries. The VMAP0 country boundaries coverage was converted to 30 arc seconds landform, country and subcontinent grids. The first was used as the landform reference grid, as clipping and nibbling mask to create a spatial extent of valid pixel values common to all the geodatasets, while the second and the third grids were used to extract statistical tables by country and subcontinent.

Subcontinent Grid



2. MOD44B – MODIS/Terra Vegetation Continuous Fields

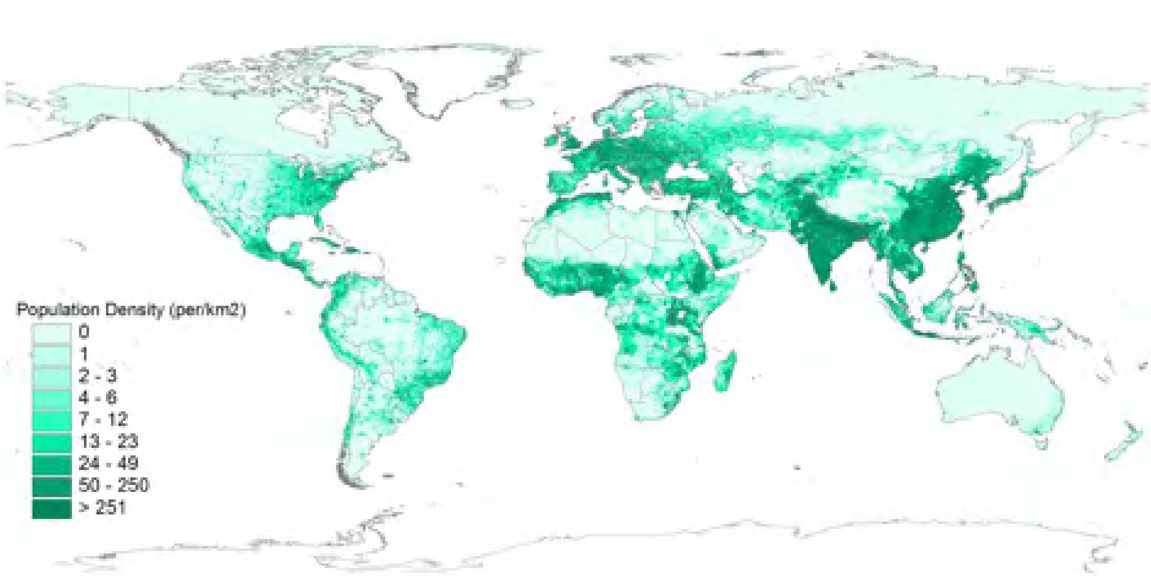
The MODIS vegetation Continuous Fields (Hansen, 2003) was developed from the University of Maryland and provides a global estimates of vegetation cover in terms of woody vegetation, herbaceous vegetation and bare ground percentage. It has been developed using the 7 MODIS bands with highest resolution (500 meters) and field data collected across the globe as training data. The training data and phenological metrics are used with a regression method to derive the global assessment of cover percentage of vegetation. Full description available at:

http://glcf.umiacs.umd.edu/data/modis/vcf/description.shtml

Vegetation continuous rasters of tree, grass and bare soil cover percentage were downloaded by continent as tiff format. Tiff files were imported with the IMAGEGRID command in Arc module. However the Tiff files for Europe and North Asia had an error in the header format and both extent and projections parameters were recalculated separately in order to import these TIFF files correctly. The continental grids were then masked to exclude waterbodies and then merged using the MERGE command into a global raster of Tree Cover Percentage.

3. Global Rural-Urban Mapping Population (GRUMP) in year 2000, version 1

This dataset (Ciesin, 2004) describes the population density for year 2000 in persons per square kilometer, adjusted to match UN totals, with a specific computation of Urban Reallocation in which spatial and population data of both administrative units and urban extents are gridded at a resolution of 30 arc-seconds. The dataset is available as ArcInfo export format on a continental basis.



4. Global Rural-Urban Extent

The global extent of urban and rural areas have been defined from CIESIN in the contest of the GRUMP project and reports areas which are urbanized or affected by the impact of urbanization in the surrounding areas. The dataset was downloaded as ESRI ascii file from GRUMP project web page and converted in a Raster geodataset.

5. Aridity Index

A global model of aridity ((Zomer et al. 2006, 2007). was used to stratify ecological conditions based upon climatic and agroecological charactistics. Aridity is expressed as a function of precipitation, temperature and potential evapotranspiration (*PET)*. Based upon a attempt to classification of climatic zones by moisture regime (UNEP 1997), the Aridity Index (*AI*) quantifies precipitation deficit over atmospheric water demand as:

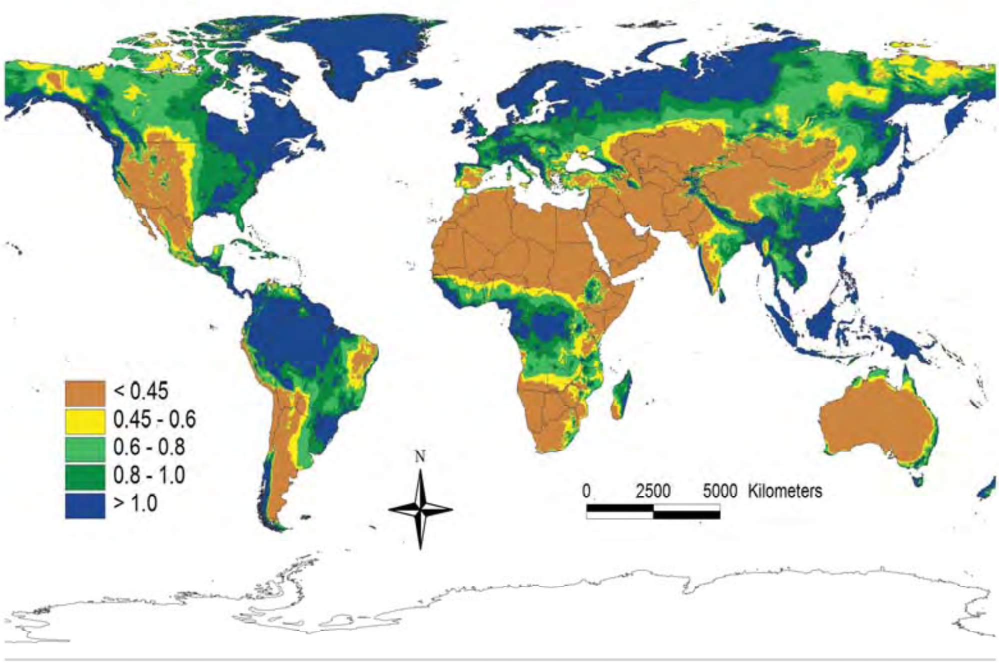
$$\text{Aridity Index } (AI) = MAP \,/\, MAE$$

where:

MAP = mean annual precipitation

MAE = mean annual evapotranspiration.

Monthly values for precipitation and temperature were obtained from the WORLDClim dataset (Hijmans et al. 2005) for years 1960-1990, at a resolution of 30 arc-seconds, or ~1 km at equator, and used to estimate MAP and MAE, based on a global modeling of PET (Zomer et al. 2006, 2007).



Appendix 2: Regional analysis of tree cover by population density

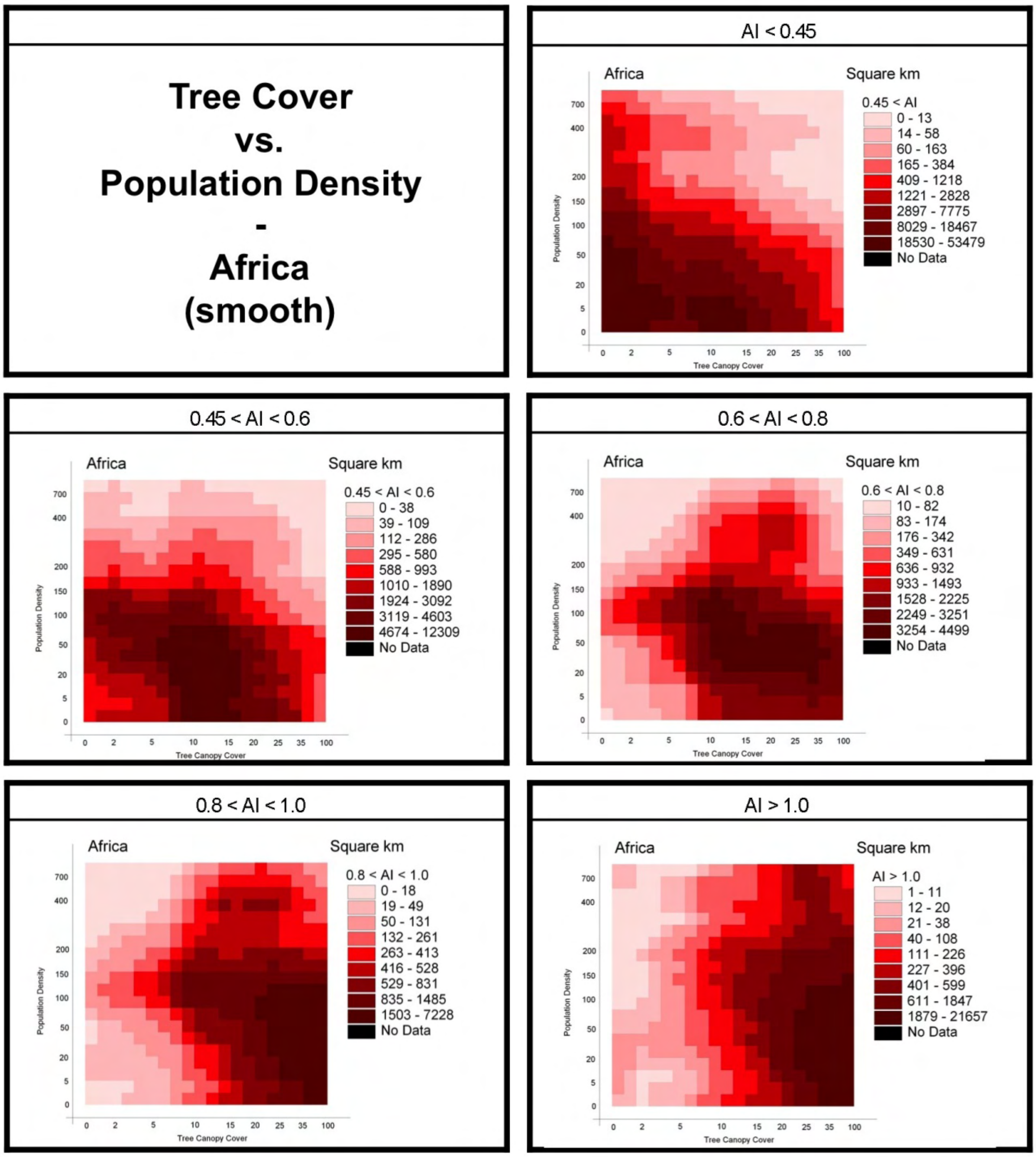


Figure A-1. Distribution of tree cover on agricultural land in Africa in relation to population density. Darker reds indicate class combinations with more area, while lighter colors indicate classes with less area (in km^2).

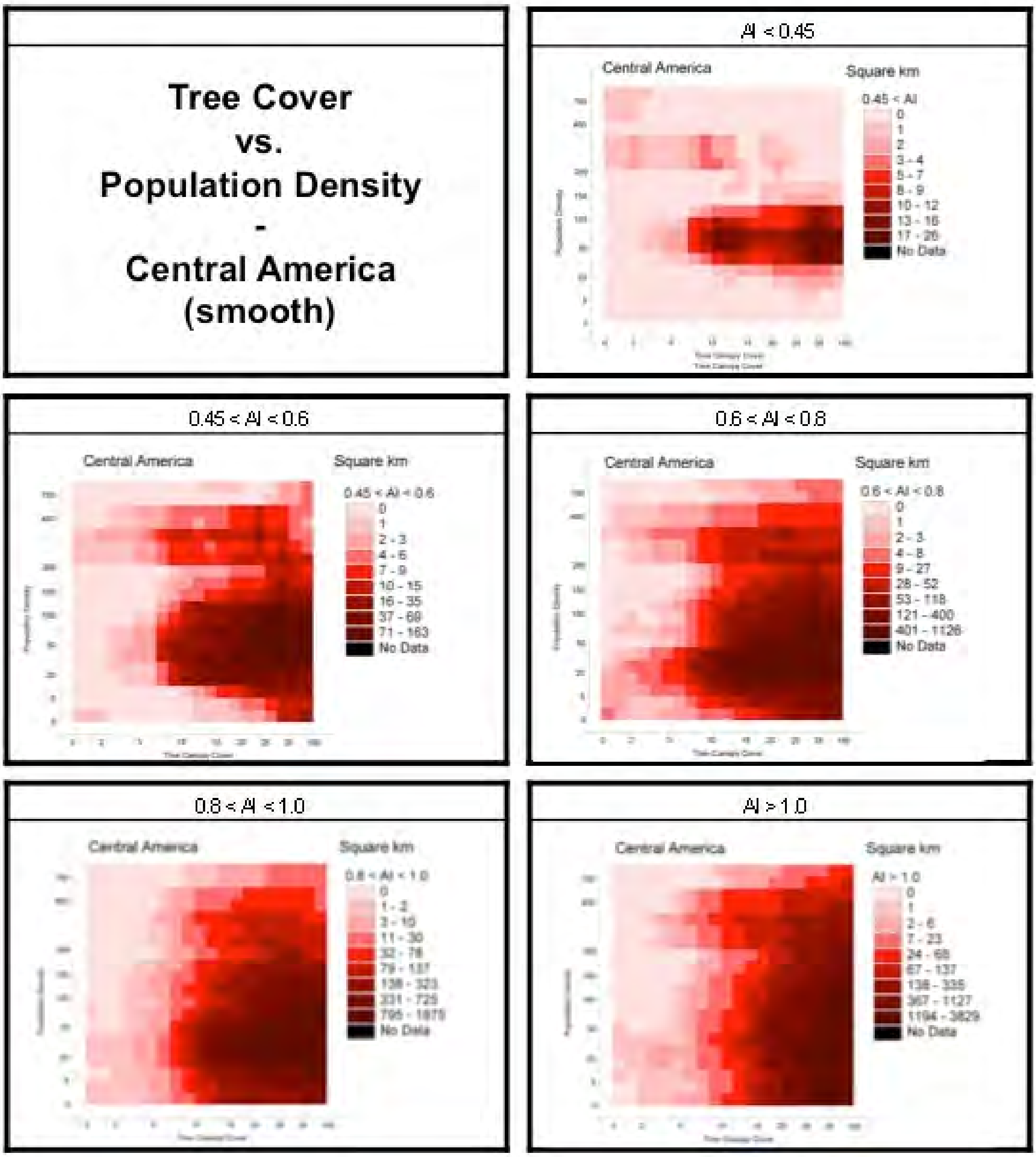


Figure A-2. Distribution of tree cover on agricultural land in Central America in relation to population density. Darker reds indicate class combinations with more area, while lighter colors indicate classes with less area (in km^2).

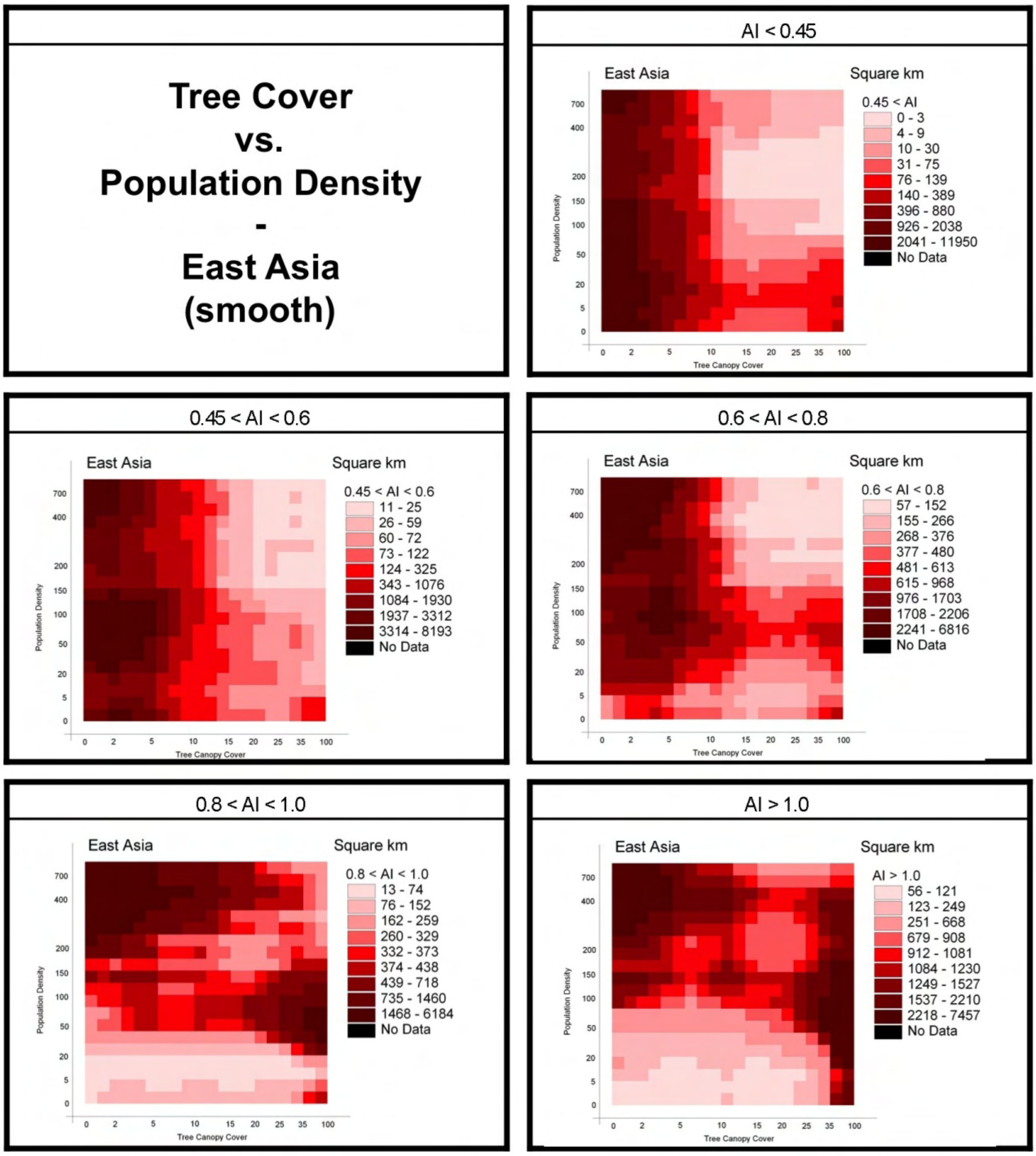


Figure A-3. Distribution of tree cover on agricultural land in East Asia in relation to population density. Darker reds indicate class combinations with more area, while lighter colors indicate classes with less area (in km^2).

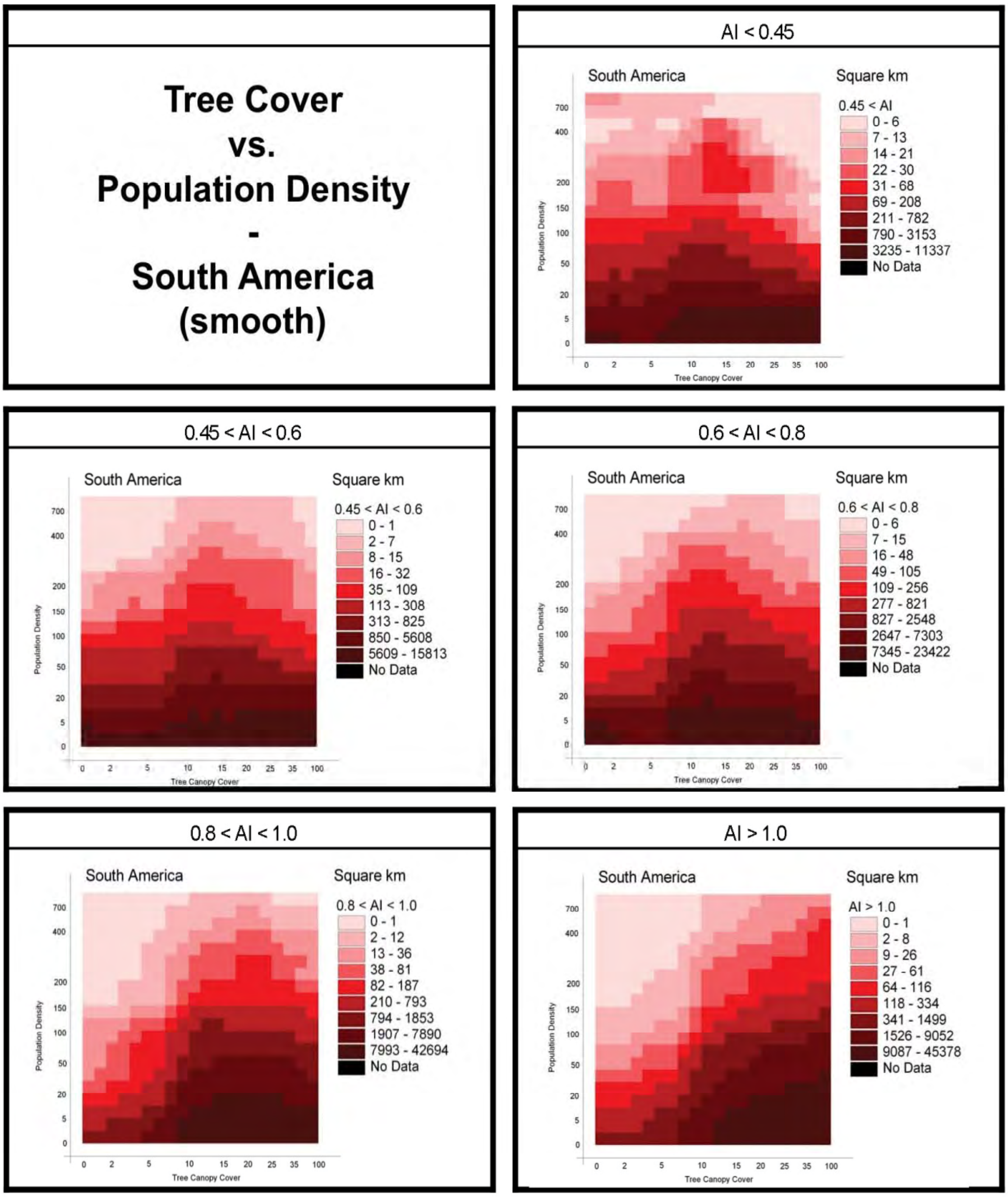


Figure A-4. Distribution of tree cover on agricultural land in South America in relation to population density. Darker reds indicate class combinations with more area, while lighter colors indicate classes with less area (in km^2).

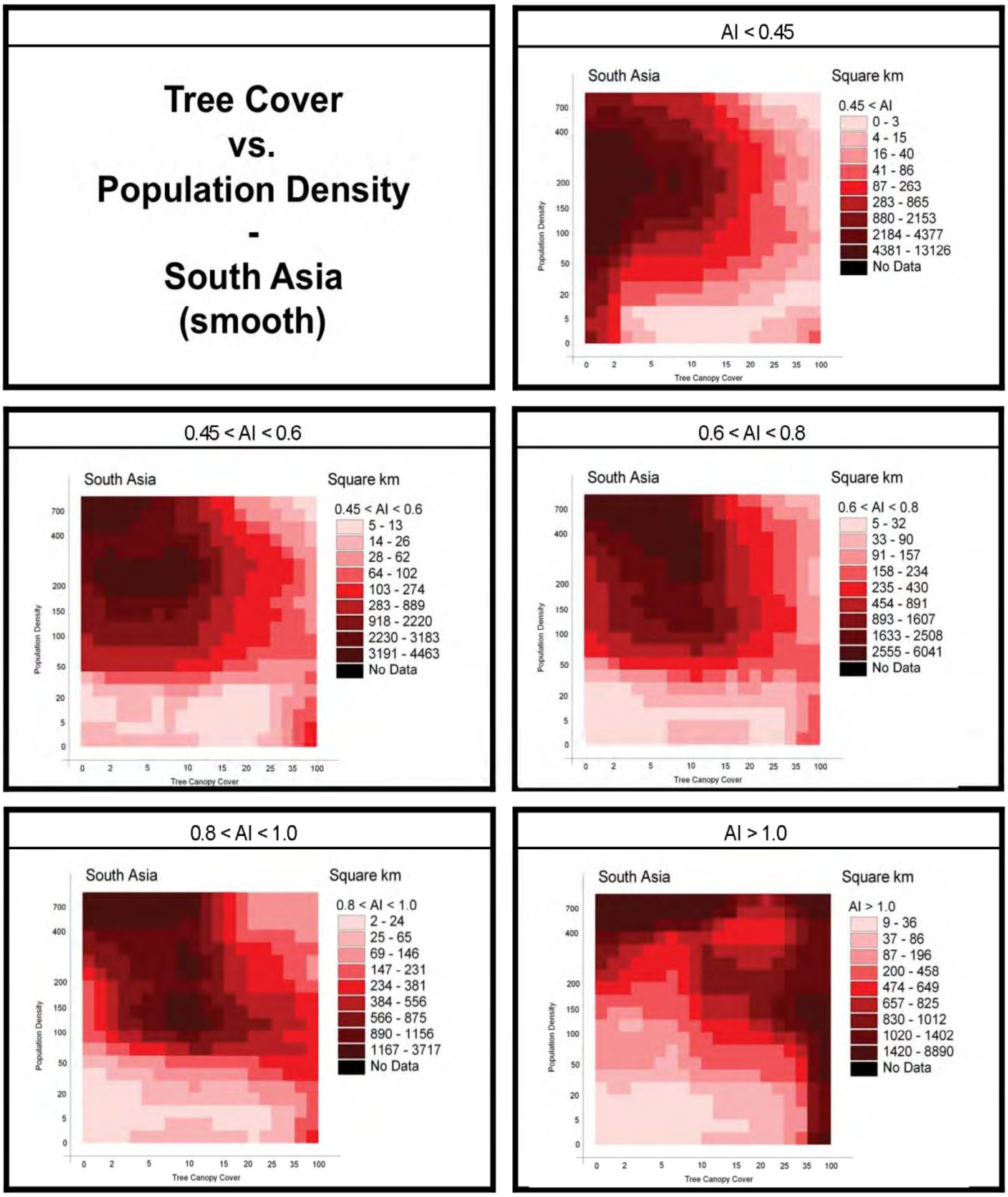


Figure A-5. Distribution of tree cover on agricultural land in South Asia in relation to population density. Darker reds indicate class combinations with more area, while lighter colors indicate classes with less area (in km^2).

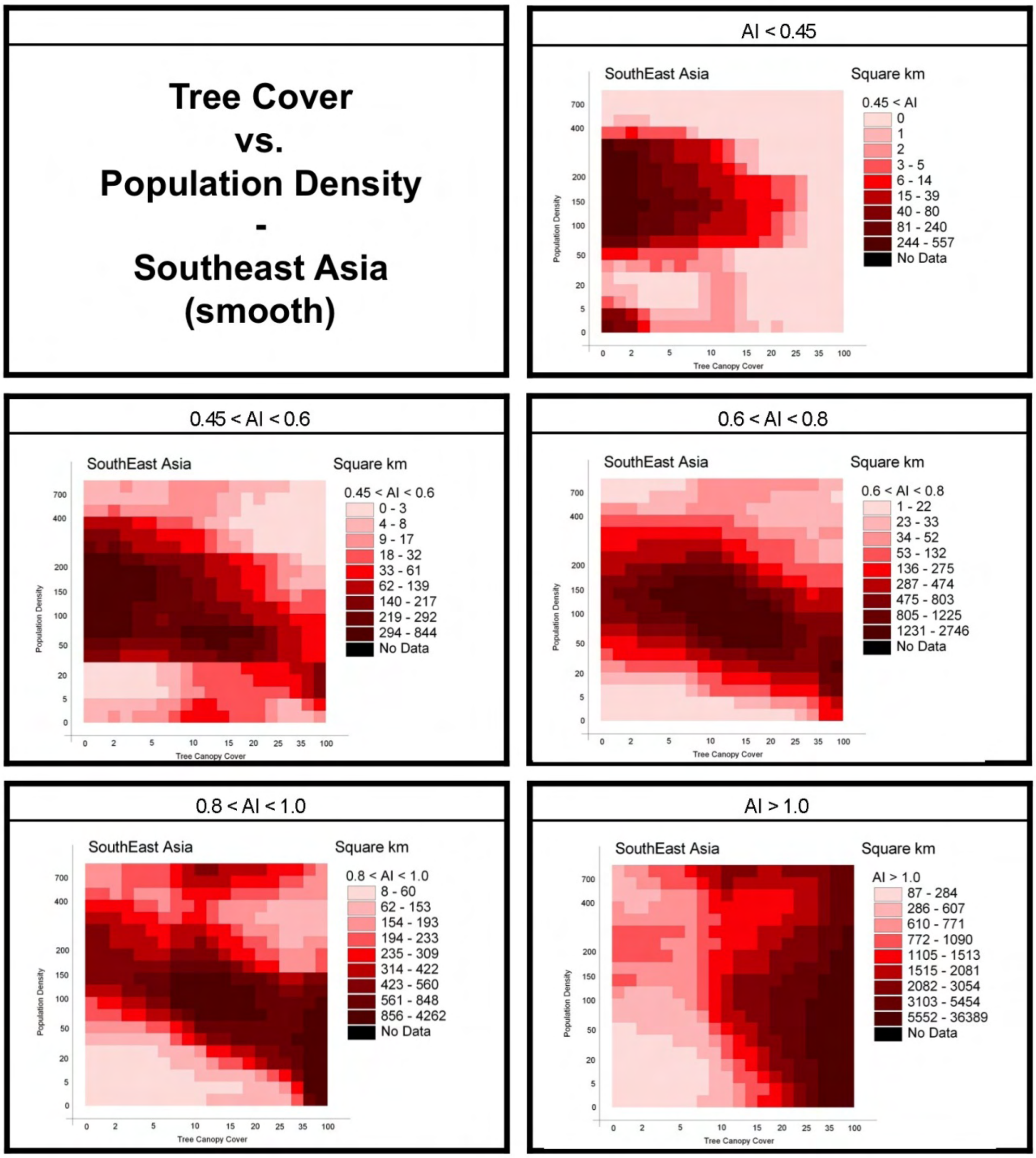


Figure A-6. Distribution of tree cover on agricultural land in Southeast Asia in relation to population density. Darker reds indicate class combinations with more area, while lighter colors indicate classes with less area (in km^2).

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