A Closer View of Smallholder Agriculture in Congo Basin Forests: Use of High Resolution Imagery to Quantify Spatial Relationships of Agriculture with Roads and Land Management After Recent Intensification of Commercial Logging Operations

by

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DEDICATION

To my family, friends and love ones.

In loving memory of William C., Maripaz C., Karla S. and Courtney W., you are always in my heart.

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ABSTRACT

In the Congo Basin, changes in forest policy promoted the development of commercial timber activities and defined different forest-use zones. Timber activities have extended the road presence in the Basin, while zoning has attempted to control where anthropogenic activities are occurring, including smallholder agriculture, an activity considered as one of the main causes of deforestation in the Basin. Therefore, the main concern of the lengthening of the road network is that it could support the development of agriculture. Relationships between roads and agriculture has been studies in other tropical regions, however little work has been conducted in the Basin under the current policies. This study aimed to evaluate the spatial relationships between agriculture, roads, and current land-zoning practices. To do so, twenty-six very-high resolution images, within seven case study sites within Cameroon and the Republic of the Congo were employed to map and characterize agriculture at its smallest size, roads and other anthropogenic activities. Results of multiple analyses indicated that, considering the dominance of small plots (64% <1-ha) agricultural clearings presented characteristics associated with smallholder agriculture. Distance relationships between agriculture and roads indicated that 60% of all clearing occurred near (<1-km) roads, but not all roads were in proximity to agriculture, in special, clearings were more likely to occur near maintained roads: 53% of all clearing were <1-km to a maintained road while only 8% were <1-km to unmaintained roads. Further, Gibbs spatial point pattern modeling methods indicated that that nearness to roads influenced the incidence of agriculture when the following conditions were present: 1) presence of active logging, 2) dominance of maintained roads, and 3) nearness to large towns. Forest-use zoning analysis indicated that most clearings occurred within agricultural friendly zones (non-permanent forest in Cameroon and community development series in Congo) but also clearings occurred within the permanent forest zones (production forest in Cameroon and Congo). In Cameroon, 99% of the clearings within the production forest (n=148) occurred < 3 km from a road, while in Congo, 64% of the clearings within production forest (n=443) occurred at the same distance range; however, analysis suggested that some of the clearings within the production forest could

be associated to transient agriculture conducted by logging workers. Results updated the understanding of agriculture and roads in the Basin, while emphasize the need for further research and resources to integrate agricultural activities as part of the conservation efforts while guaranteeing food security and improving local peoples’ livelihoods.

CHAPTER 1.

VERY HIGH SPATIAL RESOLUTION REMOTE SENSING SHEDS LIGHT ON FINE-SCALE RELATIONSHIPS BETWEEN AGRICULTURE, LOGGING AND ROADS IN CONGO BASIN FORESTS

1. Introduction

Tropical deforestation and degradation has been attributed to multiple underlying and proximate factors, including economic policies, population growth, road-building, logging, and agricultural expansion (Geist and Lambin 2002). Of proximate factors, agriculture expansion, both *in situ* and through colonization, is considered the greatest risk to permanent forest loss (Achard *et al* 2002). Multiple studies have evaluated the relationships between agriculture expansion and road-building in tropical regions (Laurance *et al* 2002, Mertens *et al* 2002), however these relationships vary among tropical regions (Geist and Lambin 2002). Within the Congo Basin, the area of southern Cameroon and northern Republic of the Congo comprises one of its largest remaining significantly intact forest expanses (Bryant 1997, Potapov *et al* 2008b). Here, the extent of agriculture and its relationship to road building is particularly important to examine. Policy in recent decades – promoted by the World Bank – has endorsed economic growth through increased commercial logging (Ezzine de Blas and Ruiz Pérez 2008), which in turn has led to expanded road-building (Laporte *et al* 2007, Wilkie *et al* 2000).

Within the forested parts of the Congo Basin, agriculture has been predominantly for subsistence, based on shifting cultivation systems and the production of grains, roots and tubers, and artisanal cash crops (cocoa, coffee; Tollens 2010). Countries in the region have invested little (<10% of national budgets) in commercial agriculture in recent decades (Tollens 2010); however, any expansion of commercial agriculture quickly contributes to local deforestation rates (Geist and Lambin 2002). While shifting cultivation has historically maintained mostly intact forests, by allowing for regrowth or cleared forest, even though this practice may contribute to deforestation and degradation if clearing and re-clearing expands (Bogaert *et al* 2008, Megevand 2013, Robiglio and Sinclair 2011). New clearings associated with shifting cultivation typically start as small canopy openings and may expand over time into larger mosaics of active agriculture and fallow land (Yemefack *et al* 2006). Therefore, in order to assess the relationship between agriculture and recent road expansion, it is important to observe agriculture inclusive of the smallest rural clearings. Local ethnographic studies suggest that these clearings may occur at sizes of 1 ha or less (Rupp 2011, Yemefack *et al* 2006).

Because of large geographic extents and difficulties of on-the-ground measurements in tropical forests, much of what is known quantitatively of their deforestation and degradation has come from remote sensing (Joseph *et al* 2010, Mayaux *et al* 2005). Studies in Amazonia proposed that reliable assessment of canopy clearings <1 ha may require use of high (HSR ~<10 m) or very high spatial resolution imagery (VHSR ~0.25 – 5 m; Asner *et al* 2002, Hurtt *et al* 2003, Souza and Roberts 2005). In addition to having the spatial detail need to observe agriculture, VHSR sensors facilitate observation of other fine-scale features (Laporte *et al* 2007) such as logging decks and felled trees, farmers' forest paths and dwellings, all potentially useful for verifying agriculture occurrence and patterns. Thus within Congo Basin forests, case study sites using VHSR imagery could function both as a broader geographic extension to local field studies, and as a sample of information at finer detail to supplement mapping from synoptic moderate spatial resolution imagery (MSR ~20-100 m; Duveiller *et al* 2008, Mayaux *et al* 2013, Molinario *et al* 2015, Potapov *et al* 2008b).

The goal of this research was to develop new quantitative information about the spatial characteristics of agriculture over the entire range of clearing sizes, plus new knowledge of relationships between agriculture and roads, within one of the largest still significantly intact forest regions in the tropics. For this purpose, we acquired multiple VHSR WorldView-1 (WV-1) images taken within one year over multiple case study sites in southern Cameroon and northern Republic of the Congo. We started with two overarching research questions: 1) what is the footprint of agriculture in terms of its size distributions and spatial patterns? and 2) how are roads, especially the more recently built parts of the network, associated with occurrence of agriculture? To answer these questions, we pursued four specific objectives:

1. Map and characterize all types and sizes of anthropogenic forest canopy clearings (agriculture, settlements, logging) and transportation corridors (roads and navigable rivers);

2. Quantify and interpret size distributions and spatial patterns of mapped agriculture clearings on the landscape;
3. Quantify the relationships between mapped agriculture clearings and transportation corridors (roads and rivers), by proximity and by characteristics of these corridors.

2. Study area

Seven case study sites (hereafter "sites") were established within a broader study area of 170,215 km2 (Figure 1.1). The broader study area was defined as: 1) within the southeastern Republic of Cameroon (CAM) and northern Republic of the Congo (ROC), 2) within the Northwestern Congolian Lowland Forest ecoregion (Olson et al 2001), 3) dominated by forest cover (Mayaux et al 2003), 4) having low to very low average population density (< 10 inhabitants/km2; CIESIN and CIAT 2005); and 5) predominantly open to commercial or other logging (Mertens et al 2007, Minnemeyer et al 2007). For the sites, twenty-six WV-1 (0.5 m spatial resolution, 0.45-0.90 μm spectral range) panchromatic images (APPENDIX A. were selected from an archive of transects taken during 2008. Each was approximately ~18 x 18 km in area (Figure 1.1). The criteria used to select images were: 1) representation from the geographic extent of the study area, 2) low cloud contamination, and 3) preference for multiple groups of contiguous images. Together, the sites covered 7,529 km2.

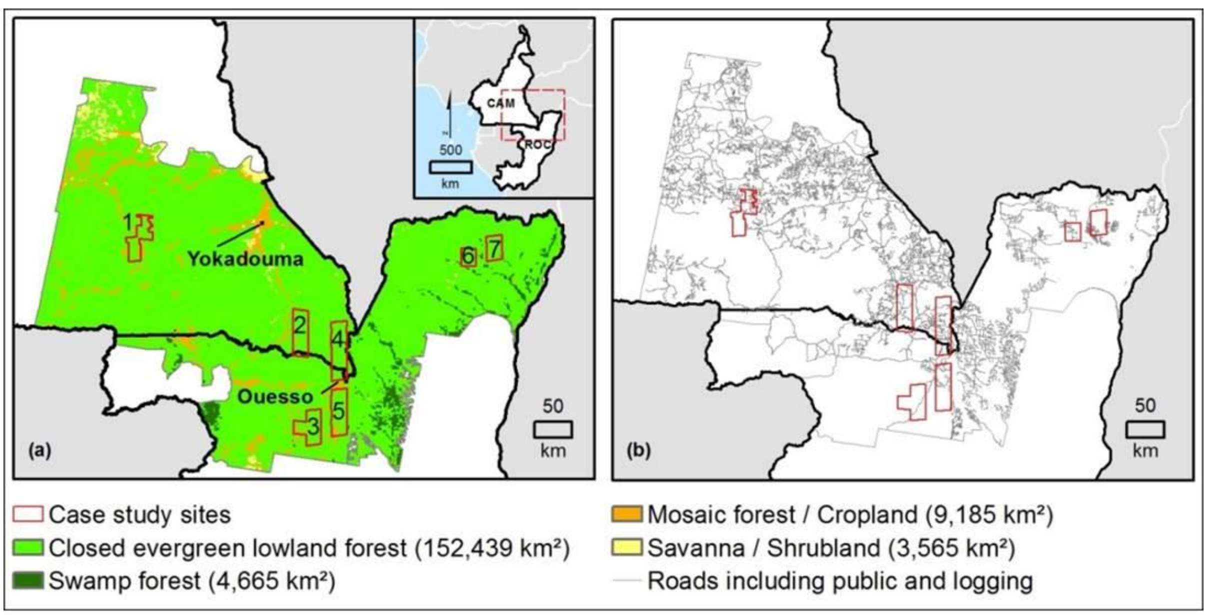

Figure 1.1. Study area: (a) broader study area with 1-km land cover (Mayaux *et al* 2003) and WV-1 sites (numbered red boxes); (b) road network in 2008.

Throughout the broader study area elevation ranges from 300 – 1,000 m ASL (METI-NASA 2008). There are two dry (November-February, June-July), and two rainy (March-May, August-October) seasons (Timah *et al* 2008). The hydrologic network includes tributaries of the Congo River. Lowland tropical evergreen forest, including timber-valuable species, is predominant, with fractions of swamp forest (Vande weghe 2004). While forest cover dominates (Mayaux *et al* 2003), delineations of intact forest landscapes (IFL) show deforestation and degradation in some areas (Potapov *et al* 2008a). With the exception of two large towns (Yokadouma in CAM and Ouesso in ROC), the population is sparsely distributed in rural forest areas or smaller settlements (Wiggins 2000). The small populations embedded within the forest depend on smallholder agriculture (Tollens 2010), along with hunting and fishing activities (Robiglio *et al* 2003, Rupp 2011). Since the late 1990s, the vast majority of the forest within the broad study area (approximately 64%) has been allocated to commercial timber activities (Mertens *et al* 2007, Minnemeyer *et al* 2007), and most of the extraction permits has been allocated to international companies (Ruiz Pérez *et al* 2005). Cash crops are present within the broad study area, but in a smaller extent, i.e. 256 km^2 of land were allocated in ROC for palm oil plantations, equivalent to 0.2% of the broad area extent (Tessa *et al* 2012); in addition, Rupp (2011) indicated the presence of small scale cocoa plantations within forested land. For both countries, commercial agriculture (e.g. oil palm, sugar, rice, bananas) occur outside the denser forested areas, near larger population centers and distribution ports (Tessa *et al* 2012, Feintrenie 2014).

For several of our analyses, we segmented sites by overlaying a 1-km^2 grid over each site. We used the 1-km^2 grid to visually observe spatial patterns of AFCCs and transportation corridors. To evaluate the representativeness of the case study sites within the broader study area, we also calculated and compared road density (km/km^2) within all 1-km^2 grid cells in the case study sites with those in the entire broader study area using roads interpreted from Landsat ETM+ imagery from across the study area for the same year as the WV-1 data. Road density was used for this comparison because of the expected relationship between roads and agriculture, and availability of road density data study area-wide. Mean road density values were similar between the two extents (study area = 0.15 km/km^2; sites = 0.19 km/km^2) when zero grid cell values (cells without roads) were included, and also when zero value cells were excluded (study area = 0.92

km/km^2; sites = 0.93 km/km^2). When road densities for both extents were compared in increments of 0.5 km/km^2 they exhibited very similar distributions (Figure 1.2).

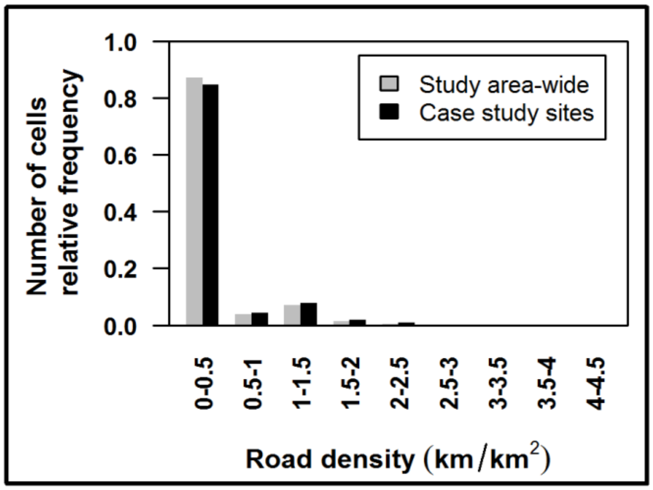

Figure 1.2. Road density distributions for case study sites and broader study area as a test of sites' representativeness. The X-axis gives binned density increments, and the Y-axis the relative frequency of 1-km^2 grid cells.

3. Methods

3.1. Image interpretation and mapping

Schemes for classifying anthropogenic forest canopy clearings (AFCCs) and transportation corridors were developed based on 1) examination of the WV-1 imagery, 2) ~600 geolocated field observations with photographs taken in the broader study area in 2010, and 3) the ecological, anthropological and socio-economic literature (Table 1.1 and Figure 1.3). A protocol for mapping at a scale of 1:1500 was developed based on systematic visual interpretation of the WV-1 imagery. *Agricultural clearings* were identified as the set of individual plots, mosaic plots, and family homesteads, where the latter were labeled dually as agriculture and small settlement. Homesteads were considered the more basic land associated with agriculture, as it contained the family's home gardens living areas (Rupp, 2011), while individual plots, which represent clearings outside homesteads that contain only one season crop and had the potential to become in future mosaic plots contained different crops and/or fallow land (Yemefack *et al* 2006). *Transportation* was considered to be any road or navigable river. For road type, labeling closely followed the definitions in the region's Global Forest Watch (GFW) roads database (Mertens *et al* 2007, Minnemeyer *et al* 2007). Road construction period was assigned by comparing WV-1 imagery with time series Landsat imagery (1975 – 2009). Road transitability (Sessions 2007) was inferred from canopy closure over a road. After initial mapping and classification, multiple iterations of quality checking of the data and labeling were conducted. For a quantitative accuracy assessment, a subset of the geolocated field data was used, supplemented by maps of settlements (Cameroon MINFOF 2010, Republic of the Congo MEFED and CNIAF 2011), and an independent set of multispectral VHSR images (Google and CNES/Astrium 2016).We prepared images in ERDAS IMAGINE (Integraph 2010) and completed mapping in ArcGIS (ESRI 2009, 2014).

3.2. Statistical analyses

We calculated descriptive statistics to quantify characteristics of agriculture, roads, and other mapped features by 1-km^2 grid cell. Number and area of AFCCs were summarized across clearing types and road length distributions were calculated by type, transitability, and construction period. We distinguished results from all grid cells within the total area (TA) of the case study sites from the agriculture-affected area (AgAA), defined as the set of grid cells containing at least one agricultural clearing.

We conducted two point-pattern analysis (PPA) tests, each of which uses a slightly different statistical approach to compare an observed spatial pattern to complete spatial randomness (CSR). For the observed pattern, each mapped individual agriculture plot, mosaic plot and homestead (Table 1.1) was represented by its center location. The quadrat count (QC) test evaluated whether the observed numbers of agricultural clearings within grid cells was homogeneous (evenly distributed on the landscape; H_0) or inhomogeneous (Cressie 1993, Illian *et al* 2008). To test scale sensitivity of the results, we ran the test at 1 km^2 and other cell sizes between 250 m^2 to 2 km^2. We used the Clark and Evans aggregation index (R) evaluated whether the observed pattern was regular ($R>1$, H_0) or aggregated ($R<1$) (Clark and Evans 1954, Illian *et al* 2008). Both teste were conducted employing the spatstat package (Baddeley *et al* 2015) in R with RStudio (R Core Team 2013, Rstudio 2013).

Table 1.1. Classification scheme used to interpret AFCCs and transportation from WV-1 imagery.

Feature	Attributes	Attribute values
		Anthropogenic Forest Canopy Clearings (**AFCC**)
Agriculture clearing	Plot spatial adjacency	-Individual plot: a single agriculture clearing surrounded by forest or other non-agricultural land use -Mosaic plot: groups of two or more agriculture clearings sharing a common edge distinguished by their different vegetation cover (open and burned fields, short/herbaceous, medium-bush and tall/tree crops)
Settlement	Type	-Family homestead: clearing dedicated to smallholder agriculture mosaic plot and living area (house/s); not always adjacent to road transportation -Village: presence of multiple different living areas/buildings and on a transportation route -Town: large settlement with many living areas/buildings and infrastructure; along main public roads
	Number of roofs	N
Logging opening	Type	-Logging opening: small canopy opening with visible felled tree or log. -Logging deck: clearings for the temporary storage of harvested logs
Transportation		
Road	Type	-Main public road (**MPR**): long-distance, wide and permanent roads (usually older roads); connect towns and villages to markets -Auxiliary public road (**APR**): similar to MPR but shorter road segments connecting to MPR -Primary logging road (**PLR**): located mostly within logging concessions; connect logging areas with MPR/APR and markets; relatively permanent and used for multiple harvesting seasons -Secondary logging road (**SLR**): located mostly within logging concessions; connect active harvesting zones with PLR; often used for one or a few harvesting seasons and may not be maintained afterward -Internal network (**IN**): paths that connect settlements with agriculture areas within the forest -Skid trail (**ST**): exclusive to logging operations, used to pull logs from the tree base to the edge of a road
	Transitability	-Open (**O**): Completely visible roadway, without vegetation regrowth or canopy coverage (allowing the roadway to keep dry); high motor vehicle transitability -Partially closed (**PC**): Roadway partially visible and partially covered by vegetation regrowth/canopy coverage; lower motor vehicle transitability -Closed (**C**): Roadway itself is not visible and mostly covered by vegetation regrowth/canopy cover; very low to no motor vehicle transitability
	Construction period	-Road built pre-1991 (**P1**) -Road built 1991-2000 (**P2**) -Road built 2000-2008 (**P3**)
Navigable river	Type	Main waterways (navigable > 10 m width)

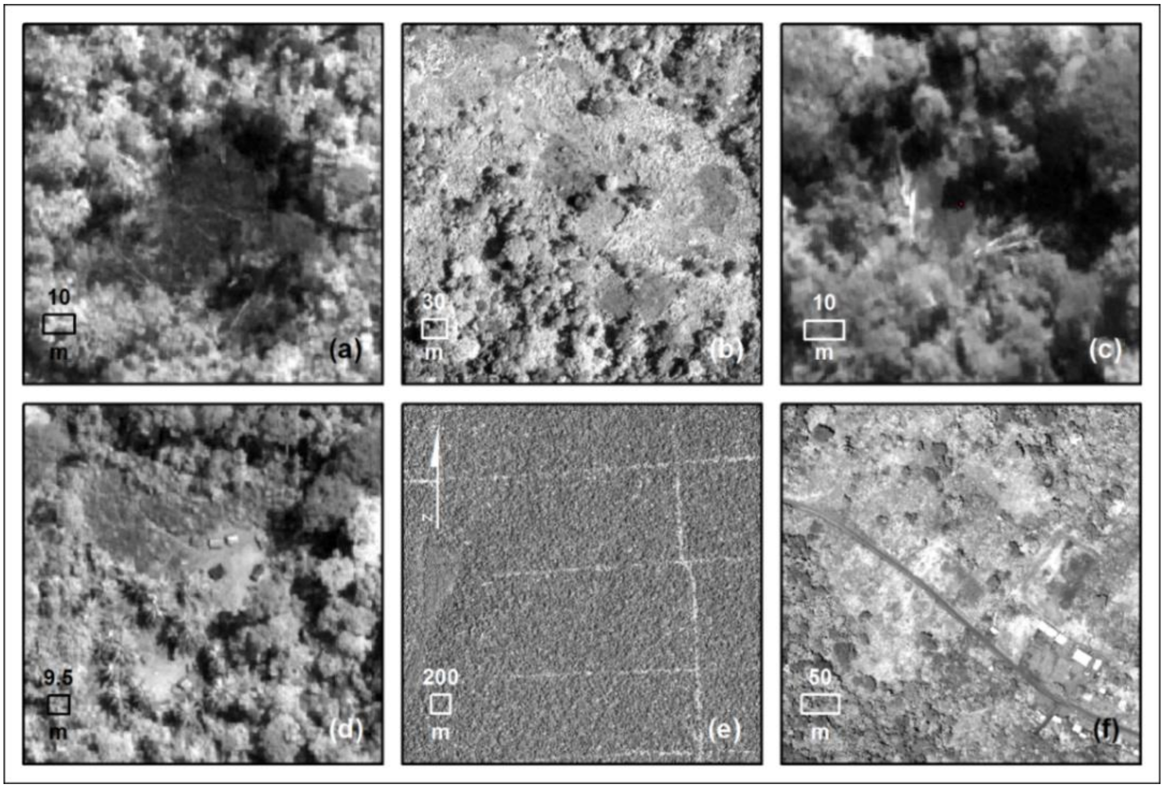

Figure 1.3. Selected examples of roads and anthropogenic forest canopy clearings (AFCC, Table 1.1) on WV-1 imagery: (a) individual plot (recently burned) surrounded by forest, (b) mosaic plot: (several open and short/herbaceous vegetation plots), (c) active logging opening (felled trees), (d) family homestead, (e) primary logging road (PLR: N-S) and secondary logging road (SLR: E-W), and (f) main public road (MPR) plus town.

To understand the association of agriculture clearings with transportation, we calculated the amount of agricultural land (ha) and the number of clearings (n) by proximity of each agricultural clearing to its *nearest* transportation feature. Distance was measured from the center of each agricultural clearing based on Euclidean distance grids created at a 50-m cell size and aggregated to 0.5-km increments. We then characterized these proximity relationships according to transportation type, road transitability, and road-construction period. For those agricultural clearings, whose closest type was a public road (MPR, APR), we also analyzed their proximity to larger settlements (villages and towns).

4. Results

4.1. Mapping accuracy

Based on the set of field and other ancillary and image data, the overall accuracy of the WV-1 mapping was 93.3%, with class accuracies (reported as producer's) ranging from 82.3% to 100% and agriculture accuracy of 93.9% (Table 1.2).

Table 1.2. Mapping accuracy statistics based on a combination of field and ancillary data.

Class	N of test locations	Producer's & overall
Forest	55	92.9
Agriculture	82	93.9
Logging	17	82.3
Settlement	53	90.5
Road	45	100
River	16	93.7
Total/Overall	**269**	**93.3**

4.2. Distributions of agriculture, other AFCCs and transportation

Agriculture was the dominant AFCC type in all sites (Table 1.3), with 1,264 agriculture clearings (individual plots, mosaic plots and homesteads) occupying nearly 3,000 ha in all sites combined. Approximately 70% of the clearings were individual plots, 20% mosaic plots and 10% homesteads. The frequency distributions by size were all positively skewed (Table 1.4). The majority of the mosaic plots consisted of two adjacent subplots (57%). Groups of 3-6 subplots within a mosaic plot were observed in 36% of the cases.

Table 1.3. Statistical summary (area in ha) *of* the AFCC features mapped with WV-1 imagery.

Site	Anthropogenic forest canopy clearings											
	Agriculture				Settlement						Logging	
	Individual		Mosaic		Town		Village		Homestead			
	N	Area	N	Area	N	Area	N	Area	N	Area	N	Area
1	158	138	66	633	3	19	11	9	18	5	2	6
2	148	114	21	64	1	12	11	5	27	15	1	16
3	76	120	21	120	1	5	9	5	3	1	1	8
4	182	198	47	628	---	---	13	14	26	10	1	13
5	152	150	58	301	1	5	9	12	14	3	9	17
6	129	97	29	256	---	---	3	3	17	8	1	1
7	45	30	12	94	---	---	2	3	15	3	--	---
Tota	**890**	**847**	**254**	**2096**	**6**	**41**	**58**	**51**	**120**	**45**	**4**	**61**

Table 1.4. Statistical summary of agriculture clearings grouping and size (ha).

Plot Type	N	Min	Max	Mean	SD	Median	IQR		Skewness
							Q1	Q3	
Individual	890	0.02	32.59	0.95	1.85	0.46	0.24	1.02	8.79
Mosaic [a]	254	0.16	309.05	8.25	23.28	3.45	1.58	6.60	9.57
Homestead	120	0.01	2.56	0.37	0.47	0.21	0.10	0.40	2.66

[a] 254 mosaic polygons contained 918 subplots

Over 1,500 km of roads were mapped within the TA; whereas only 14.5% of the total mapped road length was within the AgAA (Table 1.5). The majority of the road length within the TA was SLR (76%); within the AgAA MPR and SLR were dominant (35% each; Figure 1.4a). In the TA, 42% of total road length was Open, whereas 85% in the AgAA was Open (Figure 1.4b). Within the AgAA roads were about equally likely to have been built in either P1 (49%) or P3 (44%) (Figure 1.4c); for both the TA and AgAA most roads built in P3 were SLR.

Table 1.5. Summary by case study site of the mapped roads and navigable rivers.

Site	Road type length (km)				Rivers (km)	Roads Total (km)
	MPR	APR	PLR	SLR		
1	17.1	4.5	56.7	115.4	21.1	193.6
2	30.1	0.1	32.7	153.4	24.8	216.4
3	41.5				75.3	41.5
4	40.1	9.1	23.2	287.1	48.4	359.5
5	13.0	10.4	34.3	228.7	50.4	286.4
6			31.9	100.4	17.9	132.3
7			27.8	272.4	---	300.2
Total	**141.9**	**24.1**	**206.6**	**1157.2**	**238.0**	**1,529.9**

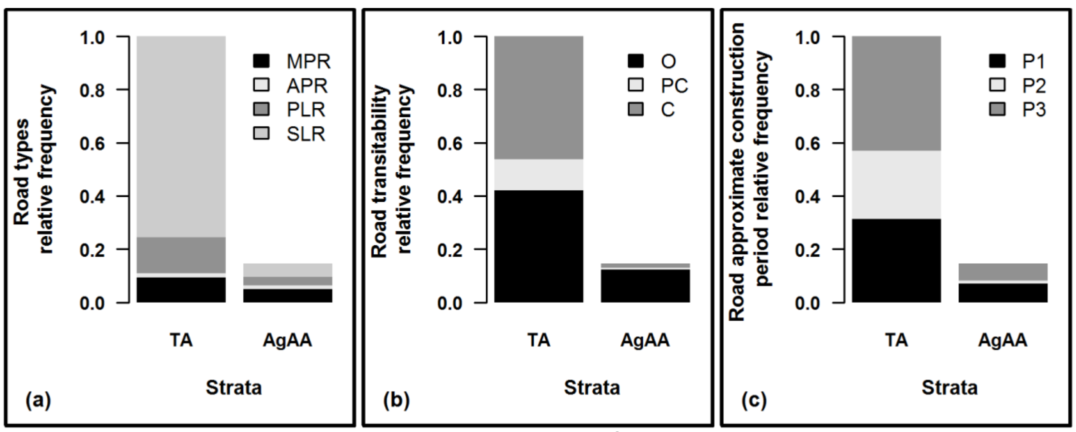

Figure 1.4. Road length relative frequency within the 1-km^2 grid total area (TA) and within the agriculture-affected area (AgAA). Frequency values for the AgAA are shown as the proportion of the total road length. Shown are: (a) road types, (b) road transitability, and (c) road construction period (Table 1.1)

4.3. Agriculture spatial pattern

Within the TA, 76% of the 1-km^2 cells did not contain AFCCs or roads. Some combination of AFCCs and roads was found in 24% of cells, while cells within the AgAA comprised just 6% of the TA. The number of agriculture clearings within the AgAA ranged from 1 to 15 clearings (of varying sizes) per km^2 (Figure 1.5).

Figure 1.5. Density of agriculture clearings by count; density defined as the number of agriculture clearings (individual, mosaic and homestead types) per km^2.

Over the range of scales of observation, the spatial pattern of agriculture clearings on the landscape was inhomogeneous (p<0.05) according to the PPA analysis, thus the null hypothesis (of homogeneity under CSR) was rejected. Results from the Clark-Evans aggregation index (Table 1.6) indicated that the spatial pattern of the agriculture clearings tended to be aggregated for all sites (R<1) when compared with an equal intensity CSR pattern (p<0.05).

Table 1.6. Agriculture clearings Quadrat count (QC) and Clark Evans aggregation index (R) test results.

Site	Quadrat count test (QC)				Clark-Evans aggregation index (R)	
	1-km^2 quadrats (N)[a,b]	Clearings (N)	χ^2	*p*-value	*R*	*p*-value
1	617	242	3,153.8	< 0.001	0.583	< 0.001
2	1,170	196	4,061.1	< 0.001	0.454	< 0.001
3	515	100	1,833.1	< 0.001	0.339	< 0.001
4	1,005	255	4,629.8	0.002	0.460	< 0.001
5	1,114	224	5,855.7	< 0.001	0.375	< 0.001
6	374	175	1,972.1	0.0012	0.369	< 0.001
7	629	72	2,240.2	0.002	0.500	< 0.001

[a] Number of quadrats (number of 1-km² cells) per site varied based on site size. [b] QC results are shown only for the 1 km² quadrat size; the pattern was inhomogeneous at all tested scales

4.4. Proximity relationships

Of the total area (ha) cleared for agriculture, 54.6% was within the first 0.5 km from a road or navigable rivers (46% within 0.5 km of a road), and 93% was within the first 2 km (Figure 1.6). When stratified by individual, mosaic, and homestead types, we observed similar tendencies. For individual plots and homesteads, the largest clearings (32.6 ha and 2.6 ha respectively, see Table 1.4) occurred within the first 0.5 km from transportation. For mosaic plots, the few very large plots (i.e. > 50 ha) occurred within the first 1 km from transportation. Overall, for all plot types, the larger plots were closer to transportation while small clearing sizes tended to occur both near and further from transportation.

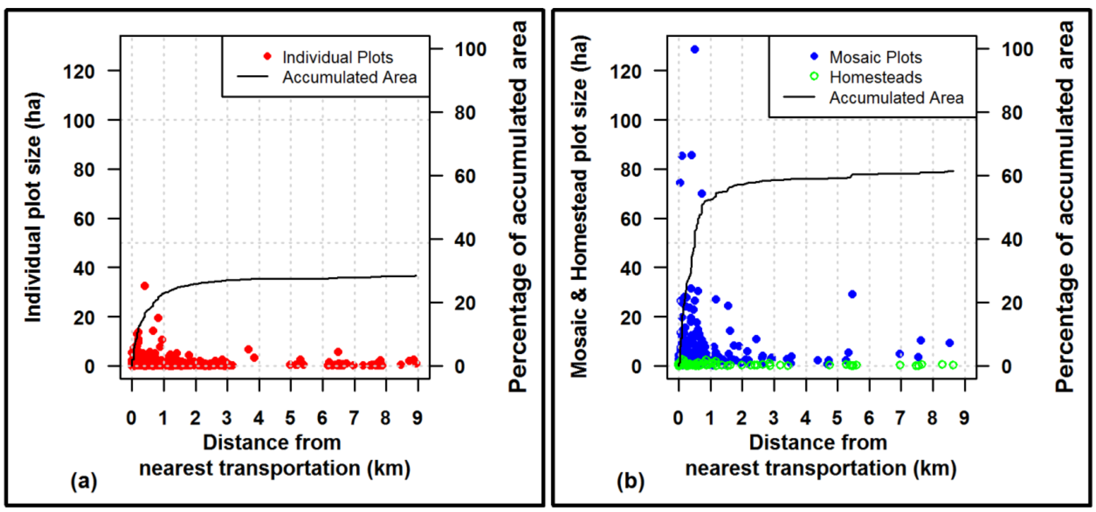

Figure 1.6. Agriculture clearings size plus accumulated area versus distance to nearest transportation (roads and navigable rivers). Shown are relationships for (a) individual (n=890) and (b) mosaic and homestead plot types (n=374; accumulated area totals 100% for a) and b) combined.

By nearest transportation type, 52% of all agriculture clearings occurred within the first 0.5 km from a road and 62% were within 0.5 km of a road or a river. By all transportation types, agriculture plots tended to occur most frequently within 0.5 km from MPR (24%), followed by PLR (12%), SLR (12%), Rivers (10%), and APR (4%) (Figure 1.7a). By road transitability, 46% of agriculture clearings occurred within 0.5 km of Open road types (Figure 1.7b). By road construction period, agriculture clearings within 0.5 km of transportation were most frequently near P1 roads (32%), followed by P3 roads (17%) and very few P2 roads (3%) (Figure 1.7c). Agriculture in proximity to major roads is frequently further influenced by proximity to settlements along those roads (Figure 1.8).

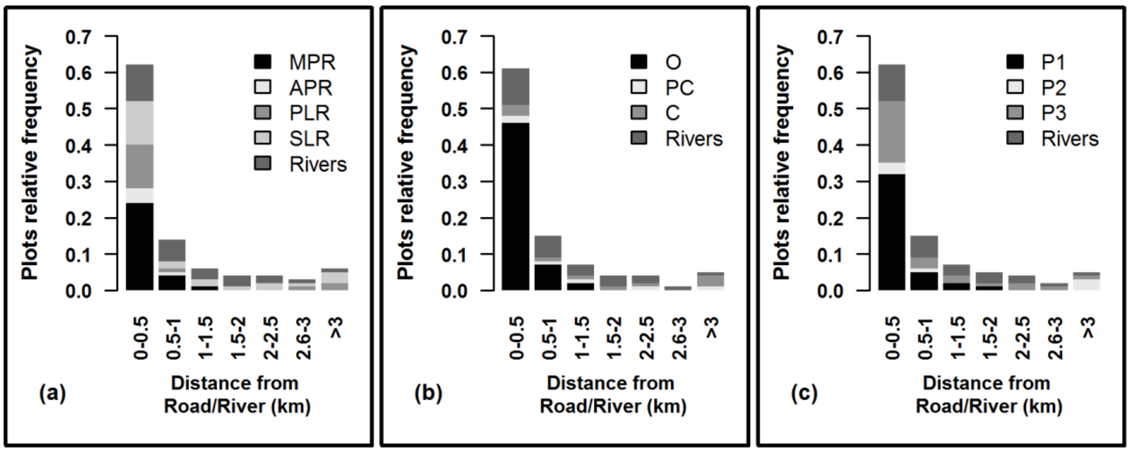

Figure 1.7. Distribution of distances of agriculture clearings to the nearest transportation based on: (a) transportation type, (b) road transitability, and (c) road approximate construction period (see Table 1.1 for abbreviations); navigable rivers are included in all graphs.

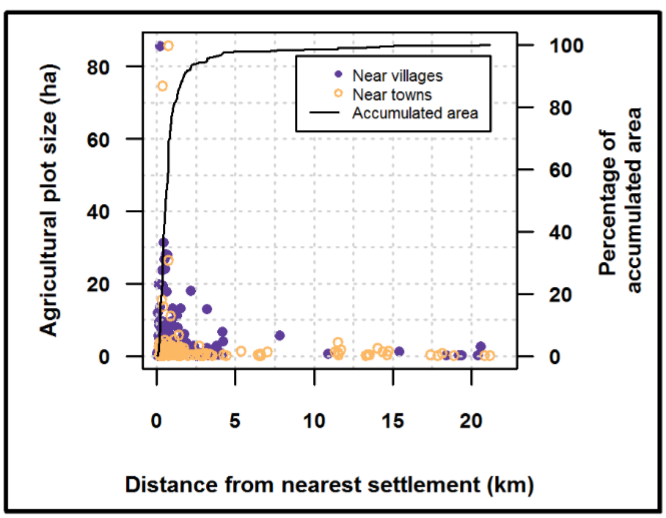

Figure 1.8. The subset of agriculture clearings (individual, mosaic and homestead; n=448) for which the nearest transportation type was a major road (MPR or APR). Shown are clearings size plus accumulated area versus distance to larger settlements (villages and towns).

5. Discussion

5.1. The footprint of agriculture and relationship with roads

By executing the most extensive known fine-scale analysis of the sizes, spatial characteristics, and spatial relationships of agricultural activities within Congo Basin forests, we were able to identify clear size variations by clearing type and associations among agricultural activities and with roads. Homesteads (n=120) were the smallest (75%<0.4 ha and 95%<1.2 ha), similar to local field observations of Rupp (2011) who reported home gardens as small as 0.5 ha. Results showed that 26% of all area cleared by individual and mosaic plots was <1 km from a homestead, underscoring the importance of rural family-based farmers for the use and management of forest resources. Individual plots (n=890) tended to be larger than homesteads but smaller than mosaic plots, with 75%<1 ha and 95%<3 ha. Mosaic plots (n=254) were the largest, with 75%<7 ha and 95%<26.6 ha. Most mosaic plot sizes (83%<10 ha) were similar to those described by Yemefack et al (2006), who reported shifting cultivation mosaic plots as large as 10 ha. One large mosaic clearing (~300 ha) on the outskirts of the town of Ouesso was identified. Only 13% of this clearing was recently cleared or planted, while the majority (87%) was mixed herbaceous and shrub vegetation.

Other researchers have suggested a spatial pattern of agriculture in the Congo Basin consisting of “corridor” and “diffuse” components (Geist and Lambin 2001, Mayaux et al 2013, Mertens and Lambin 1997). Corridor patterns in tropical regions have been described as cleared areas along major routes that connect settlements, while a diffuse pattern refers to apparently random sets of small clearings within the forest (Borrego-Lorena 2008, Mertens and Lambin 1997). Our analysis refines this for the study area, indicating that agriculture mostly occurred in an aggregated pattern along some major roads segments though not their entire road extent, thus not a continuous corridor pattern. It also was observed that larger settlements also positively influenced aggregation of agriculture along those road segments. The PPA statistics confirm a lack of randomness of the agricultural pattern. The inhomogeneity of the pattern, could be related to migration patterns during the slavery trade, in where new settlers scattered in low densities within the dense forest areas (Dounias and Lecrerc 2006).

Overall, the observed footprint of all anthropogenic activity for the case study sites was low (76% of the TA 1-km2 grid cells had no roads or AFCCs). Within the remaining 24% of the TA, extensive land conversion was not observed. Instead, observations showed a landscape characterized by shifting agriculture practices and shifting logging activities, surrounded by large expanses of mostly intact forest but also by secondary forest patches (near logging roads and settlements). Since the date of the imagery, the logging road network has continued to expand (Brandt et al 2014, Kleinschroth et al 2015) as timber companies complete their first cycle of extraction rights (permits are granted for a once-renewable 15-year harvesting cycle; Karsenty et al 2008).

The dominance of logging roads on the landscape within the sites is consistent with observations by (Laporte et al 2007), who reported a high incidence of newer road networks (built after 2000). This is attributed to the establishment of large extractive timber concessions in the late 1990s (Ezzine de Blas and Ruiz Pérez 2008). Brandt et al (2014), also reported various types of forest disturbances in close proximity with roads. The detailed classification scheme in our research allowed us to further explore the proximity relationships of agriculture and roads by considering more specific road characteristics Agriculture was most frequently found in proximity to older public roads, but also in smaller proportions with the newest logging roads. Agriculture tended to occur near open roads regardless of road type or era, making inferred road transitability a key factor.

Based on our analysis of the data aggregated to 1-km2 grid, only 15% of the total road network was within cells affected by agriculture (AgAA). Despite the dominance of logging roads, only 27% of all agriculture clearings occurred within the first km from a logging road as the closest transportation feature (roads and rivers); this statistic dropped to 6% (or 7.8% as a percent of just road transportation) when logging road transitability was low. The high incidence of agricultural clearings along public roads has its roots in the regroupment policy, enforced during colonial times, where villages were relocated to designated areas and along roads for census and taxation purposes (Giles-Vernick 2002). Agricultural clearings near open logging roads may be associated with the need to supply food to logging workers while timber extraction activities are active; this has been documented in the neighboring Democratic Republic of the Congo (DRC) by Molinario et al (2015). The fact that agriculture does not occur as a continuous corridor along major roads could also be due to farmer’s preferences for particular conditions (e.g. availability of good soils) not evaluated by this study (Brown 2006, Geist and Lambin 2001). Overall, these results support conclusions by Rudel (2013) and Mayaux et al (2013) regarding the effect of roads as a potential driver of deforestation in the region – they suggest that by itself a road, which can provide access to land and markets, must interact with other incentives (e.g. population growth, access to credit) to result in agricultural expansion.

5.2. Methodological observations

Within the study area, the isolation and often-small spatial footprint of local farming populations make their systematic field study – or even discovery – difficult. Field-based ethnographic works consider some spatial characteristics but are mostly focused on local sites (Robiglio et al 2003, Rupp 2011, Timah et al 2008). Use of VHSR imagery allowed for observation of patterns over multiple large case study sites within a broader area and in an unbiased way rather than biased to areas of feasible ground access. Further, using VHSR imagery associated features could be seen within meaningful distances not easily visible to a ground observer. MSR sensors provide broader coverage and are reliably used to detect agricultural patches in the region greater than ~1 ha, especially in fragmented forest (Thenkabail 1999), but do not capture the entire range of agriculture clearing sizes. VHSR imagery allowed for mapping clearings no matter how small (75% of individual plots were < 1 ha). Additionally, while roads are mostly visible on MSR imagery (Laporte et al 2007), features such as footpaths, trails or buildings are not (Hayes et al 2002). VHSR imagery allowed for observation of skid trails, felled logs, forest footpaths, individual houses and other fine-scale features differentially associated with logging or with agriculture; these were critical to accurate labeling of many AFCCs during the classification process.

Even 0.5 m VHSR panchromatic imagery had some limitations. As with other passive optical imagery, crops underneath a tree canopy are difficult to observe (Cordero-Sancho and Sader 2007). Cocoa tree crops are grown under or interspersed with other trees (Asare 2005); those that were not part of discernible agriculture mosaic plots in the sites may have been missed. Due to widely distributed case study sites, including some with low accessibility, field observations for validation were restricted to a subset of sites (four of seven). The use of a spatial sample of sites also meant that rare but possibly regionally important features in the broader study area could be missed. For example, the sites did not include the few known commercial agriculture plantations (oil palm, ROC), or the two large towns per se (site 4 included a very large mosaic clearing on the outskirts of one of those towns). Given the above advantages and limitations, VHSR imagery and mapping may be considered complementary to both in-depth fieldwork and regionally synoptic MSR imagery mapping – and vice versa.

6. Conclusions

Based on a quantitative analysis of agriculture clearings and settlements, findings showed that seven case study sites in the central Congo Basin retain very typical characteristics of a rural landscape, this even after recent logging road intensification. Roads, shifting agriculture (and logging) characterized the landscapes, rather than extensive land conversion. Statistical tests of spatial clustering confirmed that agriculture occurred in an inhomogeneous-aggregated pattern, and when compared with visual observations, suggested that proximate features on the landscape (e.g. roads and larger settlements) are associated with the pattern of agriculture occurrence. Proximity analyses confirmed that agriculture occurred close to transportation corridors (roads and rivers), especially when roads were older public roads, and when they were open (no canopy regrowth). Results also showed that agriculture clearings frequently occurred near open logging road types built post-2000, suggesting that during the more recent era, newer roads and logging activities have indeed influenced the presence of agriculture. However, the low association between agriculture and logging roads having partially or fully regrown canopies suggests that the relationship between logging activities and agriculture may also often be transient. The use of VHSR remote sensing for mapping will likely expand in the Congo Basin region, including to larger contiguous mapped areas, greater use of multi-spectral modalities (Douard and Hanson 2014) and repeat assessments of change. The results of this study using 0.5 m VHSR panchromatic imagery to focus on agriculture occurrence over its entire range of sizes, and to quantify its spatial patterns and relationships with road characteristics, should inform future mapping and modeling objectives.

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CHAPTER 2.

A SPATIAL MODEL TO ASSESS THE INFLUENCE OF ROADS ON THE INCIDENCE OF SMALLHOLDER AGRICULTURE IN FORESTED AREAS OF THE CONGO BASIN

1. Introduction

For almost two decades, road presence within the Congolian lowland tropical moist forest has been increasing, largely to support commercial timber extraction activities (Laporte *et al* 2007). Globally, roads in tropical forest areas have been identified as a driver of deforestation (Geist and Lambin 2002), and they facilitate the spread of agriculture, urban development, and other anthropogenic activities (Laurance *et al* 2002, Etter *et al* 2006, Wyman and Stein 2010). Despite the extension of the road network within the Congo Basin forests, recent deforestation rates in the Basin are lower than deforestation rates observed in other tropical regions that had also experienced commercial timber activities (Arima *et al* 2005, Mayaux *et al* 2005, Rudel 2013, Kim *et al* 2015). Nevertheless, a recent land-cover change study in the Basin suggested an increase in the deforestation rate, from 0.09 % (period 1990-2000) to 0.17% (period 2000-2005; Ernst *et al* 2012). Mayaux *et al* (2013) warned that despite the low deforestation rates in the Basin, a "*delayed deforestation*" process could occur given its high and growing density of roads.

Contemporary understanding of the relationships between roads and agriculture in tropical regions is summarized in the seminal work by Geist and Lambin (2002). The authors indicate that road construction in forested areas may act as a "catalyzer" for land clearing when occurring in conjunction with a combination of underlying drivers (i.e. policies that provide access to financial credit) and proximate drivers (i.e. settlement growth) that encourage clearing. The authors also emphasized that no single factor can be solely responsible for land clearings. In the Basin, the increase in deforestation rates was associated with infrastructure development, subsistence agriculture, and collection of fuel wood (Ernst *et al* 2012); therefore, considering that the livelihoods of rural communities in the Basin depend on smallholder agriculture (Tollens

2010), it is of great relevance to understand the current relationships between farmers and the expanding network.

Assessment of the role of roads and agriculture has relied on the use of spatiotemporal data from diverse remote sensing platforms (Baccini *et al* 2008, Wyman and Stein 2010, Getahun *et al* 2013). Data derived from those platforms have been analyzed with non-parametric (e.g. Barni *et al* 2014) and parametric (e.g. Freitas *et al* 2010, Kirby *et al* 2006) models to assess the relationship between roads and deforestation. Generally, with parametric methods (e.g. logistic regression), binary land cover classes (forest/no forest) are evaluated as a function of proximity to roads and other independent variables (e.g. see works by Alvarez and Naughton-Treves 2003, Bax *et al* 2016, Wyman and Stein 2010). Non-forest classes comprised different land cover types (e.g. pasture, agriculture, built; as seen in Wyman and Stein 2010), thus, road inferences are related to the condition of land that has been cleared but inferences would not necessarily explain the role of roads on a specific use (e.g. smallholder agriculture).

Studies that had assessed the relationship between roads and agriculture in the Basin suggested that roads were favoring the development of agriculture by migrants but with little effect on local subsistence agricultural markets (Mertens and Lambin 2000); this study was based on multitemporal satellite data (several periods between 1973 and 1996) under the assumption that most of the non-forest classes were associated with smallholder agriculture. However, these inferences do not reflect the increase in road construction after 2000 (Laporte *et al* 2007). Analysis of the role roads and agriculture in denser and isolated areas of the Basin has different challenges, including the detection of the range of agricultural clearings types and sizes. Plot sizes can be smaller than 0.5 ha (Rupp 2011); thus, use of moderate resolution sensors may provide inconsistent observations for clearings <1 ha (Thenkabail *et al* 2004). Therefore, this study relied on data derived from very high resolution (VHRI) which has the capacity to detect small canopy clearings over relatively extensive land areas (Asner *et al* 2004).

Selection of statistical analysis considered methods associated with presence data (i.e. the spatial location of agricultural clearings), which included: generalized linear models (GLM) generalized additive models (GAM), maximum entropy (Maxent) and spatial point pattern analysis (PPA) methods. The first two types (GLM and GAM) require the generation of a set of pseudo- absence data, as they are not strictly presence data methods; however it has been argued that sampling design and the number of pseudo observations could influence inferential results

(Chakraborty *et al* 2011). Although Maxent models have been widely employed in species distribution studies, inferences are suspected to be sensitive to spatial autocorrelated data (Elith *et al* 2011); with mechanisms to correct for it, mostly reliant on distance base sampling strategies which could considerable reduce the number of observations used in the model (Halvorsen *et al* 2016). PPA modeling methods have been also proved useful in species distribution studies (e.g. Law *et al* 2009, McIntire and Fajardo 2009, Funwi-Gabga and Mateu 2011), as well in the assessment of conditions associated with settlement establishments in archeological studies (Eve and Crema 2014); however, at difference with Maxent, PPA modeling methods can statistically account for spatially autocorrelated data while assessing the effects of different covariates (Baddeley *et al* 2013). Thus, PPA models, in specific Gibbs modeling methods were employed to assess the relationships between the incidence of smallholder agriculture and proximate factors of accessibility by different road properties (type, construction period and maintenance) plus a set of environmental and social variables. To do so, I proposed an explanatory model for the location of smallholder agriculture aimed at answering the following questions:

1. Do roads present within the forested areas of the Congo Basin explain the incidence of smallholder agriculture?
2. Are specific road properties more likely to be associated with smallholder agriculture?
3. How important are environmental and social characteristics in the incidence of smallholder agriculture?

2. Methodology

2.1. Study area

The study was conducted within seven case study sites (hereafter “sites”) within the forested Congo Basin. The combined extent of the sites was 7,533 km² with an average area of 1,072 km². Three sites are in the Republic of Cameroon (CAM) and four are in the Republic of the Congo (ROC). The Cameroonian sites are in the East province, one in the Haut-Nyong district (Site 1) and the Boumba et Ngoko district (Site 2 and Site 4). The Congolese sites are in the Sangha (Site 3, Site 5) and in the Likouala departments (Site 6 and Site 7; Figure 2.1). Sites are representative of forest use, including for commercial timber extraction activities, a dominant activity within the basin (Laporte *et al* 2007). Characteristics among sites include low elevations (between 320 to 830 m ASL), relatively gentle topography (average ~ 5%) and the presence of a dense hydrographic network, ranging from small streams to large tributaries of the Congo River (Farr *et al* 2007). Land-cover is dominated by broadleaved evergreen forests with some areas of swamp forest (near rivers) and mosaic cropland (trees, shrubs and crops) (Mayaux *et al* 2003).

Although even today the forest within this region of the Congo Basin is considered mostly intact (Potapov *et al* 2008a), humans and agriculture have been present for over 3000 years ago (Willis *et al* 2004, Brncic *et al* 2009). Farming practices in the Basin relied on different forms of slash and burn agriculture (Miracle 1967). Current forest peoples and communities include: 1) nomadic and semi-nomadic groups whose livelihoods are associated with hunting and gathering activities and 2) villagers, whose livelihoods depend on the production of subsistence and small cash agricultural crops. The livelihoods of both groups have exhibited increasingly close ties regarding exchange of knowledge, cooperation and trade (Hardin *et al* 2008).

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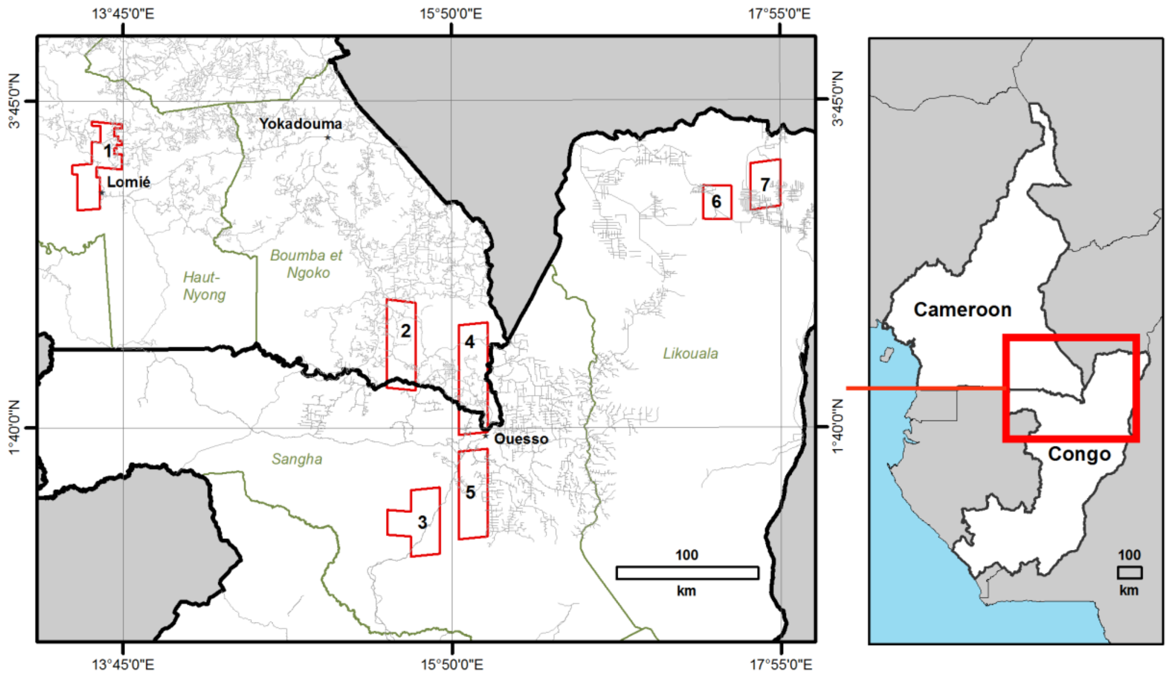

Figure 2.1. Location of the seven case study sites. Left panel shows location of case study sites (each site is delimited by red boxes and numbered 1 to 7) plus country and administrative boundaries and roads (Mertens *et al* 2012a, 2012b). Right panel shows the location of the broader study area within Cameroon and the Republic of Congo.

2.2. Agriculture incidence conceptual model

The proposed agricultural statistical model and variable selection was supported by a conceptual model (CM). The CM in turn was based on an extensive literature review of studies that had investigated forest communities, their livelihoods and agricultural practices, with preference given to studies conducted within the same region as the present case study sites. The CM considered a set of environmental, social and accessibility conditions.

Environmental conditions were represented with proxy variables for soil fertility and soil drainage. Clearings initial levels of *fertility* are important because use the use mineral fertilizer are not a common practice in the region (Wiggins 2000). Thus, farmers' decisions of where to clear land for agriculture depends on fertility indicators (e.g. the color of soil; fallow age; Brown 2006). Fallow age and level of canopy coverage are considered indicators of soil nutrient content, this because as canopy closes, the accumulation of biomass and organic matter increases (Guariguata and Ostertag 2001). In addition, fallow age also influence the required workforce, this as clearing activities do not relied on the use of machinery, which influence preferences for land that has recovered some levels of fertility and also that it is easy to clean (Wiggins 2000, Dvořàk 1992). A database of the percentage of canopy of canopy coverage was used as a proxy for fertility. In the model, it was expected that incidence of agriculture would be associated with moderate to low levels of canopy coverage. *Soil drainage,* considers the preference for well-drained soil conditions to avoid root water damage, especially in a region with a dense hydrological network (Giles-Vernick 2002). Soil drainage was assessed with the use of the topographical wetness index (TWI), which describes the soil saturation based on terrain conditions (Wilson and Gallant 2000). In the model, it was expected for clearings to prefer well-drained soils (low TWI values).

Social conditions were represented with the variables proximity to settlements and population density. *Proximity to settlements* considered that year-round crops are expected to occur in close proximity to families living quarters (within about 3 km; Rupp 2011, Robiglio *et al* 2003). In the model, it was expected a higher incidence of clearings near settlements. *Population density* influenced the amount of land required to satisfy demand (Lambin *et al* 2000) for both subsistence and likely small cash crop agriculture. It was expected that the incidence of agriculture would be influenced by locations near high population areas. Accessibility conditions considered proximity to navigable rivers and roads. *Proximity to rivers* accounted for traditional transportation ways that facilitated the movement of people, trade and access prior the presence of roads (Justice *et al* 2001). It was hypothesized that isolated communities and their crops were more likely to be near rivers. *Proximity to roads* considered the recent increase of roads in the region and the effect of this road network on access to land for agriculture use (Lambin and Geist 2003, Laporte *et al* 2007). Historically, the use of roads by peoples and communities in the region is related to *regroupement* policies imposed under the European colonial rule; these policies encouraged the relocation of settlements along the then newer roads (Giles-Vernick 2002). Based on proximity analysis results (see Chapter 1, Section 4.4), it was hypothesized that agriculture was more likely to occur near older public roads but specially maintained ones (free of canopy coverage). Figure 2.2 summarizes the conceptual model and expected responses.

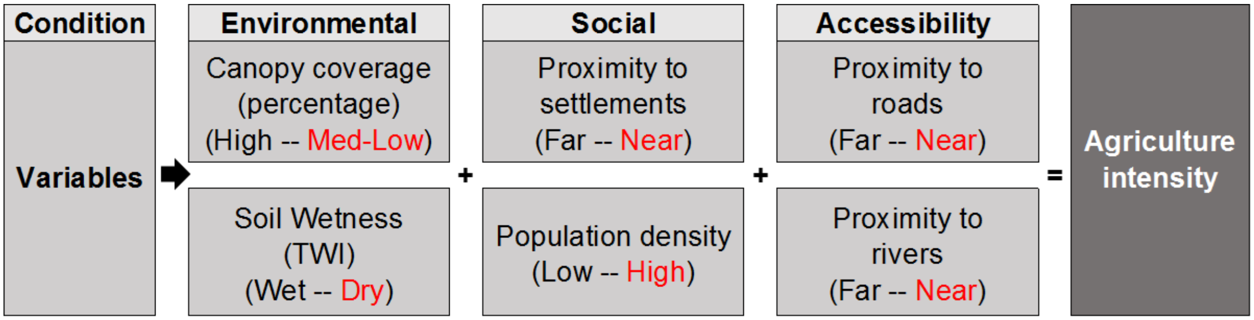

Figure 2.2. Agriculture conceptual model: each condition is represented by two variables, and for each variable the figure indicates the variable quality that would likely favor (*red-italics*) the presence of agriculture clearings. Roads were further evaluated by their specific properties: type, construction period and maintenance (not shown).

2.3. Data

Agriculture and other landscape features in the sites were mapped with twenty-six World View-1 (WV-1) images (0.5 m resolution, circa 2008). Mapping was based in a detailed anthropogenic canopy clearings classification scheme (see Chapter 1, Section 3.1 and APPENDIX C.). I used on-screen digitizing in ArcMap (ESRI 2009, 2014) to map the different features at a scale of 1:1,500 meters. Points were used to represent agriculture clearings (Figure 2.3), settlements, and roofs within settlements. Roofs were mapped as a proxy to describe population size. Lines were used to represent roads and road segments were characterized by three properties, 1) road type, 2) road construction period, and 3) road maintenance (Table 2.1). Navigable rivers (riverbed more than 10 m wide), were mapped as polygons. Mapped agricultural clearings represented individual clearings (n=890, 75%< 1.02 ha), mosaic plots (n=253, 75% < 6.3 ha) with at least two adjacent clearing with different vegetation cover (57% had 2 clearings, 20% had 3 clearings, remaining 23% had between 4 to 27 clearings) and homesteads which contain land for family home gardens (n=120, 75% < 0.40 ha).

Data derived from WV-1 imagery were employed to define the location of agricultural clearings and to represent social and accessibility conditions. Euclidean distance grids (30 m resolution) were created to represent proximity to settlements, rivers and roads, while roofs were used to create density surfaces. Environmental conditions were represented with auxiliary databases. For fertility, the database Vegetation Continuous Fields (Sexton *et al* 2013) was employed, it was originally derived from Landsat products (TM and ETM+) and for this study, it was modified with a 5x5 average kernel filter to assess the surrounding conditions of the mapped clearings. *Soil drainage* variable used the TWI derived from SRTM data (Farr *et al* 2007).

Details of the creation of each variable is summarized in Table 2.2 (see Table E.2. for summary statistics of the variables used in the model).

Table 2.1. Road types and properties used to characterize mapped road segments.

Road main property	Road sub-properties	Acronym	Definition:
Type	Public roads	PUB	Connect settlements with markets
	Primary logging roads	PLOG	Used to move timber from forest to markets. Employed for multiple harvesting seasons.
	Secondary logging roads	SLOG	Used to move logs from forest to PLOG. Roads are only open and maintained while timber extraction is active.
Construction period	Before 1990	PER1	Roads built before 1991
	1990-2000	PER2	Roads built between 1991 and 2000
	2000-2008	PER3	Roads built between 2000 and 2008
Road maintenance	Maintained	MNTD	Roads free of canopy cover
	Unmaintained	UMNTD	Roads partially or completely covered by tree canopy coverage

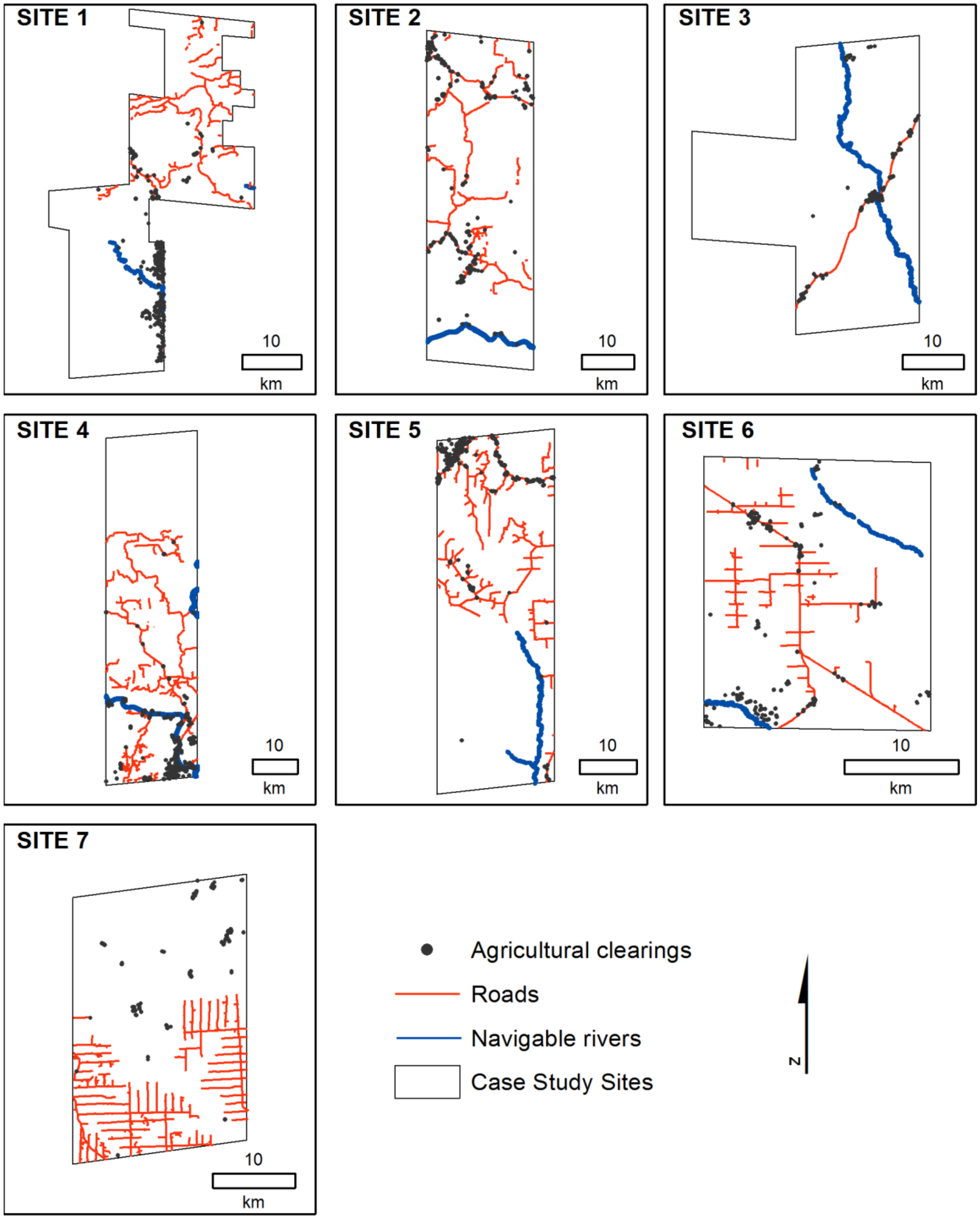

Figure 2.3. Location of agricultural clearings and transportation networks (roads and navigable rivers) within case study sites.

Table 2.2. Characteristics of the spatial databases employed to model the conditions affecting the incidence of smallholder agriculture in forested areas within the Congo Basin forest.

Condition	Variable	Acronym	Database	Description	Creation / Manipulation	Original Source
Environmental	Percentage of canopy coverage (Vegetation continuous fields)	CFF	Landsat TM and ETM + Vegetation Continuous Fields	Originally each pixel represents the percentage (0-100) of tree canopy coverage, including all vegetation greater than 5 m height. Imagery circa 2000 and 2005.	Use of a 5 x 5 kernel average function, with the purpose to represent nearby canopy coverage. Procedure was conducted in ArcGIS (ESRI 2014).	(Sexton *et al* 2013)
	Topographical Wetness Index	TWI	Digital elevation model	Pixels with low values indicate water accumulation (poor drainage) and pixels with larger values indicate water movement (better drainage).	Derived from SRTM data. Procedure combined information from flow direction, flow accumulation and percentage of slope layers in ArcGIS (ESRI 2014). Original pixel size was 90 m, resampled to 30 m	(Farr *et al* 2007)
Social	Population density [a]	POPD	Roofs	Roofs within settlements x-y location used as a proxy of population density Units: km^2.	Created with functions *bw.diggle* and *density*, the first defined the smoothing bandwidth value, the second used this value to create a raster grid. Procedure conducted in spatstat package in R (Baddeley and Turner 2005, R Core Team 2013).	World View-1 panchromatic imagery (2008)
	Distance to settlements	DSET	Settlements	Settlements x-y location Units: km	Created with Euclidian distance function ArcGIS (ESRI 2014) Pixel size 30 m	
Accessibility	Distance to roads	DARO	Roads	All roads and then each one of the road property Units: km		
	Distance to navigable rivers	DRIV	Navigable rivers	Units: km		
	Road density	RDEN	Roads	Units: km/km^2	Created with function line density in ArcGIS 10.0 (ESRI 2014), employing a with a 1-km search radius. Pixel size 30 m	

Notes: [a.] Density layers were calculated individually for each site, except for sites 4 and 5. Density for sites 4 and 5 included information from these two sites plus information from the city of Ouesso. This was done with the purpose to provide a more complete account of population as the two sites and Ouesso were near each other.

[b.] When a model evaluated a specific road property (e.g. proximity to maintained roads), the effect of the non-evaluated roads (e.g. unmaintained roads) was assessed in the model by including the non-evaluate roads with a density (not distance) to avoid collinearity.

2.4. Analysis based on a Gibbs spatial point pattern model

Gibbs models are part of spatial point pattern analysis methods (PPA). A spatial point pattern is defined by a set of spatially-referenced events ($\boldsymbol{x}$, with x-y locations), within a bounded region ($\boldsymbol{w}$) (Illian *et al* 2008). The window is a part of an "*n-dimensional*" space, and $\boldsymbol{x}$ is a realization of finite point process (**X**), and both elements occur on a dimensional space ($\mathbb{R}^d$, where $d \geq 1$) (Baddeley *et al* 2013, Diggle 2003). A spatial point pattern is expressed as follows:

$$\boldsymbol{x} = \{x_1, \dots x_n\}, \ \boldsymbol{n} \geq 0, x_i \in \boldsymbol{w} \qquad \text{(equation 1)}$$

where: $\boldsymbol{x}$ indicates a set of a set of events, $\boldsymbol{w}$ indicates the window of observations and $\boldsymbol{n}$ indicates the number of observed events within the pattern.

A PPA assumes that $\boldsymbol{x}$ follows a Poisson distribution and its spatial distribution is product of complete space randomness (*CSR*). It is under this assumption that the null hypotheses (H_0) for PPA tests are formulated (Bivand *et al* 2008, Illian *et al* 2008). A point pattern could also be described by its intensity (λ). For a Poisson process, intensity is homogeneous and constant throughout $\boldsymbol{w}$ (Diggle 2003, Illian *et al* 2008).

For inhomogeneous point patterns (meaning the pattern is not random) the intensity is not constant, suggesting that spatial distribution of $\boldsymbol{x}$ could be product of spatial trends (e.g. distance to roads) and/or event-interaction (attraction/inhibition between events) (Bell and Grunwald 2004, Baddeley 2010). The intensity of an inhomogeneous pattern is described by the *Papangelou* conditional intensity $\lambda(u, x)$ which acknowledges that the presence of an event $\boldsymbol{u}$ depends on the configuration of the remaining events on $\boldsymbol{x}$ (Baddeley and Turner 2000). The conditional intensity is expressed as a log-linear function in the form (Stoyan 2006):

$$\lambda(u, x) = \exp(\psi^T B(u) + \varphi^T C(u, x)) \qquad \text{(equation 2)}$$

where: ψ and φ are parameters to be estimated, $B(u)$ represents the spatial trend (dependence on the spatial location) and $C(u, x)$ represent the spatial interaction between events.

Gibbs process models (GPM) assess the conditional intensity as a function of spatial covariates and event-interaction. In this study, GPM parameters were derived employing a log-linear function of the maximum pseudolikelihood (Baddeley and Turner 2000):

$$logPL(\theta;x) \approx \sum_{j=1}^{m}[z_j \log(\lambda_\theta(u_j;x) - \omega_j\lambda_\theta(u_j;x)] = \sum_{j-1}^{m}\omega_j(y_j log\lambda_j - \lambda_j) \text{ (equation 3)}$$

where: u_j is the set of quadrature points and $u_j \epsilon W$ and $j = 1....m;$ ω_j is the set quadrature weights and $\omega_j \geq 0$; z_j indicator that differentiate between events (value =1) and dummy point (value =0); $y_j = z_j/\omega_j$ and $\lambda_j = \lambda_\theta(u_j, x)$.

For GPM the intensity of the pattern is given by an integral function of the weighted sum of the pseudolikelihood, this process depends on a discretization process which is defined by a weighted quadrature scheme (Berman and Turner 1992, Baddeley and Turner 2000). In this study, the quadrature scheme comprised the observed events (agricultural clearings) and a set of “dummy” points (absence of agriculture) on $\boldsymbol{w}$**.** During the discretization process, the system differentiate between events and dummy points by assigning weights (events = 1, dummy = 0; Baddeley and Turner 2000).

Aside from the spatial trends, GPM models allow the inclusion of a parameter that represents the interaction between events. In this study, preliminary tests indicated that two types of interaction (inhibition and interaction) was present within clearings (see, Table E.1, Figure E.1, Figure E.2. for event integration test results). Interaction was represented with a hybrid interaction model (Baddeley *et al* 2013); inhibition was characterized with a Hard-Core (Hc) model (event distance < 100 m) and attraction with the Area-Interaction process model (event distance ≥ 100 m). Additionally, in the implementation of GPM it is suggested the use of edge correction methods, this to avoid distortion within the events at the edge of $\boldsymbol{w}$ (Stoyan 2006). In this study, edge correction consisted of an erosion process of the original extent of $\boldsymbol{w}$; the erosion distance was the value of the Hc distance as suggested by Baddeley *et al* (2013).

2.5. Model implementation and evaluation

Analysis was conducted with the spatstat package 1.42-2 version (Baddeley and Turner 2005) in R version 3.2.2, employing the RStudio interface (R Core Team 2013, RStudio 2013). Per site, several sets of variable combinations were evaluated. These were: 1) a base model that included environmental and social variables plus distance to rivers with inter-event correction, 2) the base model without inter-event correction (to assess interaction effect), 3) the base model plus distance to any road, and 4) the base model plus each one of the different road conditions. A total of 108 models (Table 2.3) were analyzed. Due collinearity, DSET was omitted for models in S3, S4, S5, and S1 with the following road conditions: PUB, PER1 and MNTD (for correlation results per site see Figure E.3 throughout Figure E.9).

The fitting of the models was assessed with three tests. The first test evaluated the overall goodness of fit. The other two tests evaluated the residuals, specifically: 1) residuals on the trend (covariates) and 2) residuals from the inter-event interaction correction. In PPA, residuals are quantified from the difference between the produced intensity surface and the original one, analogous to generalized linear models, the sum of the residuals must be equal to zero (Baddeley *et al* 2005).

Table 2.3. Set of variable combinations tested in the proposed agricultural model tested in seven case sites.

ID	Variable grouping	Condition/variables						Interaction correction term
		Environmental		Social		Accessibility		
		CFF	TWI	POPD	DSET	DRIV	Roads	
1	Base (NI)	X	X	X	X	X	NA	No
2	Base +I	X	X	X	X	X	NA	Yes
3	Base +I + DARO	X	X	X	X	X	All roads	Yes
4	Base +I + PUB [1]	X	X	X	X	X	Public roads	Yes
5	Base +I + PLOG [1]	X	X	X	X	X	Primary logging	Yes
6	Base +I + SLOG [1]	X	X	X	X	X	Secondary logging	Yes
7	Base +I + PER1 [1]	X	X	X	X	X	Period 1	Yes
8	Base +I + PER2 [1]	X	X	X	X	X	Period 2	Yes
9	Base +I + PER3 [1]	X	X	X	X	X	Period 3	Yes
10	Base +I + MNTD [1]	X	X	X	X	X	Maintained	Yes
11	Base +I + UMNTD [1]	X	X	X	X	X	Unmaintained	Yes

[1] *Note*: *RDEN also include as a variable in models 4-11*

Goodness of fit was assessed with the summary *L-function* ($\sqrt{K}$), a transformed version of the Ripley's *K-function* (Baddeley 2010). Per site and set of variable combinations, the test compared the actual pattern with simulated patterns created from the model outputs. If a model has a good fit, the simulated patterns would show the same tendencies as the actual (Baddeley *et al* 2015). Evaluation of the *trend* employed a lurking tool to compare the magnitude of the residuals along the Cartesian coordinates. If at any point along x or y, the residuals were different from zero, this indicates that the set of covariates were not completely explaining the incidence of agriculture; the magnitude of the deviance was assessed based on 5% significance bands (Baddeley *et al* 2005). Evaluation of the *event-interaction* was based on Q-Q plots, which displayed the fitted residuals against the quantiles of an expected point pattern. The quantiles of the expected pattern were derived from 100 simulations of the pattern; the plots show two dotted lines representing the 2.5 and 97.5% percentiles. (Baddeley *et al* 2005). All the above three tests generated graphical outputs (see Figure E.11 throughout Figure E.31). To simplify these results, a summary graph was created. For each test-output (goodness of fit, lurking and Q-Q plot), a score of fitness was given. Fitness scores ranged from 0 to 5, where 0 indicated a perfect fit and 5 a poor one. For the interpretation of the summary graph: 1) models which residuals (Q-Q plots and lurking tests) were within the confidence bands and the simulations (Goodness of fit test) followed the same trend than the actual pattern, were considered to have a very good fit; 2) models which residuals were slightly out of the confidence bands and the simulations and the trend of simulations were slightly out the actual pattern were considered as acceptable fit and 3) models which residuals were completely out of the confidence bands and simulations were did not follow the trend of the actual pattern were considered to have poor fitting.

After fitting evaluation, the AIC values for each of the outputs were compared to assess their strength following method by Burnham and Anderson (2004). This included: 1) calculation of the delta AIC (Δ_i), and 2) definition of the Akaike weights (ω_i). These terms were calculated as follows:

If *i* is a simulation from a set *R*, then:

$$\Delta_i = AIC_i - AIC_{min} \quad \text{(equation 4)}$$

where: AIC_i is the AIC value for the i-model; AIC_{min} is AIC with the lower value for the set *R*

Models with $\Delta_i > 10$ do not provide empirical support for the model, while $\Delta_i < 2$ supports the model (Burnham and Anderson 2002). To understand the strength of the model, weights were given to each model as follows:

$$\omega_i = \frac{exp(-\Delta_i/2)}{\sum_{r=1}^{R} exp(-\Delta_r/2)} \quad \text{(equation 5)}$$

where: Δ_i is the delta AIC for simulation *i*; *R* is the set simulation to be compared.

Weights per set add to one. If the weight value for the best simulation (AIC_{min}) is closer to 1, it suggests high strength and low uncertainty, low value weights suggest poor strength and higher uncertainty. In this study, models with $\omega > 0.9$ were considered of high strength (Johnson and Omland 2004).

3. Results

3.1. Models evaluation

Results from the three fitting tests were scored and summarized into one score graph (Figure 2.4). None of the models presented a perfect fit. For S1, S2 and S5, at least one of the tested variable combinations provided a very good fitting. For sites S3, S6 and S7, all variable combinations that included interaction showed acceptable fitting. Within sites, models with very good fitting that included distance to different road conditions were observed in S1, S2 and S5, while for all sites, the variable combination with the poorest fitting was *Base (NI).* For S4, the fitting was poor for all variable combinations regardless. Considering the poor fitting of S4 models, the results from this site were omitted from further analysis.

Based on the residuals tests, the most common problems were: 1) in lurking tests, residuals tended to differ more from zero in locations with high incidence of clearings, suggesting that lurking variables could be explaining locations with high incidence of agriculture 2) in Q-Q plots, the attraction (interaction) between clearings was not completely corrected.

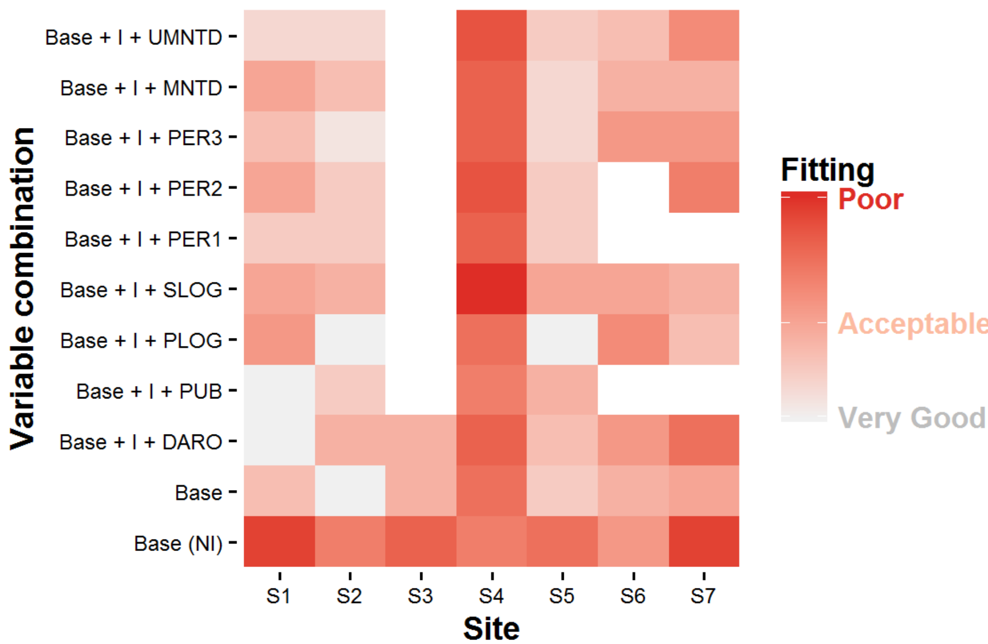

Figure 2.4. Fitting tests summary for models (n=108). Fitting was evaluated with three different tests (general goodness of fit, trend residual test and residual interaction test).

3.2. Conceptual model and variable responses

The conceptual model posited the type of relationship (i.e. a positive or negative) of each variable toward the incidence of agriculture. Coefficient values for variables within the models generated for the case sites indicated that responses mostly hold the expected relationships.

For the environmental conditions, the coefficient value for CFF (Figure 2.5) was always negative, suggesting preference for locations with moderate to low canopy coverage and supporting the expected relationship. For the variable TWI (Figure 2.5), the coefficient values were positive S1, S2, S3, S5, S6, but negative for S7; however, it was expected for this relationship to be a negative one (preference for locations with good drainage represented by low TWI values).

For the social conditions, the coefficient values for the DSET (Figure 2.5) variable were negative for all sites, indicating preference for locations near settlements and supporting relationship from conceptual model. Coefficient values for POPD (Figure 2.5) varied among and within sites; for S1, 81% of models had a negative coefficient, for S5, 91% were positive, for S6, 75% were positive, while all models within S2, S3 and S7 the coefficient were positive. It was expected a preference for locations with high population density, thus a positive relationship.

For the accessibility conditions (Figure 2.5), a negative relationship was expected, reflecting a preference for nearness to transportation, for variables DRIV and DARO and especially for the following road conditions: PUB, PER1 and MNTD. Coefficient values for DRIV varied among and within sites, in S2, 45% of the models had a negative coefficient, in S3, 67% were negative, in S6, 75% were positive, while in S5 all were positive and in S1 all were negative. For roads and its conditions, the relationship was negative in S1, S2, S5 and S6, positive in S3 and in S7 it was positive in all models but one (Figure 2.5).

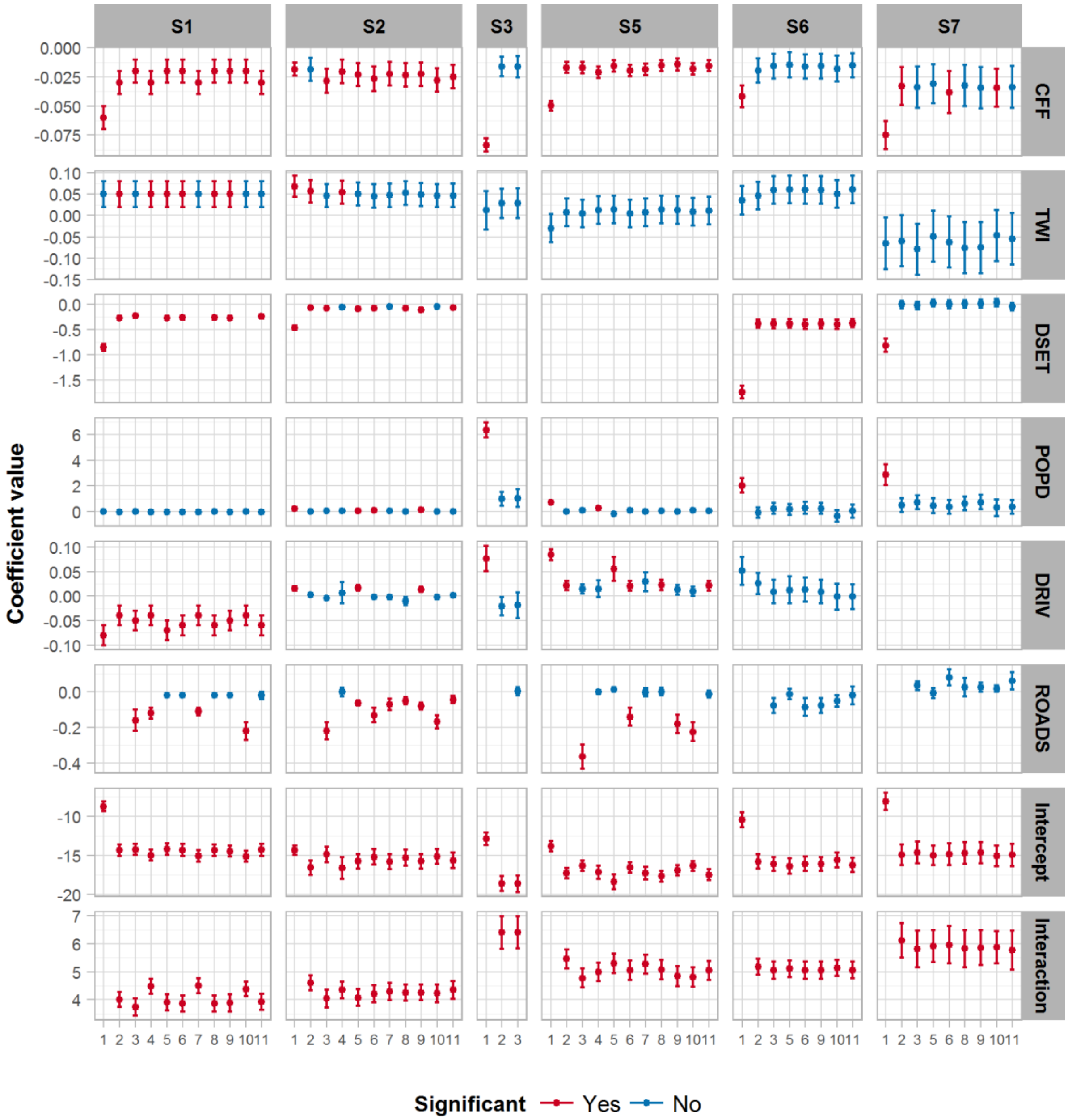

Figure 2.5. Coefficient values plus ± standard error (showed in error bars) and significance for different variable combinations tested by variable and site. Models are identified as follow: **1**=*Base (NI)*, **2**=*Base + I*, **3**=*Base+I+DARO*, **4**= *Base+I+PUB*, **5**= *Base+I+PLOG*, **6**= *Base+I+SLOG*, **7**= *Base+I+PER1*, **8**= *Base+I+PER2*, **9**= *Base+I+PER3*, **10**= *Base+I+MNTD*, **11**= *Base+I+ UMNTD*. The variable **ROADS** contain coefficient values of DARO and all other road conditions. Error bars are given for all coefficients, but in some instances error bars are not visible due the y-axis range values.

3.3. Best models per site

The best models per site were identified based on AIC values. Results indicated that there were sites which best models included roads and others that exclude them. Sites which best models included roads were S1, S2 and S5 (Table 2.4). For S1 and S5 the best model was *Base+I+DARO;* however, these models strength (ω, based on AIC weights) was below the preferred threshold (>0.9, S1: ω=0.65 and S5: ω=0.45), suggesting that other models could also provide some empirical support. The second-best model (SBM) for S1 was *Base+I+PER2* (ω=0.09) and for S5 it was *Base+I+MNTD* (ω=0.3). For S5, the weights of the best and SBM were so close that it is suggested that any road or maintained roads could be influencing the agricultural intensity. For S2, the best model was *Base+I+MNTD* (ω=0.96), and because its strength, this model strongly provided empirical support and agreement between the incidence of agriculture and the proximity to maintained roads.

The best models that excluded roads were S3, S6 and S7 (Table 2.4); for those sites the best model was *Base*, however, their strengths were low (S3: ω = 0.6, S6: ω=0.5 and S7: ω=0.3), while the SBM for those sites included roads, S3: *Base+I+DARO* (ω = 0.4), S6: *Base+I+MNTD* (ω=0.3), S7: *Base+I+SLOG* and *Base+MNTD* (both ω<0.2). These low weights suggested mixed importance between the absence or presence of roads in the incidence of the agricultural. (for AIC values and weights for all tested models see Table E.4).

Table 2.4. Akaike weights (ω_i) for the different variable combinations evaluated per site. (Best models per site are indicated in bold)

Model	Site					
	1	2	3	5	6	7
Base (NI)	0.00	0.00	0.00	0.00	0.00	0.00
Base+I	0.07	0.00	**0.62**	0.00	**0.51**	**0.30**
Base+I + DARO	**0.65**	0.03	0.38	**0.45**	0.04	0.06
Base+I + PUB	0.00	0.00		0.11		
Base+I + PLOG	0.05	0.00		0.01	0.01	0.14
Base+I + SLOG	0.06	0.00		0.02	0.02	0.20
Base+I + PER1	0.00	0.00		0.00		
Base+I + PER2	0.09	0.00		0.00		0.04
Base+I + PER3	0.03	0.00		0.08	0.04	0.05
Base+I + MNTD	0.00	**0.96**		0.32	0.35	0.18
Base+I + UMNTD	0.04	0.01		0.00	0.03	0.03

3.4. Best models per site: variables response and its influence in agriculture

For each variable within the best models per site, the value of estimated coefficients and significance were compared. Among variables, CFF was significant in S1, S2, S5, S7 (Table 2.5), DSET was significant in S1 and S6, DRIV were significant in S1, while POPD and TWI were not significant among models. For all the above variables, the magnitude of the coefficient value was below one, suggesting its contribution toward the incidence of agriculture was low. For the models that included roads, (DARO: S1, S2 and MNTD: S5), roads were always significant and the magnitude of the coefficient value was close to zero.

The magnitude of coefficients for the *Intercept* and the *Interaction* correction components strongly influence the incidence of agricultural clearings. For the *intercept*, the relationship was negative, with values ranging from -14 to -18; which described that within each site, it was more likely to encounter locations without agriculture than agriculture. The *interaction* coefficient values were positive ranging from 3.7 to 6.1, suggesting that the presence of a clearings tended to attract other clearings.

Table 2.5. Summary regression outputs for the best models. Shown per site and variable coefficient, significance as follows: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, and standard error in parentheses.

Condition	Variable	S1	S2	S3	S5	S6	S7
		Base+I+ DARO	**Base+I+ DMAN**	**Base+I**	**Base+I+ DARO**	**Base+I**	**Base+I**
Environmental	CFF	-0.025 *** (0.007)	-0.028 ** (0.01)	-0.016 (0.009)	-0.017 *** (0.005)	-0.02 (0.01)	-0.03 * (0.016)
	TWI	0.051 (0.026)	0.046 (0.027)	0.029 (0.034)	0.004 (0.005)	0.046 (0.032)	-0.060 (0.060)
Social	DSET	-0.226 *** (0.041)	-0.043 (0.03)			-0.383 *** (0.082)	-0.003 (0.075)
	POPD	-0.013 (0.027)	0.03 (0.033)	0.994 (0.521)	0.084 (0.065)	-0.074 (0.411)	0.48 (0.54)
Accessibility	DRIV	-0.045 * (0.019)	-0.003 (0.004)	-0.021 (0.019)	0.015 (0.009)	0.026 (0.022)	
	DARO	-0.155 ** (0.058)			-0.363 *** (0.067)		
	DMAN		-0.168 *** -0.037				
	RDEN		0.259 (0.505)				
	Intercept	-14.24 *** (0.704)	-15.13 *** (0.959)	-18.59 *** (0.964)	-16.34 *** (0.65)	-15.78 *** (0.908)	-14.95 *** (1.323)
	Interaction	3.74 *** (0.30)	4.22 *** (0.31)	6.4 *** (0.58)	4.78 *** (0.34)	5.17 *** (0.29)	6.12 *** (0.62)

3.5. Roads and agriculture

When comparing characteristics of sites in which roads influence the incidence of agriculture (hereafter "*roads group*") and that ones that not (hereafter "*non-roads group*"), it was observed that the two groups each presented distinctive characteristics (Figure 2.6). For the *roads group*, three common characteristics were present: 1) dominance of maintained roads: S1 had 45% of its total road length maintained, for S2 was 70%, while for S5 was 71%; 2) presence of active logging operations, including gaps for felled trees and skid networks to extract timber; and 3) sites had a relatively "large" settlement: the largest population density in S1 was 12 roofs/km^2; for S2 = 9 roofs/km^2 and for S5 was 3 9 roofs/km^2.

The *non-roads group* presented almost opposite characteristics: 1) high presence of unmaintained roads (i.e. for S6 and S7, at least 70% of the total road length was unmaintained, the exception was S3 in where 100% of the roads were maintained); 2) lack of active logging activities; and 3) settlements with low population density (i.e. in S3, S6 and S7 the maximum observed population density was < 0.14 roofs/km^2).

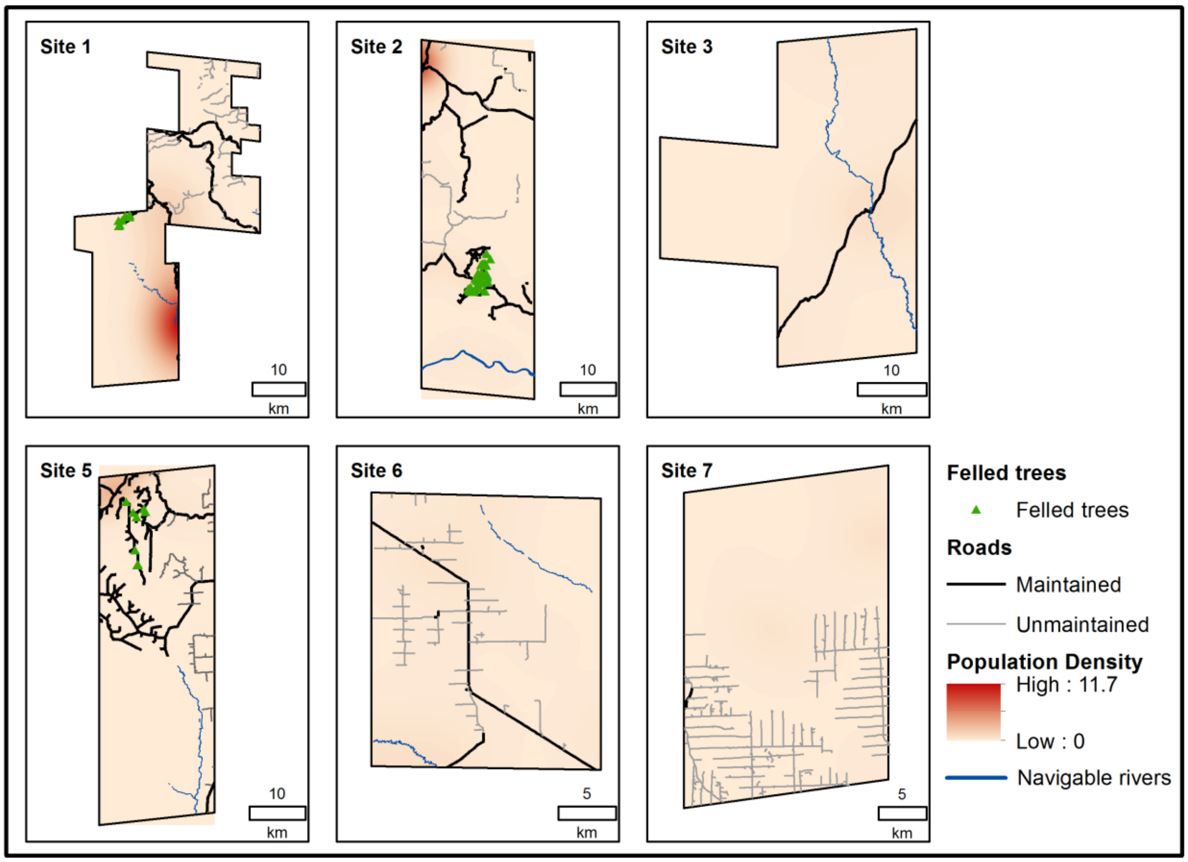

Figure 2.6. Common characteristics among roads group sites in which roads are significantly governing the incidence of agriculture (S1, S2 and S5) and the ones in which roads are not (S3, S6 and S7). Felled trees, population density and roads derived from WV-1 imagery.

4. Discussion

The proposed conceptual model and methodological approach enabled greater understanding of the characteristics and degree to which different conditions affect the spatial incidence of subsistence agriculture within the Congo Basin forests of the study area. Studies on farming practices by subsistence farmers within Congo Basin are scarce, and although Miracle (1967, 1968) provided one of the most complete depictions in this topic, his research predates current social, political and economic conditions in the region. Results from the case study sites suggested that despite the high incidence of roads in the landscape, roads are required to interact with other factors to influence the incidence of agriculture.

4.1. Conditions affecting the incidence of agricultural clearings

Of the seven evaluated sites, six (S1, S2, S3, S5, S6 and S7) had a moderate to good model fitting, while one (S4) had poor fitting regardless of the variable combination. The main difference between S4 and the other sites is its proximity to the city of Ouesso (ROC), a regional urban center with services and infrastructure including an airport and electrical grid (Figure E.32) that greatly differ from the rural conditions of the other sites. Thus, the proposed conceptual model satisfied the explanation of incidence of agriculture in rural areas but not in urban landscapes. For the remaining six sites, histogram distributions by variable (Figure E.33) indicated that environmental conditions (CFF and TWI) were homogeneous among sites, but social (DSET and POPD) and accessibility conditions (DRIV and all distance to road and its properties) tended to differ between sites.

For the environmental conditions, the variable CFF was significant in 72% of the combinations tested (n=53) and in 67% of the best models (n=6). Data preparation for the CFF applied a 5x5 average-kernel filter throughout the raster grids, this allowed for an assessment of the percentage of canopy coverage surrounding the agricultural clearings. After the filter application, the mean value of canopy coverage for approximately 50% of the clearings was 68%. Thus, model results suggest that incidence of agriculture was associated with the presence of moderate canopy cover conditions, (very likely forest that was previously disturbed, e.g. secondary forest). As established in the conceptual model, this preference could be associated with soil fertility conditions (higher levels of organic matter as canopy closes) and preference for secondary forest that it easy to clean with the use of power tools (Guariguata and Ostertag 2001, Ickowitz 2006). The response for the variable TWI was unexpected (a positive relationship) for most sites (sites 1, 2, 3, 5 and 6); this was because clearings with those sites occurred in a wide range of drainage conditions (low and high TWI values), while the clearings within the only site with a negative relationship (Site 7) occurred in well-drained soil (low TWI values). Overall, TWI was significant in 17% of the combinations (n=53), however it was not significant among the best models per site. The lack of significance for the variable TWI could be related to the majority of the sites presented well drained conditions (low TWI values; see Figure E.33).

Characteristics of the social conditions were not homogeneous among sites. For sites 1, 2 and 3, there were settlement which the variable POPD ranged between 3 to 12 roofs/km2; for sites 3, 6 and 7, the maximum densities observed were 0.6 to 0.8 roofs/km2. For comparison purposes, the population density in the city of Ouesso was 134 roofs/km2. For the variable DSET, Site 5 had the largest average distance between settlements (24 km), while for the remaining sites, the average distance was < 9 m. Despite the site differences, the responses for the social conditions were similar among sites (Figure 2.5). DSET was significant toward the incidence of agriculture in 69% of the combinations (n=53) and it was significant in 50% (n=4) of the best models. Nearness to settlements was consistently significant in explaining the incidence of agriculture and its importance reflects customary rights that grant smallholder farmers access to land in proximity to their living spaces (Rupp 2011, Robiglio et al 2003). The variable POPD was only significant in 17% of the tested combinations (n=53) and not significant among the best models. POPD lack of significance could be related to the structure of the rural landscape, in where there was a relatively high incidence of small settlements and a relatively very low incidence large settlements among sites (i.e. 120 homesteads vs 6 towns were mapped; Chapter 1, Table 1.3). Thus, incidence of agricultural clearings was observed within low and high populated areas, which reduced the variable discriminant power.

For the accessibility conditions, distance relationships (see Chapter 1, section 5.1) established a strong relationship between clearings and transportation. Despite those findings, modeling results indicated that transportation was not always significant to the presence of agriculture. The preference for nearness to rivers DRIV was observed in S1, S2 and S3, but not S5 and S6. DRIV was significant in 48% of the tested combinations (n=44; site 7 did not have navigable rivers within) and significant in one of the best models (S1); thus, within most of the sites, rivers did not seem to influence the incidence of agriculture. Roads and their properties were influential in explaining the incidence of agriculture in some sites; the variables that more consistently showed influence were DARO and MNTD. Both variables were significant in 50% of the sites (S1, S2 and S5, hereafter "roads group"), while the other road properties (road types and construction periods) seemed to have lesser influence in the incidence of agriculture (Figure 2.5). The influence of roads in the models will be further addressed in the following section).

Aside from the conceptual model variables, all models presented a strong and significant relationship between the incidence of agriculture and the interaction between clearings. This relationship suggests that the opening of a clearing would lead to the opening of a nearby clearing. This is likely because families employ several clearings by season, which requires that crop caring and harvesting activities must be efficient, thus, short distances between clearings are preferable (Brown 2008, Yemefack et al 2006).

4.2. Roads and agriculture

Close examination of the similarities within the roads group highlighted three common factors: a large proportion of maintained roads, presence of active timber extraction activities and at least one relatively "large" populated center. The large proportion of maintained roads is linked to the presence of extractive timber activities. Timber extraction requires of an extensive and dynamic road network. It is dynamic because secondary logging roads are only maintained while extraction is taking place and then, roads are abandon, allowing vegetation to re-growth on the roadbeds (Wilkie et al 2000, Kleinschroth et al 2015). The third factor was the presence of a settlement with a higher population density (in comparison to the other rural settlements), this despite that the variable POPD was not significant among the best models. However, the importance of a populated areas could be related to an active economy influenced by the by the presence of logging operation. When logging occurs, nearby populated centers tend to temporally benefit economically from the influx of logging workers and some job opportunities for local populations, however, when operations move to other parts of the forest, the economic benefit is terminated (Wilkie 1996, Rupp 2011). The influx of new people and cash may open market opportunities for local populations to sell surpluses of agricultural products to logging workers. This is similar to the market opportunities that have encouraged the sale of bushmeat in the region (Poulsen et al 2012).

The non-roads group (sites 3, 6 and 7) presented opposite trends to the roads-group. First, there was a dominance of unmaintained logging roads in sites 6 and 7; second there were no signs of ongoing logging operation and third, settlements within those sites seemed to have smaller population densities. For best models for the non-roads group had acceptable fitting, which suggest that lurking variables (e.g. detailed soil data or household social economic data) could be having more influence on the incidence of agriculture than the presence of the network.

5. Conclusions

This study, relying on non-time series presence data provided an insight into the relationships between agriculture, roads and commercial logging operations. Although agricultural clearings tend to occur near roads, modeling results indicated that not in all conditions roads significantly influence the incidence of agriculture. Roads were most likely to influence agriculture when several conditions are present (dominance of maintained road, ongoing logging operations and a relatively large population center). Ongoing logging operations have the ability to bring new economic opportunities to local populations, as noted with the bushmeat market, which may also support an increase in demand for roots and starches. However, logging operations are spatially dynamic, which implies that their impact has the potential to be only temporal. Aside from roads, agriculture responds to social spatial practices, meaning that the nearness to settlements (which are usually associated with older-maintained roads) and to the proximity to other clearings influences agricultural incidence. Modeling findings suggest that future research must evaluate how lasting is the effect of temporal non-traditional economic activities (e.g. logging related operations) on forest communities and agricultural demand and land use patterns. Additionally, future research must evaluate how capital from non-traditional economic activities is required to increase agricultural expansion? This is of great importance because it is likely that some of these forest communities could further benefit from more permanent economic logging related activities (e.g. industrial sawmills) that could take advantage of the now existent road network.

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CHAPTER 3.

AGRICULTURE AND FOREST ZONING IN THE FRONTIER FOREST OF THE REPUBLIC OF CAMEROON AND THE REPUBLIC OF THE CONGO.

1. Introduction

Worldwide, the Congo Basin encompasses the second largest continuous mass of tropical forest (Ruiz Pérez *et al* 2005), and its management and administration depend on policies and legislature of six different countries: Republic of Cameroon, the Republic of Congo, the Central African Republic, Equatorial Guinea, Gabon and the Democratic Republic of Congo. Until recently, more than 980,000 km^2 of forest within the Basin were considered part of the intact forest landscapes (Potapov *et al* 2008b). Yet, in the late1990s, changes in policy and legislature (driven by the interest to support economic growth for Basin countries) supported the development of large-scale commercial logging operations, which are estimated to encompass over 600,000 km^2 (Laporte *et al* 2007).

Along with the introduction of the forest reforms, the new legislature introduced the delimitation of forest-use zones. Zoning is a land management policy instrument based on command and control principles, this with the purpose to guide land management and to restrict or control the anthropogenic use of the forest resources (Lambin *et al* 2014). Countries within the Basin allocated forested regions within permanent forest estates (also referred as permanent forest domain), in which the set of allowed anthropogenic activities could not lead to land cover change. The principle of permanent forest has been applied to other tropical forest regions, and it is estimated that approximately 58% of the global tropical forests (including Latin America, Southeast Asia, and the Congo Basin) are under permanent forest designation (FAO and ITTO 2011). The permanent forest in the Basin accommodates different uses, including areas dedicated to sustainable forest management, conservation and protection of the forest resources (Arnitage and FAO 1998). In some countries (e.g. Cameroon) zones of non-permanent forest have been created to accommodate other anthropogenic uses that occur within the forest (e.g. small scale agriculture; Ezzine de Blas and Ruiz Pérez 2008).

In the Basin, since the introduction of the new forestry laws, a slight increase in deforestation rates has been reported in the literature. Ernst *el at* (2012), based on data derived from moderate resolution sensors (Landsat and Aster), reported that for the period 1990-2000, (which could be considered a period of transition between the older and newer policies), the net deforestation rate was 0.09%, while for the period 2000-2005, (which reflects current policies), the rate increased to 0.17%/year. Similarly, Mayaux *et al* (2013), reported that the rate of deforestation for the more recent period 2000-2010 was 0.14%/year (estimations were derived from MODIS and Landsat sensors). Both studies concluded that logging operations could be excluded as possible drivers of deforestation, but that small scale agriculture was among the principal forest threats. In the region, present and future deforestation drivers are associated with fuelwood collection, mining, agro-industrial plantations but mostly with small scale agriculture, which for most of communities in the region is their primary source of income (Tegegne *et al* 2016).

Small-scale agriculture, which includes production of subsistence crops (e.g. roots and tubers) and artisanal production of cash crops (e.g. cacao, palm oil; Tollens 2010) is usually conducted under different forms of slash and burn agricultural practices (Miracle 1967). However, mapping and monitoring the extent of small-scale agriculture with methods that rely on moderate or coarse remote sensing imagery is challenging (Thenkabail 1999) because the small footprint of some of the clearings (sometimes smaller than 0.5 ha) and also the diverse spectral responses of the clearings (Rupp 2011, Yemefack *et al* 2006). In addition, current studies in the region, like the ones conducted by Ernst *el at* (2012) Mayaux *et al* (2013), report the amount of deforested land but do not differentiate between the different sources of deforestation (e.g. agro-industry, infrastructure, subsistence agriculture), nor indicate where deforestation occur with respect the limits of the current forest-use zoning. Thus, although small scale-agriculture is considered a threat for forest conservation, especially in areas designated as part of the permanent forest domain, the real magnitude and distribution of this activity over the landscape is still unknown.

Previous analysis (Chapter 1) mapped the extent and characteristics of agriculture in forest areas employing very high resolution imagery (World-View-1 panchromatic sensor, 0.5 m spatial resolution) over 7,000 km^2 of dense tropical forest in the Republic of the Congo and Cameroon. This study provided new information about the spatial relationships between agricultural clearings and the extensive road network. The present study aimed to further explore the role of agriculture in the region by defining the relationship between the presence of agriculture and current forest-use zoning in the two countries: the permanent (PFE) and non-permanent (nPFE) forest estates in Cameroon and the permanent forest domain (PFD) in Congo. Specifically, this study aimed to quantify the extents of agriculture within the nPFE, PFE and the PFD as well as to test for differences in agriculture characteristics between estates/countries. The specific research questions were:

1) Where did agricultural clearings occur with respect the different forest-use zones in both countries?
2) If agriculture was present among the three evaluated zones, did the extent of the agricultural landscape differ among zones?
3) Did agricultural clearings characteristics (e.g. size and connectivity to roads) differ among forest-use zones?

2. Study area

The study area is located within the forested regions of southern Republic of Cameroon (CAM) and northern Republic of the Congo (ROC). Analysis was based in the information obtained from seven case study sites (hereafter "sites"), the combined extend of all sites were 7,405 km^2. Three of the sites (S1, S2 and most of S4, Figure 3.1) are in CAM, covering 3,477 km^2; the remaining sites (S3, S5, S6, S7 and the southern section of S4, Figure 3.1) are in ROC, covering 3,928 km^2. The sites were selected from a broader study area, which was representative of the Northwestern Congolian Lowland Forest ecoregion (Olson *et al* 2012). The broader area is dominated by continuous evergreen lowland forest cover (Mayaux *et al* 2003) and characterized by very-low population density (<10 inhabitants/km^2; CIESIN and CIAT 2005). The study area is sparsely inhabited by different ethnic groups including hunter gatherers (nomadic and semi-nomadic) and farmers. However, farming and hunting activities are not exclusive between groups (Hardin *et al* 2008), this as gathering groups tend to spend more time in villages and increase their dependence in farming products (Poulsen *et al* 2012). Interaction between groups includes trade, exchange of knowledge (e.g. tools), and marriage (Rupp 2011). Thus, livelihoods depend on the gathering of non-timber products, hunting, fishing, production of subsistence crops (e.g. roots and maize), and in some instances the artisanal production of crops like cacao (Robiglio *et al* 2003, Rupp 2011). However, in the legal framework, only inhabitants within the hunter gatherer group are recognized as indigenous people (Eisen *et al* 2014). Despite the legal distinction among groups, archeological evidence suggests that agriculture has been present in the Basin since before European colonization (Willis *et al* 2004), and that current forest structure and composition in the even so-called primary forest has been shaped by shifting agriculture activity (Brncic *et al* 2009).

2.1. Forest resources administration and laws

Current land and exploitation rights within the Congo Basin are linked to policies implemented during colonial times, in where the land and its resources belonged to the colony. After independence (~1960), the centralized administration of the land (including forest resources) was transferred to the then new states, this regardless of the customary rights of indigenous and local populations (Samndong and Vatn 2012). During the last two decades, due the economic crisis that has hit the region since the 1980s, the forest resources in the region became an important element in the economic recovery for countries within the basin (Karsenty 2016). The crisis prompted the aid of the World Bank (WB) and the International Monetary Fund (IMF) resulting in a series of structural adjustment programs, and later with debt forgiveness programs (Belshaw and Livingstone 2002). In the mid-1990s, re-negotiations between the WB and the Congo Basin nations led to the reform of the forestry laws, this with the purpose to improve the participation of the forest industry in the economic recovery efforts (Atyi 1998, Ezzine de Blas and Ruiz Pérez 2008).

In CAM, the forestry reform resulted in the passing of the Forestry Law 94/01 (January 20th, 1994), and the Decree of Application No. 95/531/PM (August 23rd 1995; Ezzine de Blas et al., 2009). For ROC, the reform resulted in the Forestry Law 16-2000 (November 20th, 2000), which was reviewed in 2014, and other subsequent legislation pieces including the Decree 2002-437 (December 31st 2002), which determined the conditions for the management and use of the forest (Tessa *et al* 2012). The forestry laws in CAM and ROC share some principles including the definition of different forest use zones (Figure 3.1), giving emphasis to the delimitation of areas of production forest and the definition of the conditions in which forest management has to be conducted; conditions that included the requirement of management plans and use of sustainable forest management practices (Ezzine de Blas and Ruiz Pérez 2008).

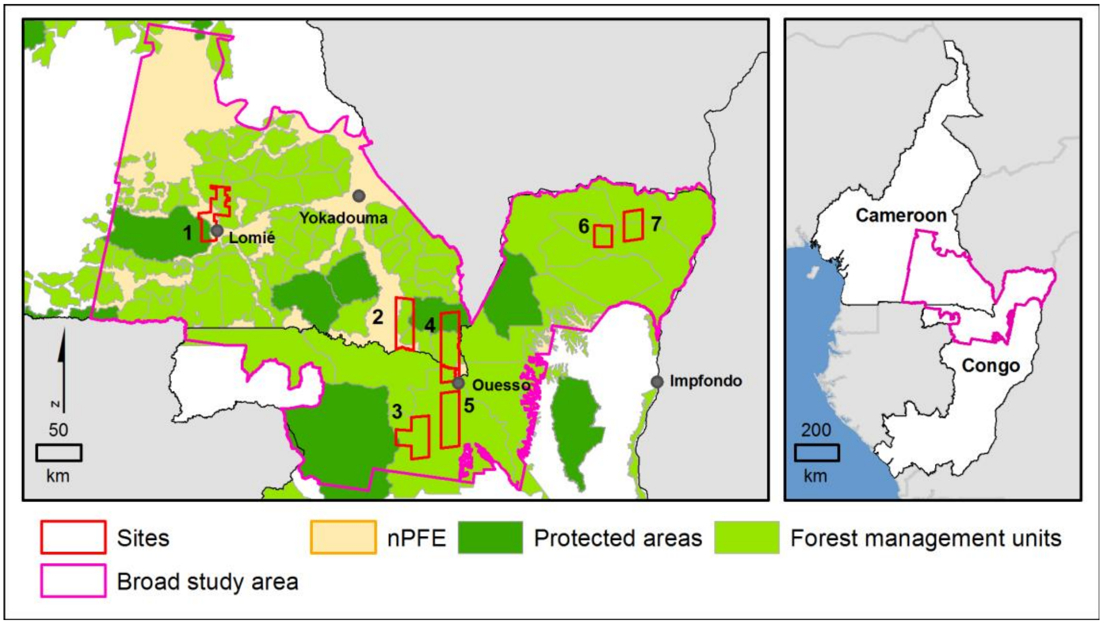

Figure 3.1. Forest use zones within the broad study area. In CAM, zones included forest under the permanent and non-permanent forest estate, in ROC the zone present was the permanent forest domain. In both countries, the permanent forest includes productive forest (forest management units) and conservation (national parks and other conservation uses).

2.2. Forest-use zones in Cameroon and Congo

In CAM, the forestry law indicates that all the forestlands belong to the *national forest estate* (NFE). For 2011, the NFE was equivalent to 174,603 km² (Mertens *et al* 2012a). Forest within the NFE was allocated into two zones, the *permanent forest estate* (PFE, ~ 93.5% of the NFE) where anthropogenic activities cannot lead to land-cover conversion, and the *non-permanent forest domain* (nPFE, ~ 6.5% of the NFE; Figure 3.2) where forest removal could occur. The PFE was subdivided into: 1) production forest (49.7% of the PFE), 2) protected areas (45.3% of the PFE), and 3) council forest (5.1% of the PFE). Land within the production forest was allocated into different forest management units (FMU). Each FMU represented an extraction permit that can be granted by a bidding process to a logging company for a period of 15 years, with the opportunity of renewal for a second 15-year harvesting cycle (Karsenty *et al* 2008, Nasi *et al* 2012, Ruiz Pérez *et al* 2005). In CAM, a FMU could encompass up to 2,000 km^2 of forest.

The *non-permanent forest estate* (nPFE) includes *ordinary land* (secondary forest, Figure F.2), land uses allowed within this zone include agriculture and extraction of forest resources under special permits (e.g. sales of standing volume and small logging permits; Mertens *et al* 2012a, Nasi *et al* 2012). The nPFE recognize special management permits under the category of community forest, which recognize use rights to local communities (Assembe-Mvondo 2013);

for the year 2011, there were approximately 6,892 km² of forest under community forest management (Mertens *et al* 2012a). For the cases in where local populations were not included as part of the nPFE, but allocated as part of FMU, the law authorizes the FMU managers to define agroforestry areas, but its extent cannot increase (Lescuyer *et al* 2012).

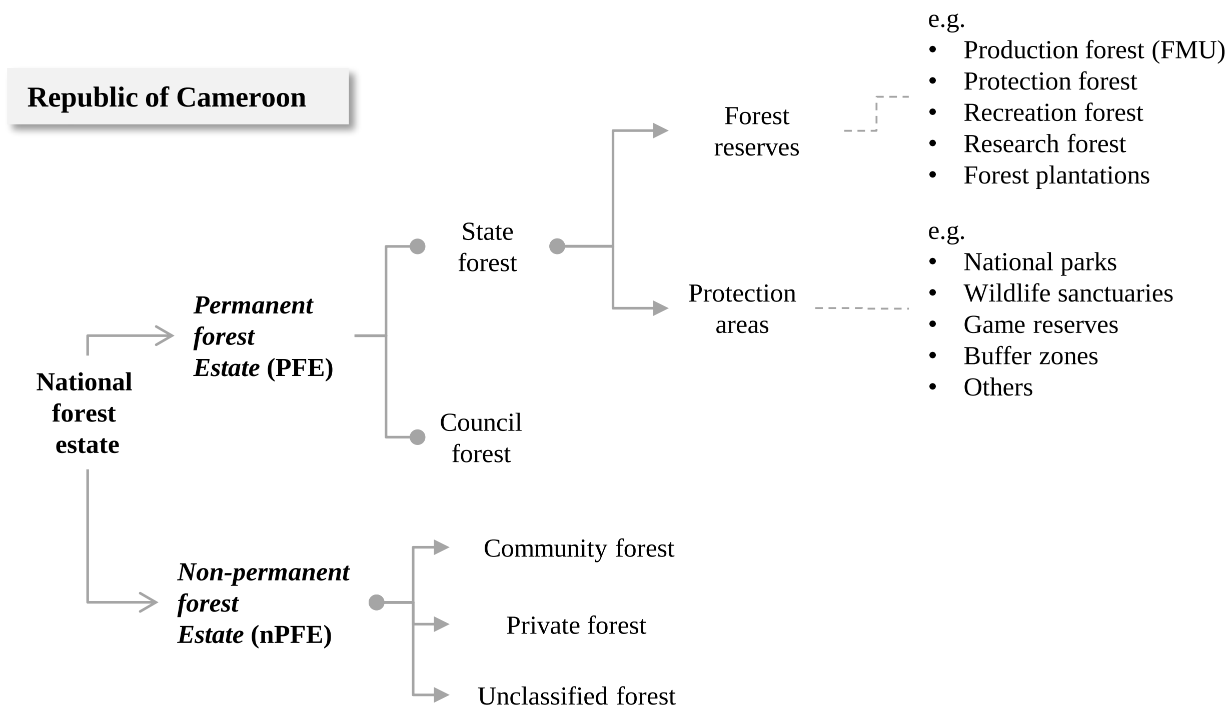

Figure 3.2. Division of the national forest estate (NFE) in the Republic of Cameroon. Two main branches are well defined, the non-permanent and the permanent forest estates (nPFE and PFE). Production and conservation forests are part of the PFE while secondary forest is allocated within the nPFE. Adapted from Mertens *et al.*, (2012a).

In ROC, similar zones were defined, however they are not completely equivalent to the ones in CAM. All forestland is part of the *national forest* domain (NFD; Figure 3.3), which in 2011 covered approximately 275,000 km^2. The NFD is divided into private and state-owned forest, as the law recognizes the possibility for private forest (e.g. development of forest plantations on abandoned land), however its current extent is unknown. The state-owned area is subdivided into the *permanent forest domain* (PFD, 72% of the NFD) with similar use connotations as in CAM, and the *non-permanent forest domain* (nPFD, 28% of the NFD), which refers to forest that has not been assigned to a specific category. The PFD is divided into three subcategories, including the *private domain of the State*, which includes production forest and protection forest. Production forest was subdivided into sixty-three FMUs of various sizes, ranging from 28 km^2 (southern Congo) up to 12,289 km^2 (northern Congo) (Tessa *et al* 2012).

However, FMUs also included territories of diverse uses (e.g. hunting and farming) that had been used by local populations under customary rights. The law indicates that the concessionaries must respect the customary rights by defining agricultural and hunting zones within the FMUs, with the condition that agricultural zones cannot increase in size. Thus, management plans for FMUs in Congo require to define different land management series, including: 1) production series: for the development of logging operations, and could also include industrial operations (sawmills); 2) conservation series: territories important for wildlife and biodiversity; 3) protection series: which include fragile ecosystems like watercourses or swamps: 4) community development series: which include territories for the development of agriculture and the extraction of timber and non-timber products by local populations and 5) research series: areas of interest for forestry or ecological research (Figure 3.4). However to date series cartographic data is not available for all FMUs (Tessa *et al* 2012, IFO-Danzer *et al* 2009, Poulsen *et al* 2010). Recently, the forestry law in Congo was reviewed in 2016, changes included better recognition of customary use rights (Government of Republic of Congo *et al* 2016).

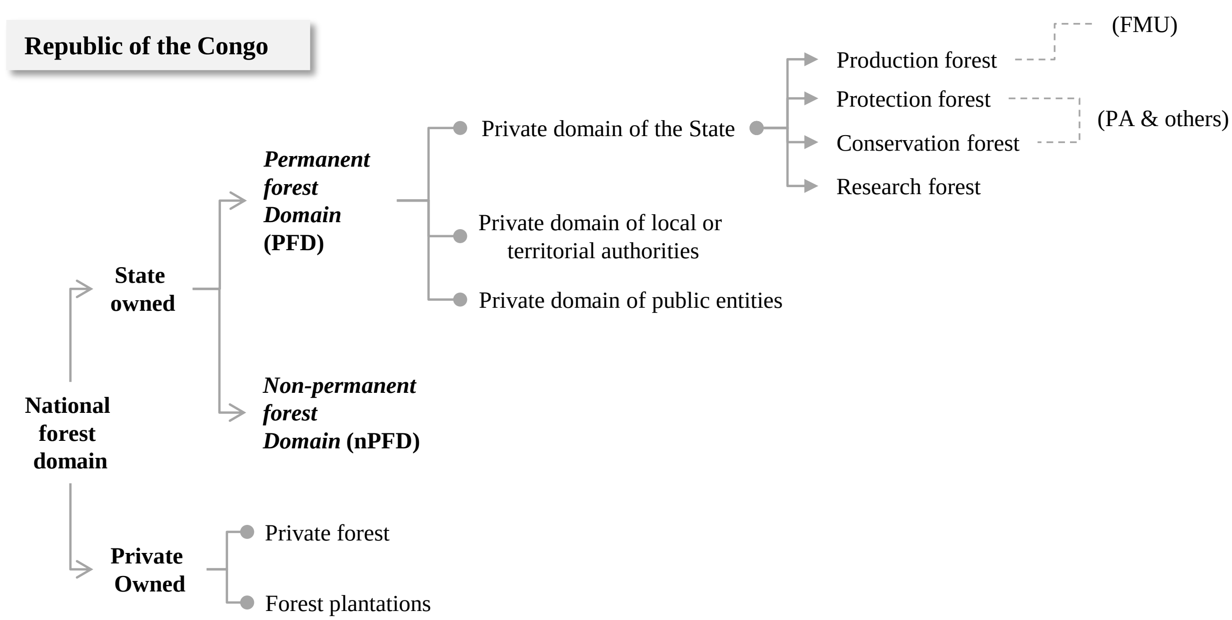

Figure 3.3.Division of the national forest domain (NFD) in the Republic of the Congo. Forest belong to the state, but law recognizes the possibility for private owned forest. Use zones within the State-owned forest includes the permanent and non-permanent and forest domains (PFD and nPFD). Production and conservation forests are part of the PFE, the nPFD includes forest that had not been yet classified. Adapted from Tessa *et al.*, (2012).

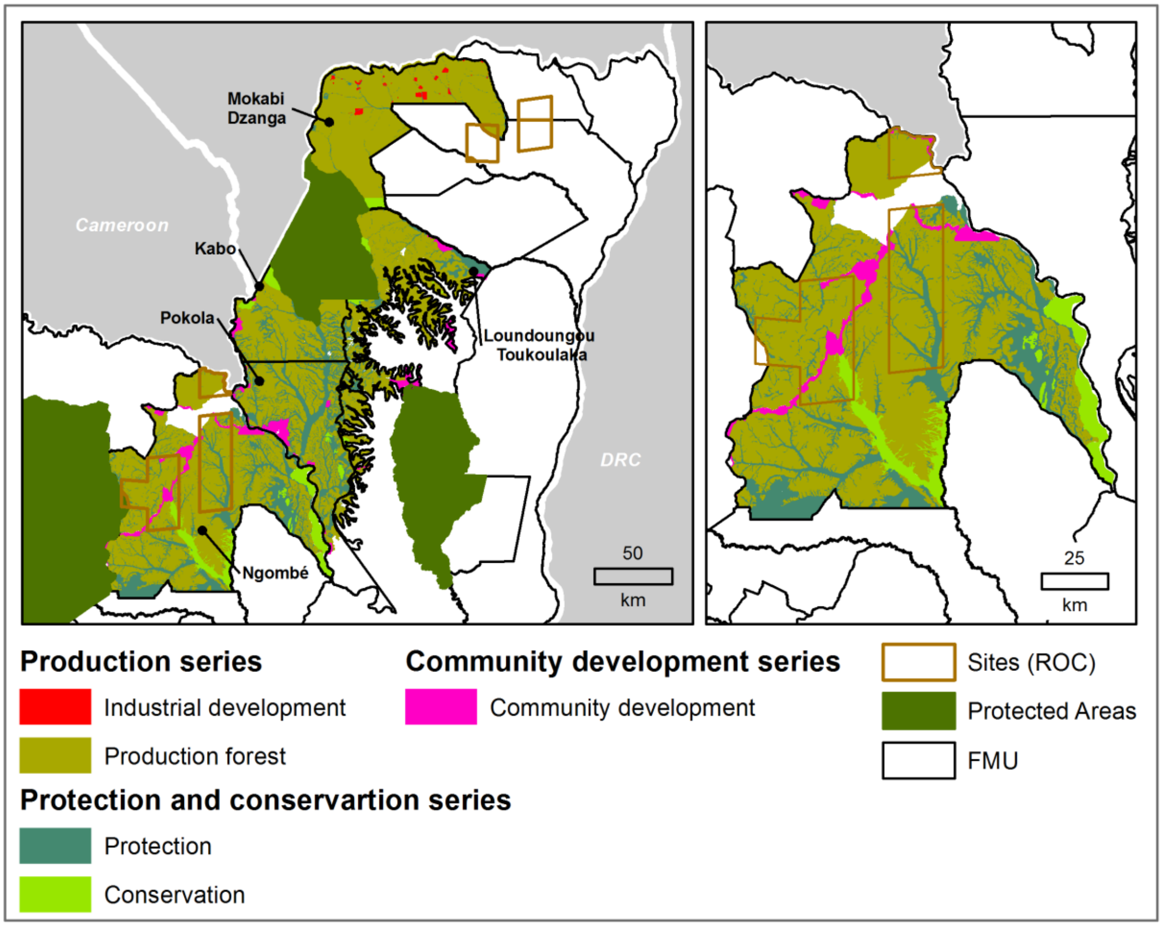

Figure 3.4. Land management series for five FMUsn the Republic of the Congo. Source: Tessa *et al.*, (2012).

3. Methods

3.1. Data acquisition and creation

On screen-digitizing procedures were employed to map anthropogenic canopy clearings (agricultural clearings, roads and settlements, plus navigable rivers) from twenty-six high resolution satellite images (World View-1 panchromatic, 0.5-m spatial resolution, each ~17 x 17 km in area). Images were taken circa 2008 and all features were mapped at scale 1:1,500 (for more details of the creation of these dataset set refer to Chapter 1, section 3.1). Boundaries of the forest-use zones come from the digital GIS atlases for CAM (Mertens *et al* 2012a) and ROC (Mertens *et al* 2012b). Agricultural clearings were considered as the set of canopy clearings that showed any or several vegetation coverage types: cleared or burned fields, land with crops, shrubs or cash crops. Those clearings could be in the form of an individual plot (one vegetation coverage type), a mosaic plot (several adjacent plots with different vegetation coverage types) and homesteads (gardens in the proximity of family living spaces).

3.2. Agriculture location and extent between land use administration zones.

For analysis purposes, the nPFE and PFE in CAM and PFD in ROC would be referred as forest-use zones. Evaluation of the location and extent of agriculture within the forest-use zones was conducted with standard GIS overlay procedures (join by location tool) in ArcGIS ver. 10.3 (ESRI 2014) and descriptive statistics. The raw numbers of agricultural plots and area cleared by agriculture were summarized by land use administration zone. In addition, because the nPFE, PFE and PFD had different extent, the number of plots and area cleared by agriculture was normalized by the extent of the corresponding forest-use zone.

To assess if the extent of the area cleared for agriculture was similar between the foret-use zones, I calculated measurements of frequency (incidence odds, IO) and measures of association (odds ratio, OR). Here the IO statistic is defined as the ratio of the area cleared by agriculture divided by area non-affected by agriculture of the corresponding forest-use zone (equation 1). The OR statistic (equation 2) describes the odds that land within a zone would be affected by agriculture. Confidence intervals (equation 3) were employed to determine precision of the OR (Oleckno 2008, Szumilas 2010). Equations 2 and 3 and interpretation illustrate the OR and CI calculations between the nPFE and the PFE, but the statistics were also employed to compare between the nPFE and the PFD and the PFE and the PFD.

$$Incidence\ Ratio = \frac{\sum Ag\ area_{nPFE}}{(\sum Ag\ area_{nPFE} - \sum Area_{nPFE})} \qquad \text{equation 1}$$

$$Odds\ Ratio\ (OR) = \frac{nPFEa/nPFEn}{PFEa/PFEn} \qquad \text{equation 2}$$

$$CI_{95\%} = \pm\, e^{\left((\ln(OR) + \left(1.96\sqrt{\frac{1}{nPDEa} + \frac{1}{nPFEn} + \frac{1}{PFEa} + \frac{1}{PFEn}}\right)\right)} \qquad \text{equation 3}$$

where:

Ag area $_{nPFE}$ *= area cleared by agricultural within the nPFE (km²)*

$Area_{nPFE}$ = total extent of the nPFE

nPFEa = area cleared by agriculture within the nPFE

nPFEn = non-affected area by agriculture within nPFE

PFEa = area cleared by agriculture within the nPFE

PFEn = non-affected area by agriculture within nPFE

Interpretation of the OR indicates that if: 1) OR = 1, the odds of area being cleared by agriculture do not differ regardless of the forest use zone (e.g. nPFE and PFE); 2) OR > 1 the odds of area being cleared by agriculture favor the nPF and 3) OR< 1, the odds of area being cleared by agriculture favor the PFE. The CI can be interpreted as: if the range of the 95% confidence interval does not includes the value 1, there are differences between the nFPE and the PFE (Szumilas 2010).

3.3. Comparing agricultural properties among forest-use zones.

Analysis was conducted to evaluate if the different three forest-use zones were influencing the ways in which agriculture was being conducted. With that purpose, a multivariate cluster analysis of the inherent properties of the agricultural clearings was conducted. Clustering is a process that identifies groups (clusters) of homogeneous (similar) conditions within a set of observations. I conducted a hierarchical cluster classification, and by hierarchical it is implied that the number of clusters was not initially defined (Everitt 2011). Analysis was conducted in R version 3.2.2, employing RStudio (R Core Team 2013, RStudio 2013).

A total of thirteen agricultural properties (i.e. characteristics) were identified and aggregated in four categories (Table 3.1): 1) *internal plot properties* refer variables that directly described each plot, including: plot type (individual, mosaic or homestead), number of subplots within a mosaic (for individual plots and homesteads, the number of subplots = 1), the area of each plot, and the subplot average area (for individual plots and homesteads, the average area of the subplot was the original individual plot area); 2) *plot neighborhood properties* described the contiguity of nearby plots; as defined by the number of plots at two different distance ranges and the distance to the nearest neighbors (1^{st}, 10^{th} and 20^{th}), differences distances to nearest neighbors were employed with the purpose to describe the near and far neighborhood of the agricultural plots 3) *social properties* intended to describe the proximity and size of nearby settlements (towns, villages and homesteads); 4) *accessibility properties* described the plot proximity to transportation ways (roads or a navigable river).

Different tools were employed to produce the above properties. Internal proprieties were obtained from the data creation process. Neighborhood characteristics were derived from neighbor distance matrices created with function *nndist* in the r package spatstat (Baddeley *et al* 2015). Proximity to settlements and transportation were based on Euclidean distance grids (30 m resolution; ESRI, 2014). As a proxy for population density, location of roofs (mapped from WV-1) within each settlement were used to create density layers with the tools *bw,diggle* and *density* in the r package spatstat (Baddeley *et al* 2015). Because the different agricultural characteristics were measured in different scales (e.g. size in hectares and distances in kilometers), all numeric variables were scaled to normalize their magnitudes with the *scales* tool in R environment.

Table 3.1. Description of the different variables employed to characterize the agricultural landscape

Property	Variable	Variable code	Description
Internal plot	Plot type	Pt	Indicates if the plot is part of a mosaic plot or individual plot
	Number of subplots	Nsp	Number of subplots within a mosaic; for individual plots: value was equal to 1
	Plot area	Ps	Plot size. Units ha
	Sub-plot average size	SPs	For mosaic plots: average subplot size; for individual plots: value equal to plot size. Units ha
Plot neighborhood	Nearest neighbors	NN1	Number of neighbors within 0.5 km radius from each plot.
	Second nearest neighbors	NN2	Number of neighbors in the range 0.5 to 1 km radius from each plot
	Distance to 1st NN	NN1D	Distance to the first nearest neighbors. Units km
	Distance to 10th NN	NN10D	Distance to the 10th nearest neighbors. Units km
	Distance to 20th NN	NN20D	Distance to the 20th nearest neighbors. Units km
	Case site	CS	Factor variable differentiating among case sites to account for possible site effect
Social	Population density (proxy)	PD	Number of roofs within settlements were employed to create a density surface. Units (N/km^2)
	Distance to settlements	Ds	Measured from a distance surface created from the location (xy) of settlements. Units km
Accessibility	Distance to the nearest transportation	DNT	Distance to the nearest transportation way (a road or navigable river). Units km

The clustering procedure consisted of fours steps (Figure 3.5). The first step was to define a proximity matrix, which is a measure of how "similar" or "dissimilar" are the elements within a group of observations (in this case, the set of agricultural plots and their characteristics). The proximity matrix was derived from an unsupervised random forest classification. Random forest is a method used to efficiently classify, characterize and summarize multivariable datasets (usually a very large number of observations and variables). The advantage of the method is that it randomly selects a subset of observations and variables, and from each subset it generates an independent "tree" (meaning that the results of this tree do not depend on previous trees), each independent tree contains a set of nodes (or groups of data). The generation of trees is repeated n-times (defined by the user) until it a "forest" is created (Breiman 2001). An unsupervised random forest implies that the data is classified without a prior direction under the assumption that similar observations would end in the same node of a tree. Thus, the proximity matrix generated from a random forest classification describes the proportion of observations that are grouped within the same node in a tree (Seoane *et al* 2014). Because this was an unsupervised procedure, I tested 10 different proximity matrices, each one generated with different numbers of trees (from 1,000 trees to 10,000 trees in increments of 1,000); this with the purpose to compare the consistency among the outputs of the clustering procedure.

In step 2, the proximity matrix was employed to represent "*adjacency*." Adjacency is a graphical representation of the proximity matrix, transforming the matrix into a network that describes the set of observations referred to as "vertices" (in our case agricultural clearings) and the "edges" or the lines that connect pairs of vertices (vertices connect by edges when vertices are similar) (Newman *et al* 2010, Clauset *et al* 2004). In step 3, the *adjacency* (from step 2) was employed to define *communities*, which is the process of the optimization of the gathering of groups of vertices in such way that there are higher density edges within groups than vertices within groups (Clauset *et al* 2004). The final step, is the *membership,* in where the community output is transformed into a numeric vector, so for each vertex (an agricultural plot) a unique value (describing the cluster membership) is assigned (Csardi and Nepusz 2006).

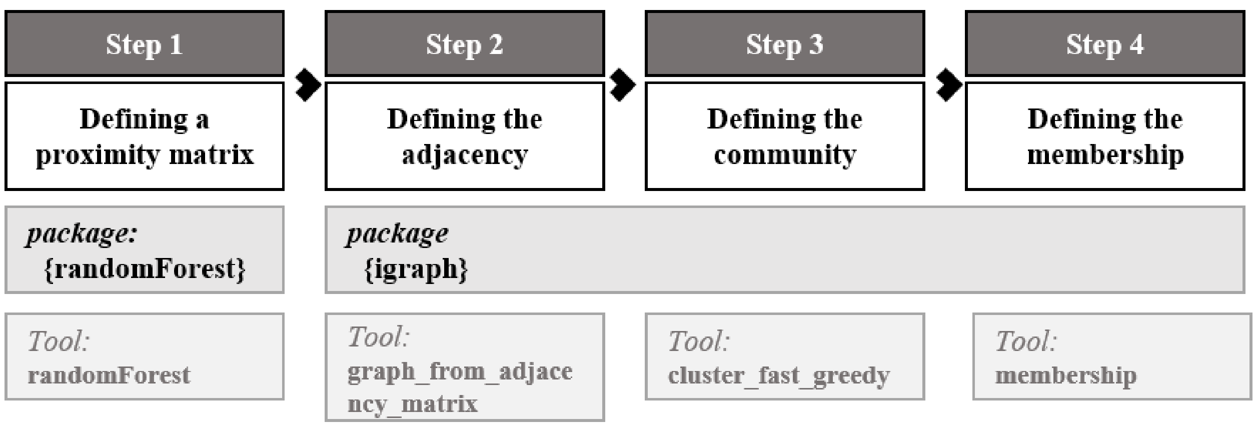

Figure 3.5. Sequence of steps followed to define clusters of agricultural clearings based on the inherent agricultural properties. The process employed two different r packages: randomForest (Liaw and Wiener 2002) for step 1 and igraph (Csardi and Nepusz 2006) for steps 2 through 4.

The results of the membership procedure from each of the ten different proximity matrices were compared to assess if the procedure consistently grouped the same set of agricultural clearings into similar clusters. The membership results were compared with the command *compare* in igraph (Csardi and Nepusz 2006) employing the normalized mutual information "*nmi*" measure. This measure compares the structure of clusters within two membership outputs, scoring if the grouping within two memberships are the same. It provides a score value ranging from 0 to 1, the closer the score value to one the more similar the clusters are, the closer the score value to zero, the more dissimilar the clusters are (Danon *et al* 2005).

Then, after assessing the consistence of the different outputs, one of the outputs was selected to explore the agricultural characteristics that defined each cluster. Results then were mapped and overlaid against the forest-use zones employing GIS procedures, then the number of observations per cluster per zone was assessed and compared with the purpose to assess if different clusters (meaning different agricultural characteristics) were associated with different forest-use zones.

4. Results

4.1. Forest-use zones and presence of agriculture

Based on the spatial overlay of the location of agricultural clearings and the corresponding zone boundaries, it was assessed that agriculture was present within all forest-use zones (Table 3.2). The proportion of clearings within the different zones indicated that most of them (59%, n=1,261) occurred within the PFD, followed by nPFE (28.7%) and the PFE (11.7%). However, the extent of each zone was unequal and for the total sampled area (7,405 km²), 9.9% were allocated within the nPFE, 37.1% within the PFE (both in CAM) and 53% within the PFD (ROC). Thus, when considering the areal differences, the nPFE had the highest incidence of agriculture among all zones (0.49 clearings/km^2), followed by the PFD and the PFE with less than 0.2 clearings/km^2 (Table 3.2).

Table 3.2. Total number of agricultural clearings and normalized number clearing per zone size within the different forest use zones.

Country	Forest-use zone	Number of clearings (N)	Zone extent (km^2)	Normalized Incidence (N/km^2)
Cameroon	nPFE	362	733	0.49
	PFE	148	2744	0.05
Congo	PFD	751	3927	0.19
Total	---	**1,261**	**7404**	

4.2. Incidence and odds ratio measurements and area cleared for agriculture

Among all forest-use zones, the total area cleared by agriculture was 26.8 km². Based in this total, the PFD had the largest proportion of area cleared by agriculture (56%), followed by the nPFE (38%) and the PFE (6%). When further comparisons were conducted considering not only the extent of agriculture but also the extent of the non-affected area by agriculture by each zone (IO, incidence odds test), results indicated that the nPFE had the largest incidence (IO=0.014) of land under agriculture among zones. The IO within the nPFE was three times larger than the one within the PFD (IO=0.004) and fourteen times larger than IO within the PFE (IO=0.001; Table 3.3).

Table 3.3. Area cleared for agriculture (km^2), area sampled by administration zone and incidence ratio (IO) per administration zones.

Country	Forest-use zone	Area cleared by agriculture (km^2)	Zone extent non-affected by agriculture (km^2)	Incidence odds (IO)
Cameroon	nPFE	10.1	722.96	0.014
	PFE	1.7	2742.16	0.001
Congo	PFD	15.0	3912.39	0.004
Total		**26.8**	**7377.51**	**---**

Further analysis assessed the odds of land being cleared by agriculture within zones (odd ratio test, OR). Results indicated that the odds of land being cleared for agriculture within nPFE (OR>1) were higher than the ones within the other two zones (PFE and PFD). However, the odds of land being cleared for agriculture were similar between the PFE and the PFD (OR < 1; Table 3.4).

Table 3.4. Odds ratio (OR) and confidence interval of the area affected by agriculture between administration zones

Country	Forest-use zone	Odds ratio (OR)	95% CI upper	95% CI lower
Cameroon Cameroon	nPFE PFE	22.26	112.28	4.41
Cameroon Congo	nPFE PFD	3.65	8.15	1.64
Cameroon Congo	PFE PFD	0.16	0.80	0.03

4.3. Agricultural clearings properties clustering procedure.

Clustering analysis were based on ten different random proximity matrices. Clustering results indicated that regardless of the proximity matrix, the clustering procedure identified four clusters and that 96% of the observations (n=1,261) were grouped into two clusters large clusters (Table 3.5).

Table 3.5. Summary of the clustering analysis procedure summary detailing number of clusters obtained from each proximity matrix (a proximity matrix was defined by the number of trees used in the random forest procedure).

Membership output	Proximity matrix (N. trees)	Number of clusters (n)	Number of agricultural clearings per cluster [a] (N)				Percentage of agricultural clearings in two larger clusters
			C1	C2	C3	C4	(%)
Mem-01	1,000	4	21	644	29	567	96.0
Mem-02	2,000	4	582	660	16	3	98.5
Mem-03	3,000	4	3	13	660	585	98.7
Mem-04	4,000	4	6	32	585	638	97.0
Mem-05	5,000	4	27	11	586	637	97.0
Mem-06	6,000	4	27	15	583	636	96.7
Mem-07	7,000	4	633	13	32	583	96.4
Mem-08	8,000	4	26	16	581	638	96.7
Mem-09	9,000	4	7	35	635	584	96.7
Mem-10	10,000	4	35	17	635	574	95.9

[a] *Note:* that the naming of the cluster (e.g. C1, C2, C3 and C4) in each output is random and it does not suggest that the properties that are grouping C1 in Mem-01 are the same than in C2 Mem-02.

Further, pairwise comparison of each membership output (Mem-01 through Mem-10) employing the normalized mutual information measure (*nmi*) indicated that regardless of the initial proximity matrix, agricultural clearings were being classified similarly, suggesting that the clustering classification procedures were consistent into grouping the same agricultural clearings into a specific group (Table 3.6).

Table 3.6. Normalized mutual information "nmi" measure matrix. Pairwise comparisons are scored in a range from 0 and 1. Values closer to 1 indicated similarity in the ways data was being partitioned.

Membership output	Mem-01	Mem-02	Mem-03	Mem-04	Mem-05	Mem-06	Mem-07	Mem-08	Mem-09	Mem-10
Mem-01	1									
Mem-02	0.83	1								
Mem-03	0.82	0.91	1							
Mem-04	0.87	0.84	0.86	1						
Mem-05	0.85	0.89	0.87	0.88	1					
Mem-06	0.86	0.90	0.89	0.90	0.96	1				
Mem-07	0.88	0.90	0.86	0.90	0.92	0.94	1			
Mem-08	0.85	0.90	0.88	0.89	0.96	0.98	0.93	1		
Mem-09	0.89	0.88	0.86	0.91	0.90	0.91	0.95	0.91	1	
Mem-10	0.88	0.86	0.86	0.89	0.91	0.92	0.93	0.92	0.90	1

4.4. Common agricultural properties within clusters

For the following analysis, Mem-03 was selected to assess which agricultural properties were distinguishing the different clusters. Mem-03 was selected under the consideration that it had a good agreement with other nine outputs (*nmi* ranged between 0.86 and 0.89, Table 3.6). Also for

Mem-03 “cluster 4” (n=660) and “cluster 3” (n=585) contained 98.7% of all observations (Table 3.5). Cluster 3 and Cluster 4 from this point forward would be referred as “dominant clusters”.

Of the thirteen agricultural variables evaluated (Table 3.1), the ones that had a higher influence in the partition of the agricultural clearings into these two distinctive clusters were a combination of plot neighborhood characteristics (number and distance to nearest neighbors), accessibility (distance to transportation) and social characteristics (proximity to settlements and population density). Characteristics of the clearings in *Cluster 4* were: 1) high incidence of clearings in very close proximity to each other (i.e. 75% of the clearings had at least 13 neighboring clearings in the 0.5 km radius); 2) clearings occurred in close proximity to settlements with high population densities (i.e. 75% of the clearings occurred at least 1.4 m from a settlement); 3) occurred in areas with high population density (i.e. 75% of the clearings were at least in areas which population density was 6.4 roofs/km^2; the average roofs density for all clearings was 2.4 roofs/km^2) and 4) occurred in near transportation (100% of the clearings were located least 3.5 km from a road or a navigable river). Clearings in *Cluster 3* presented the opposite tendencies: 1) clearings were less aggregated (75% of the clearings had at least 3 neighboring-clearings in a 0.5 km radius); 2) they were further from settlements (75% of the clearings were at least 3.8 km from a settlements); 3) located within lower density population centers (75% of the clearings were within locations with at least 0.6 roofs/km^2); 4) clearings occurred near and far from transportation (86% of the clearings were at least 2 km from transportation while 9.3% further than 4 km up to 14 km). Differences between both clusters were further reflected in the distances to twentieth-neighbor, for *Cluster 3*, 75% of the clearings had their twentieth-neighbor at least at 7.6 km, while for *Cluster 4* the distance was 1.8 km.

For the clearings allocated within Cluster 1 and Cluster 2, the characteristics that described their partitioning are mostly described by the plot sizes. *Cluster 1* contained very small clearing (< 0.35 ha), occurring close to other clearings, while Cluster 2 contained clearings which size tended to be larger (75% were at least 9 ha) and tended to be located farther from other clearings (for evaluated agricultural properties. Summary statistics of the agricultural properties for all clusters in Mem03 are given in Table F.1; histogram distributions for *Clusters 3* and *Cluster 4* are presented in Figure F.1.

4.5. Administration land use zones and agricultural clusters.

In addition, the location of the clusters within Mem-03 were employed to assess the relationship of these clusters to the boundaries of the forest-use zones. Results indicated that in CAM, for the agricultural clearings within the nPFE (n=362), 64% were within the nPFE were associated with *Cluster 4* and the remaining 36% were clearings associated with *Cluster 3*; while for the clearings within the PFE (n=148), 97% of the clearings were within *Cluster 3* while 3% were within *Cluster 4*. For clearings in ROC (PFD, n=751), 51% of the clearings were part of Cluster 3 and 47% to Cluster 4, and the remaining 2% were associated to Clusters 1 and 2 (Figure 3.6).

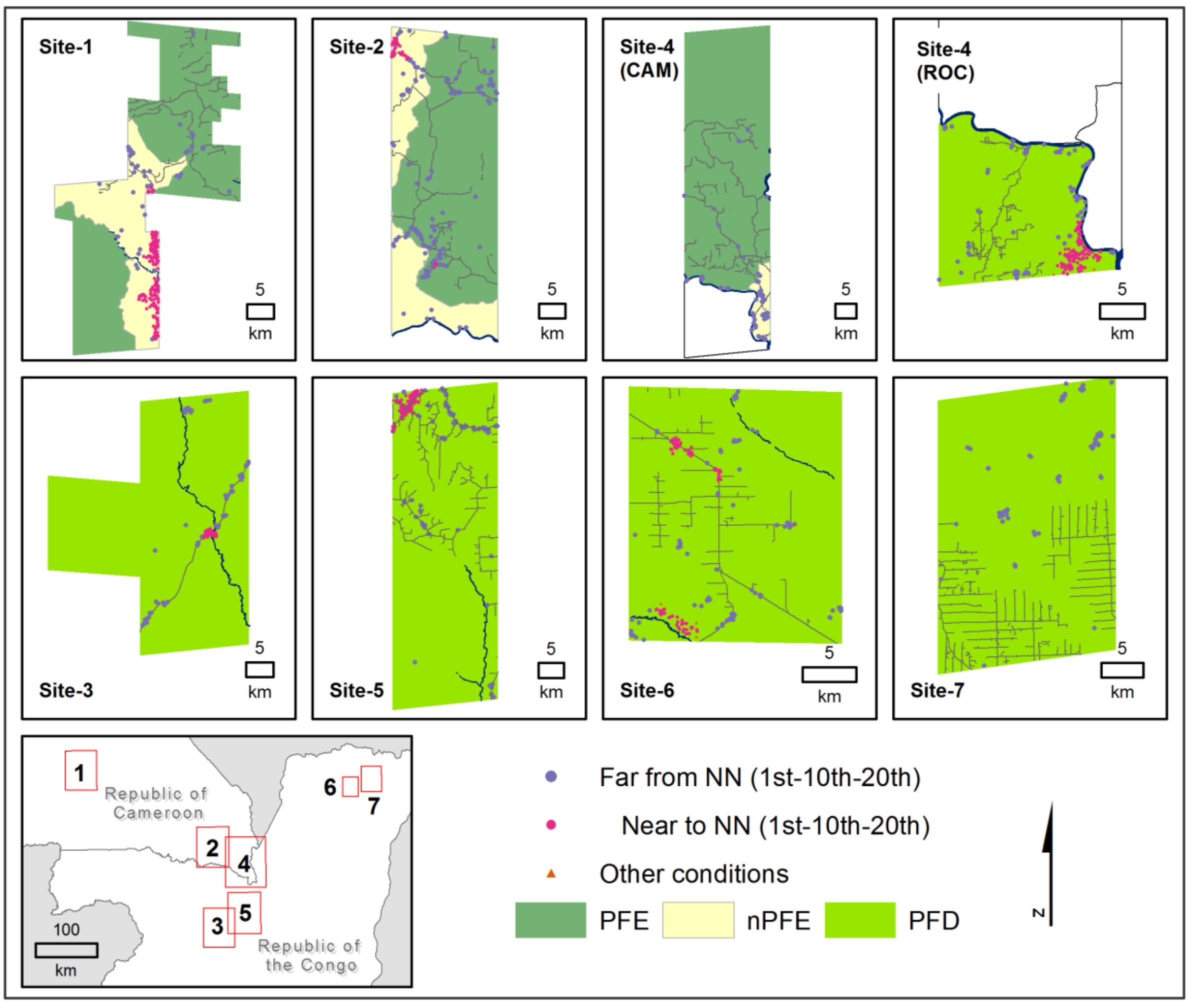

Figure 3.6. Spatial allocation of the agricultural clusters (based on agricultural characteristics) with respect to the different administration zones. Clearings within *Cluster 3* were labeled as "Far from NN" and *Cluster 4* as "Near to NN". Clearings within *Cluster 1* and *Cluster 2* were grouped into one class (*Other conditions*).

5. Discussion

This study observed the relationship between forest zoning (policy instruments to control administration of forest resources) and the presence of agricultural clearings within dense forest areas in the Congo Basin (land under customary rights by local indigenous populations). Policies toward subsistence agriculture within forested areas differed for the two countries under study. In Cameroon, the zoning defined areas of *non-permanent forest*, which included population centers and their surrounding mosaic-croplands. In Congo, the anthropogenic landscape was included as part of the *permanent forest* and it was left to the discretion of the forest managers (i.e. logging companies) to delimit "agricultural friendly areas" for the use of those populations. Results showed that agriculture was present within all the evaluated forest-use zones: the PFE and nPFE (permanent and non-permanent forest estates) in Cameroon and the PFD (permanent forest domain) in Congo. However, in Cameroon most of the agricultural incidence and extent occurred within the nPFE. When assessing the extent of agricultural clearings with respect to the extent of the three zones, results showed that the land within the nPFE had higher odds of been use for agriculture compared to the PFE and the PFD.

5.1. Forest zones and presence of agriculture

Agriculture was present within all the evaluated forest-zones. The highest incidence and extent of agricultural clearings were observed within the nPFE (0.49 clearings/km^2, IO=0.014) in contrast to the permanent forest zones. These findings were similar to the ones reported by Bruggeman *et al* (2015); in their study, researchers detected higher rates of deforestation and degradation within the nPFE than in the PFE for the period 2002-2010. Despite the low incidence of agriculture in the permanent forest zones, it was of importance to assess the nature of those clearings. Spatial assessment of the presence of clearings within the PFE indicated that clearings only occurred within the FMUs (forest management units) but not within protected areas (i.e. parks). A possible cause of the association between agricultural clearing and FMUs could be related to the need to complement logging working diets while ongoing logging is occurring (Molinario *et al* 2015). This possible association was examined by assessing 1) the distance relationships between clearings and roads within the FMUs and 2) the percentage (based on the road length) of maintained logging roads (roads free of canopy coverage; for details in roads database, refer to Chapter 1 and APPENDIX C.) within the FMUs. A higher percentage of maintained roads would suggest the presence of ongoing logging operations. The assessment indicated that there was a strong relationship between roads and agriculture, as 84% of the clearings within the PFE (n=148) occurred within 2 km from a road. Incidence of agriculture with the FMUs was higher when percentage of maintained roads was high, as observed in Site-2 (0.14 clearings/km^2, 66% of the roads were maintained); the opposite trend occurred in sites 1 and 4 (clearings incidence was less than 0.04 clearings/km^2 and percentage of maintained road was 39% of less). However, it is also possible that that some of the observed clearings were associated with new settlers, as observed Poulsen *et al* (2009) in the Democratic Republic of the Congo.

In the PFD, existing cartography of the land management series for the Congolese sites was only available for sites 3, 4 (southern site section) and 5. The sites were located within the Ngombé-FMU (FMU total extent =1,1596 km^2, Figure 3.4). Of the clearings within sites 3, 4 and 5 (n=751), only 34% were within a defined land management series; the remaining clearings were within areas that were excluded from the plan as they were part of the city of Ouesso's periphery, and defined by the FMU managers as non-forest areas (IFO-Danzer *et al* 2009, Tessa *et al* 2012). Thus, of the clearings with series cartographic information (n=256), 77.7% were located within the community development series, in which agriculture could occur. Clearings were also present in the production (20.7%), and protection (1.6%) series. Of the clearings within the production series (n=40), 85% were near (< 0.5 km) a logging roads, 10% were within 6 km from a public road and 5% were between 5 to 8 km from a navigable river; for clearings in the protection series (n=2), all were within < 0.06 km from a logging road. For sites 6 and 7, it was only possible to assume that clearings near logging roads occurred within the productive series. In these two sites, the road network was built to support logging activities after the year 2000. For Site 6 (n=175), 67% of the clearings and 67% of the area cleared by agriculture occurred within first 3 km from a logging road. Nevertheless, the high percentage of nearby clearings to roads must be taken with caution as the roads crossed the village of Mimpoutou, a population center that dated back the European arrival as recounted by O'Hanlon (2005). For Site 7 (n=72), only 18% of the clearings and 28% of the area cleared by agriculture occurred at the 3-km range and while 72% of the clearings were further than 5 km (up to 15 km). Overall, for the Congo sites, it seemed that most clearings occurred within the community development series but results also highlighted the occurrence of agriculture in production forest and that these clearings presented similar dependencies to transportation (specially logging roads) as observed in the PFE.

5.2. Characteristics of the agricultural landscape and zoning

Analysis of the characteristics of the mapped agricultural clearings indicated two distinctive patterns that describe how agriculture was occurring on the ground. Each pattern has different ecological consequences and therefore possible implication for management. One pattern described clearings that tended to occur near each other and near large population centers; this pattern was present in in 585 of the mapped clearings (equivalent to 46% of the clearings). The relationship between clearings in the aggregated pattern and the zoning boundaries indicated that 46% occurred in the nPFE, 1% in the PFE, 47% in the PFD (within sites 4 and 5 but within territories considered non-forest by the Ngombé-FMU managers) and 7% within the PFD-community development series (sites 3 and 5). Interestingly, the settlements near these clearing within the nPFE, the PFD (community development and non-forest zone) shared a common characteristic, agriculture was not the only economic opportunity. Clearings in the nPFE occurred within the periphery of the town of Lomié (located outside Site 1), which is a community forest with legal rights to manage forest resources (Oyono 2005) and also harbor a commercial sawmill (as observed in recent satellite imagery Google Earth and Digital Globe 2016, Figure E.32). Clearings in the PFD-non-forest zone, were in the periphery of the city of Ouesso (Sites 4), an important trade center (Laporte *et al* 2012) or the town of Ketta (Site 5) which in the year 2015 have an active mining permit for the exploitation of rough diamonds (Government of Republic of Congo *et al* 2016). Clearings in the PDF-community development were located in the town of Liouesso (Site 3) that in the year 2012 started the construction of an hydroelectric plant, with a capacity of 19.2MW (Lenckonov 2015). However, it is unknown if all these economic activities were actively influencing the local economies at the time in where data was collected (circa 2008) but there is evidence that these settlements are fostering a specific agricultural pattern that could be linked with common drivers of deforestation observed in other tropical regions (Geist and Lambin 2002), including demand for land and an increase in population growth encouraged by new economic opportunities. From the ecological perspective, larger concentrations of disturbances (i.e. agricultural clearings) could be related to land competition and affect fallow recovery, this as people would more likely to shortened fallow periods, in addition, large concentrations of disturbances would increase forest fragmentation and exacerbate edge effects, which would also negatively affect the forest recovery process (Brown 2006, Bogaert *et al* 2008, Lawrence *et al* 2010). From the management perspective, results showed that agricultural clearings tended to occur in an aggregated pattern within *agricultural friendly zones.* In this case (e.g. Site 1-nPFE), the development of new policies and direct programs that focused on sustainable agricultural practices compatible with local livelihoods may avoid leakage into areas of permanent forest.

The second dominant pattern (n=505) was characterized by clearings that occurred further from each other and near smaller settlements. The pattern was observed in different zones and sub-uses: nPFE (26.1%), PFE (28.3%), PFD-productive series (8.3%), PFD-community development series (23%) and PFD-non-forest (14.3%). Ecological concerns about this pattern are related more to forest degradation processes than to deforestation, as it occurs near settlements with lower population densities. Further research on degradation intensity would need to be completed, however, if fallow recovery times are respected, the detriment toward forest functions and biodiversity could decrease (Wasseige *et al* 2015). From the management perspective, especially within the PFE and the PDF, productive series must guide control efforts to enforce logging company's responsibilities to ensure that workers do not conduct agriculture within productive forest, but also increase control strategies to minimize the occurrence of new settlers.

Spatial analysis of the relationship between zoning practices and occurrence of agriculture clearings within forested areas, has the potential to guide future management practices to support forest conservation that includes small agricultural systems. The inclusion of agriculture as part of conservation strategies is a recent shift in the conservation paradigm, especially because multidisciplinary research has recognize that negative effects on the ecosystems are exacerbated when farmers are vulnerable to food security, poverty and negative effects of climate change (DeFries *et al* 2010, Morton 2007, Ickowitz 2006, Ashley *et al* 2006, van Vliet *et al* 2012).

6. Conclusions

This study helped to broaden the conversation regarding small scale agricultural practices within the Congo Basin that are often generalized as one of the main threats to deforestation in the region. Generalizations about agriculture and deforestation only promote a dialog of blaming communities that in most cases do not have the legal rights to make decisions on land administration on land under their customary rights. Findings indicated that in most instances, the observed agricultural clearings occurred within areas in where this activity was allowed. Thus, the acknowledgement of the lawfulness of the location of agriculture within forested areas allows us to shift the dialog from a problem of deforestation (under the umbrella of possible land colonization) to a focus on plausible strategies that could improve agricultural practices as part of conservation efforts, and with it ensure sustainable approaches to food security and food accessibility for local populations. Furthermore, the identification and quantification of clearings occurring outside established agricultural areas help to narrow its proximate causes and develop better mechanisms that help promote forest conservation and small scale agriculture.

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APPENDICES

APPENDIX A.

World View 1 imagery

Figure A.1. World View-1 imagery (panchromatic sensor at 0.5 m/ spatial resolution employed to map Site1

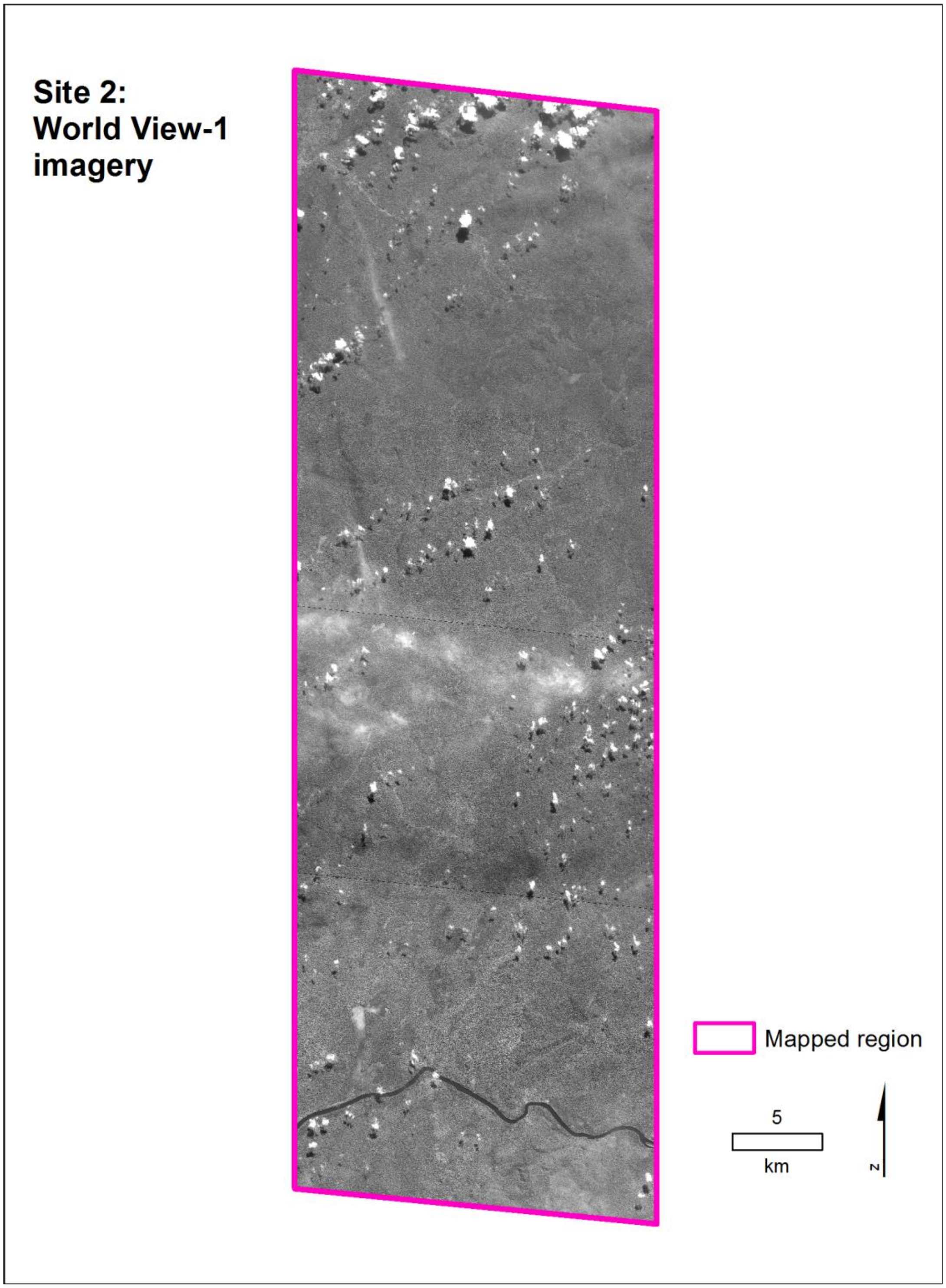

Figure A.2. World View-1 imagery (panchromatic sensor at 0.5 m spatial resolution employed to map Site 2

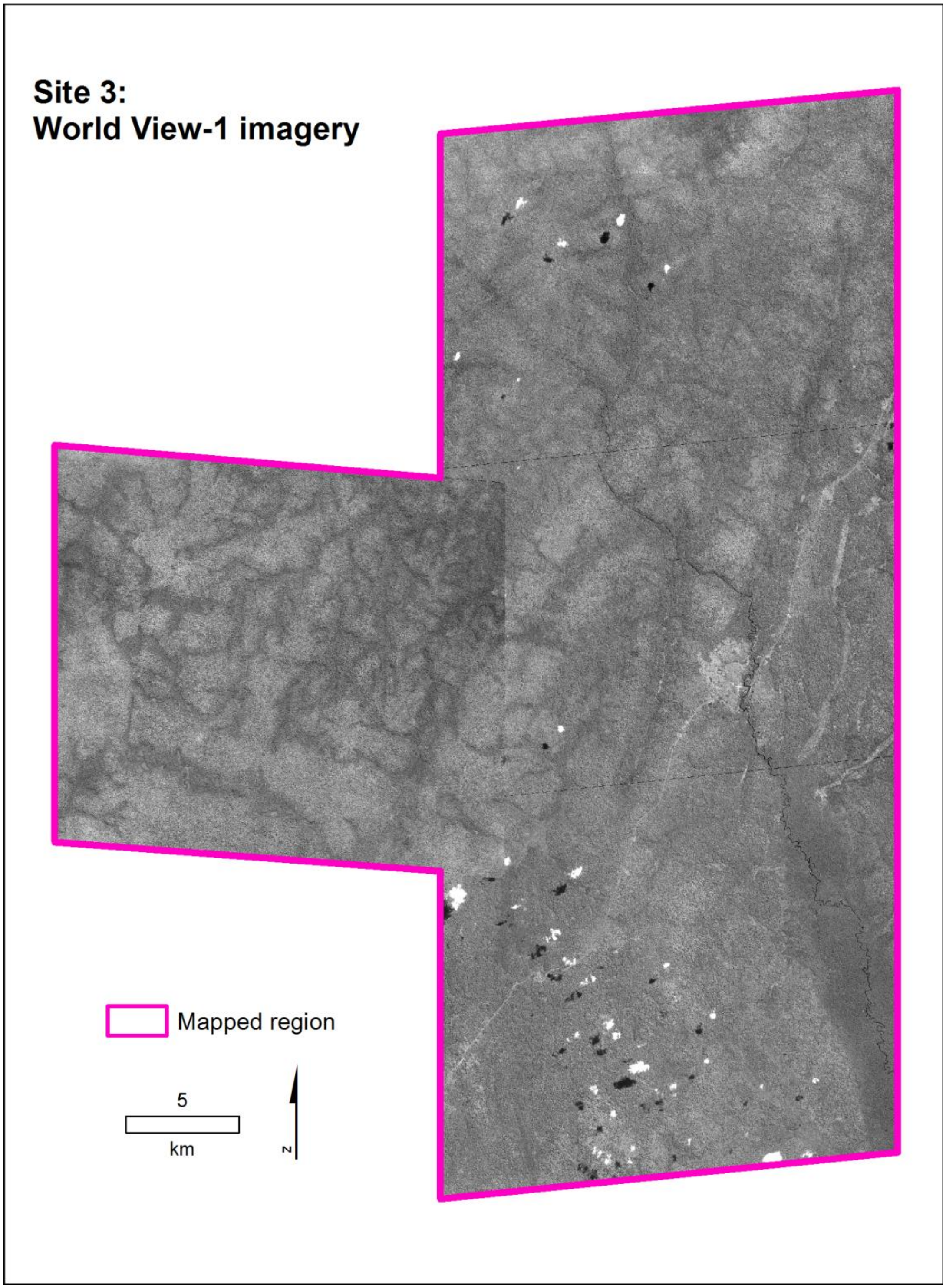

Figure A.3. World View-1 imagery (panchromatic sensor at 0.5 m spatial resolution employed to map Site 3

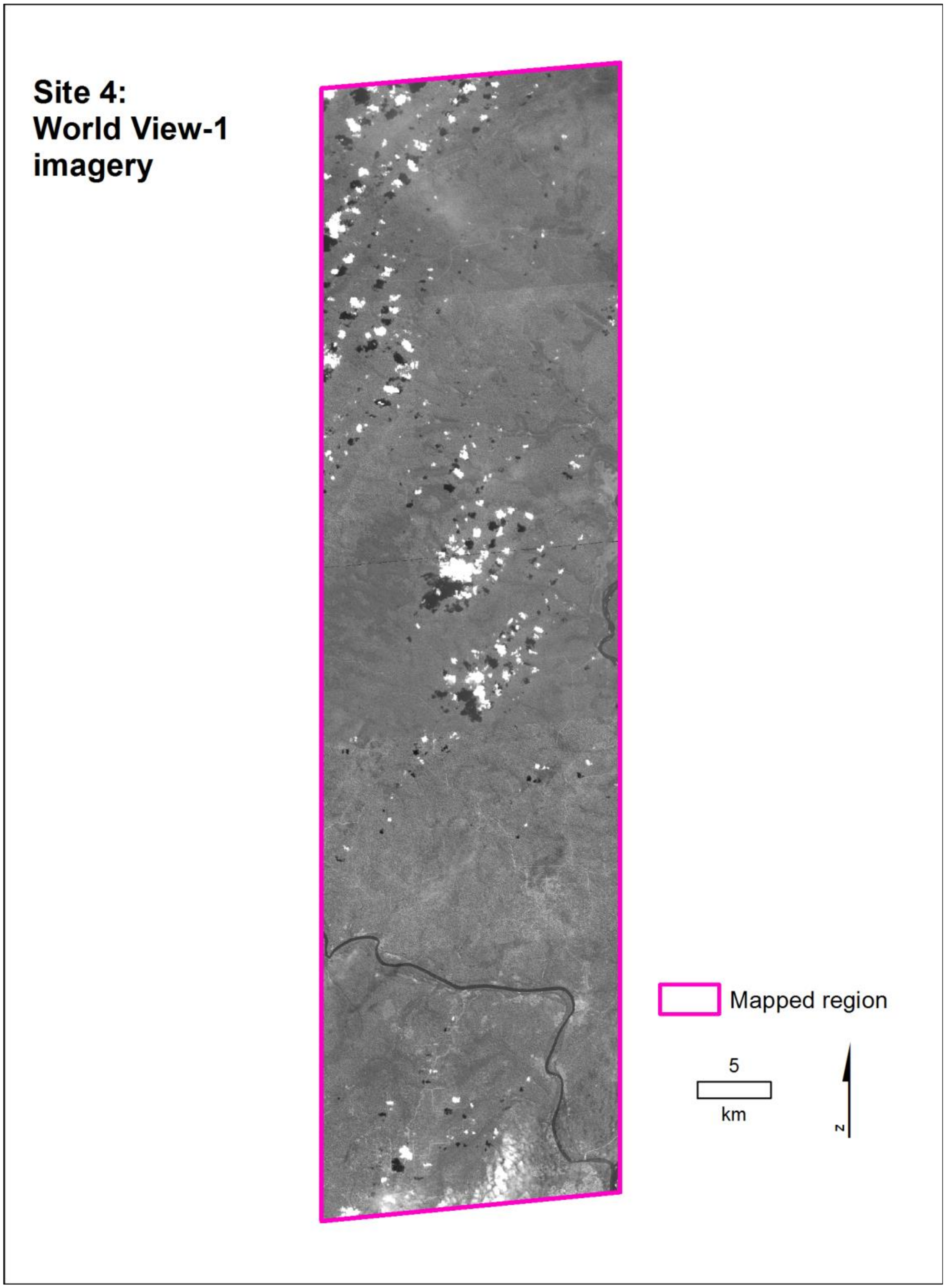

Figure A.4. World View-1 imagery (panchromatic sensor at 0.5 m spatial resolution employed to map Site 4

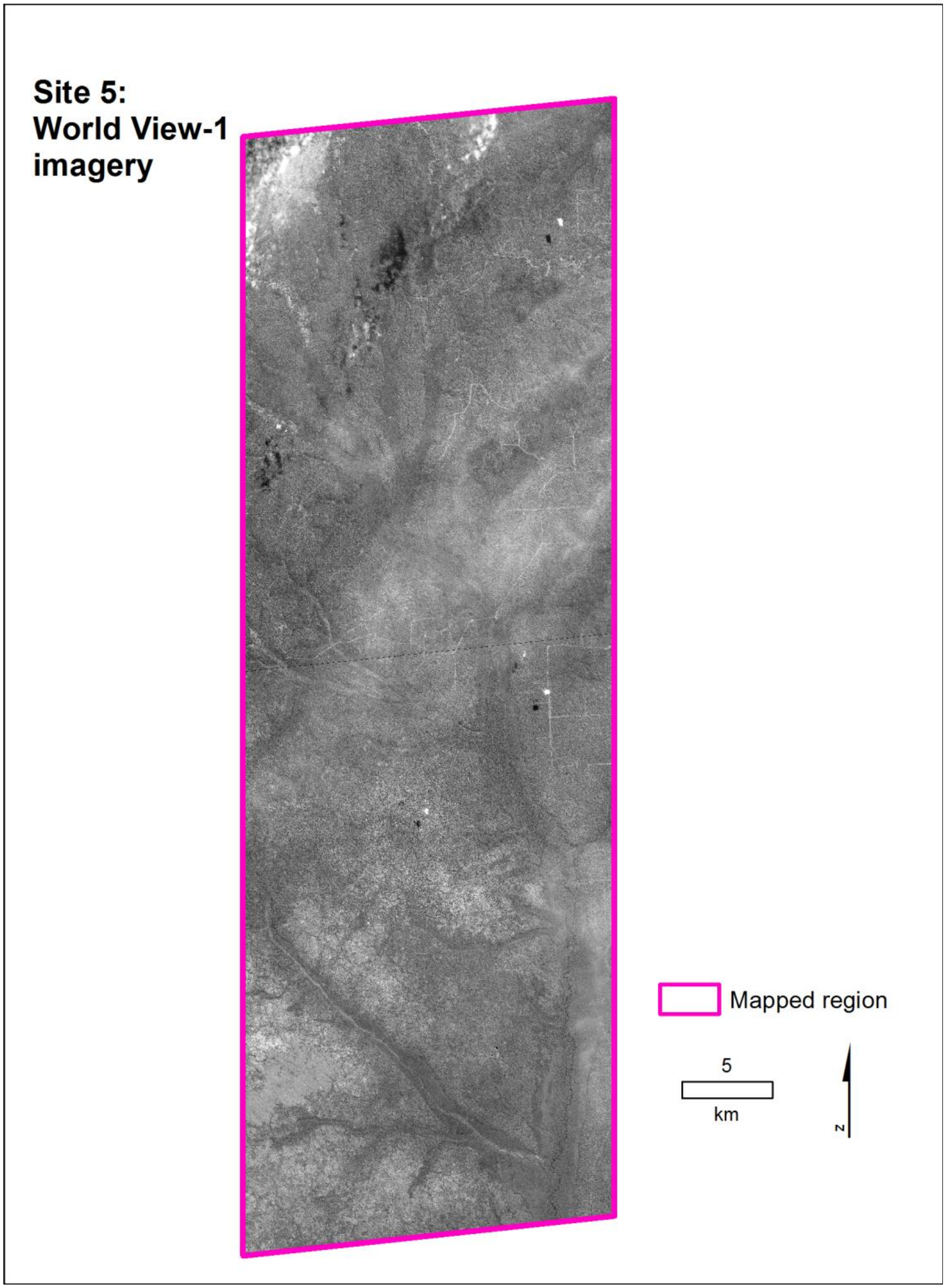

Figure A.5. World View-1 imagery (panchromatic sensor at 0.5 m spatial resolution employed to map Site 5

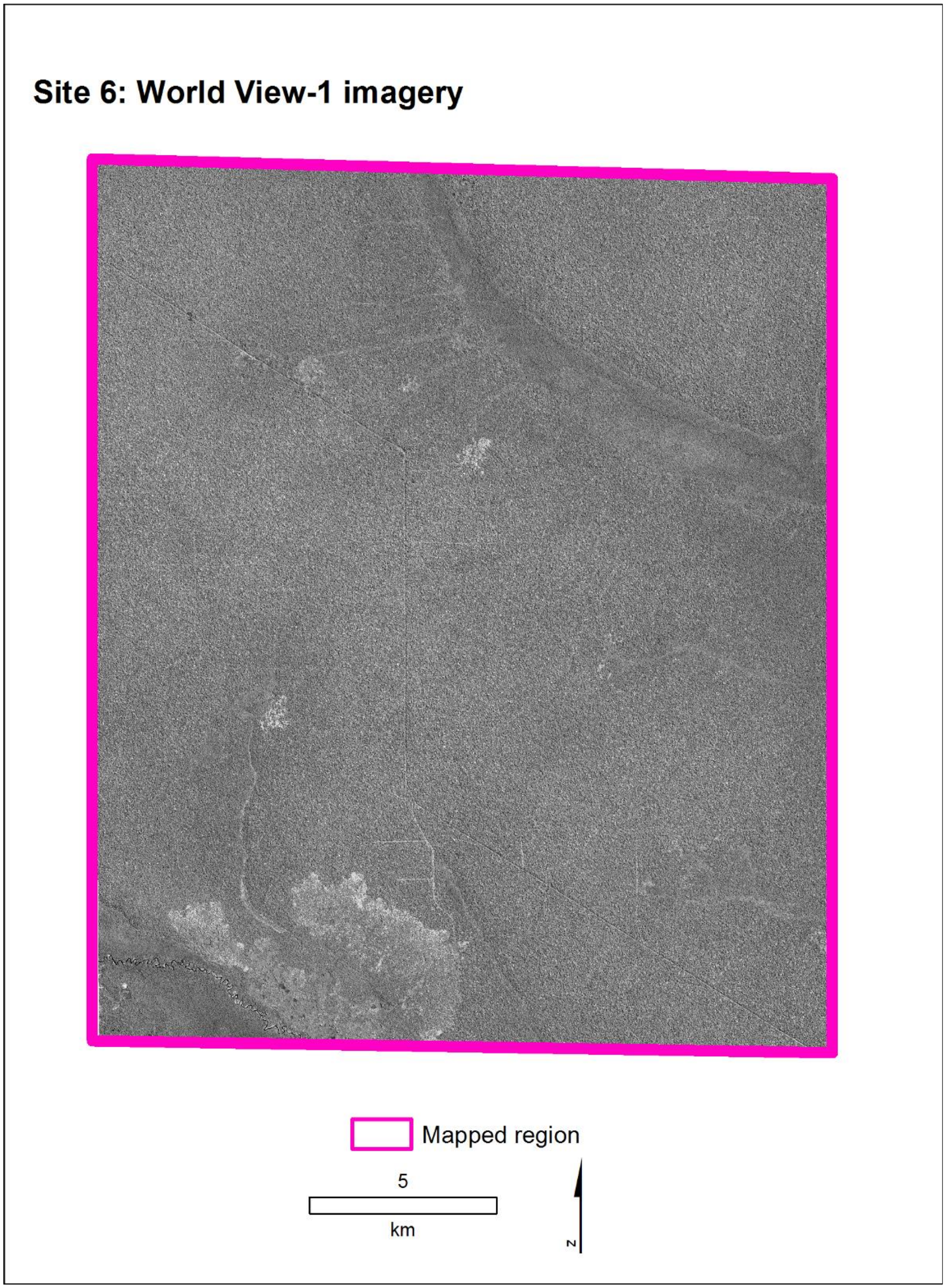

Figure A.6. World View-1 imagery (panchromatic sensor at 0.5 m spatial resolution employed to map Site 6

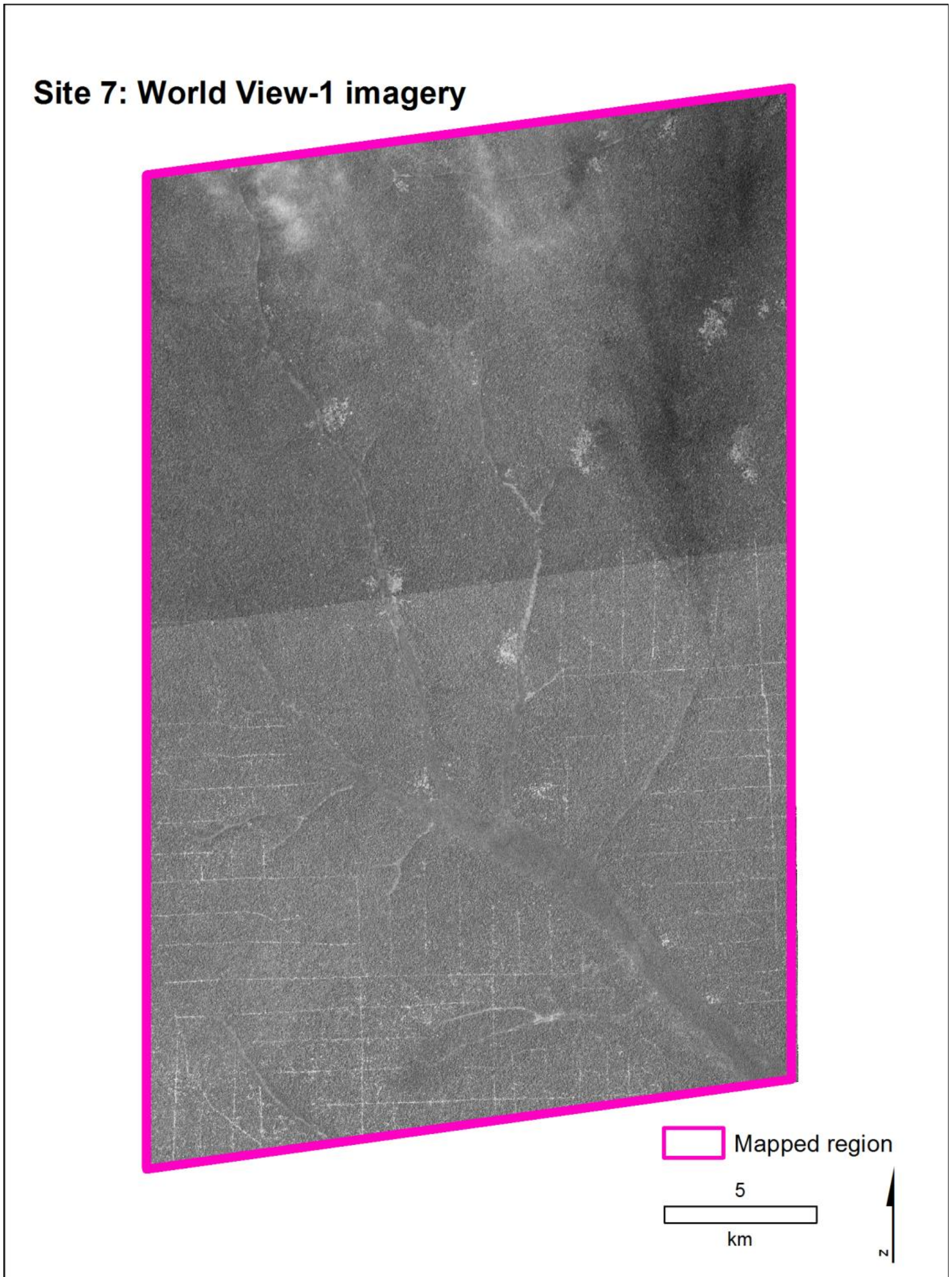

Figure A.7. World View-1 imagery (panchromatic sensor at 0.5 m spatial resolution employed to map Site 7

APPENDIX B.

Landsat imagery summary

Table B.1. Number of the WV-1 images per site employed to survey the seven case study sites by WRS-2 path and row system.

Path/Row	Date	Site (N of WV1-images)						
		1	**2**	**3**	**4**	**5**	**6**	**7**
181/058	2007/11/27	---	---	---	---	---	---	2
	2008/03/06	---	---	---	---	---	2	---
182/058	2008/05/05	---	---	---	2	---	---	---
	2008/05/31	---	1	---	---	---	---	---
182/059	2008/04/22	---	---	3	---	---	---	---
	2008/05/05	---	----	---	3	4	---	---
	2008/05/31	---	3	1	---	---	---	---
184/058	2008/05/13	2	---	---	---	---	---	---
	2008/11/01	3	---	---	---	---	---	---
TOTAL		**5**	**4**	**4**	**5**	**4**	**2**	**2**

Table B.2. Landsat (TM &ETM+) scenes used to assign proximate construction period attribute for roads mapped with WV-1 imagery

Site	Period-Before-1990	1990-2000	Period-2001-2008
1	TM: p184r058-1984	ETM+: p184r058-2000	ETM+: p184r058-2008 WV-1: 2008
2	TM: p183r058-1987 TM: p182r059-1990	ETM+: p182r059-2000 ETM+: p182r058-2000	ETM+: p182r059-2008 ETM+: p182r058-2008 WV-1: 2008
3	TM: p182r059-1986 TM: p182r059-1990	ETM+: p182r059-2000	ETM+: p182r059-2008 WV-1: 2008
4	TM: p182r059-1986 TM: p182r059-1990	ETM+: p182r059-2000 ETM+: p182r058-2000	ETM+: p182r059-2008 ETM+: p182r058-2008 WV-1: 2008
5	TM: p182r059-1986 TM: p182r059-1990	ETM+: p182r059-2000 ETM+: p182r058-2000	ETM+: p182r059-2008 ETM+: p182r058-2008 WV-1: 2008
6	TM: p181r058-1986	ETM+: p181r058-2000	ETM+: p181r058-2007 WV-1: 2007
7	TM: p181r058-1986	ETM+: p181r058-2000	ETM+: p181r058-2007 WV-1: 2007

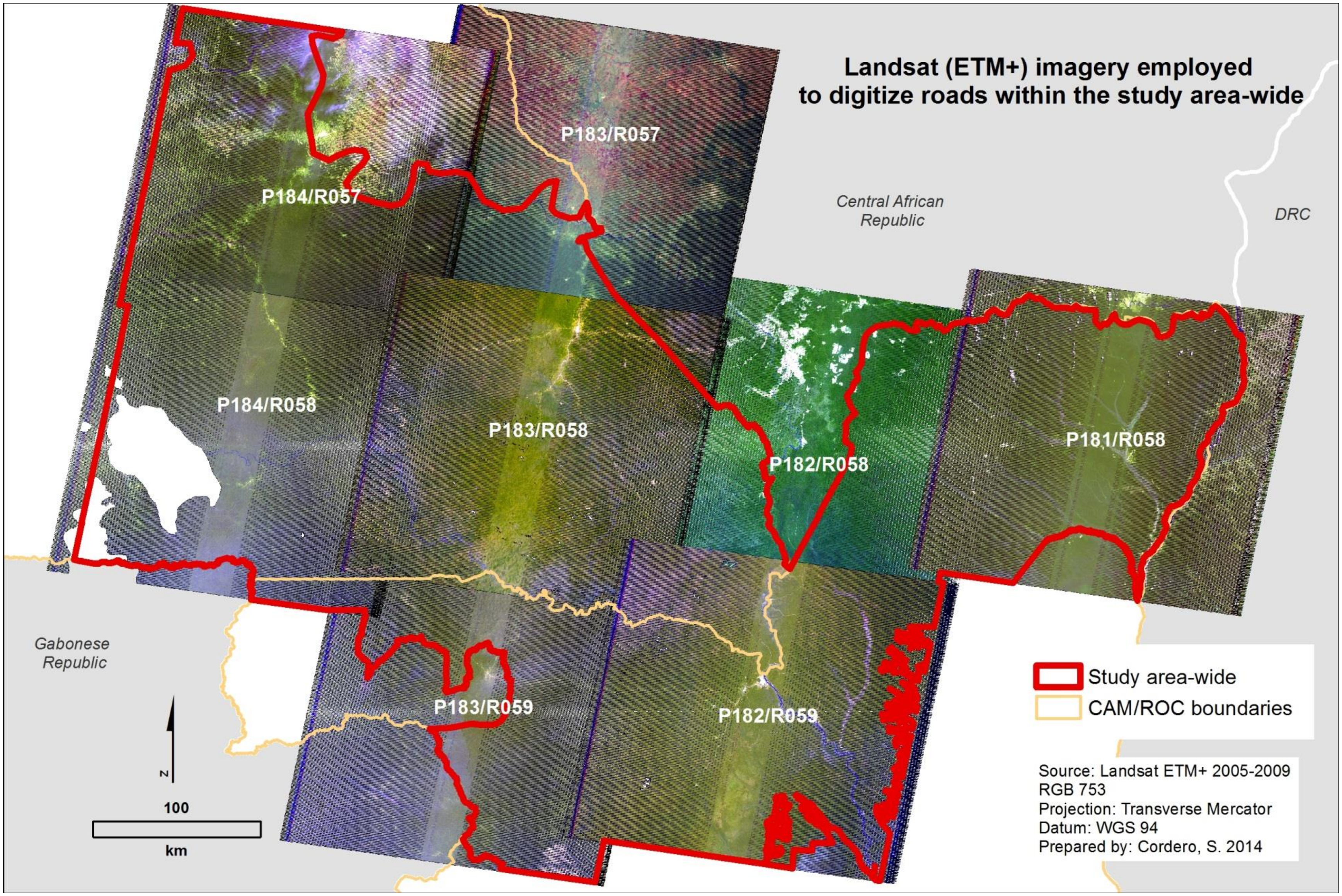

Figure B.1. Index map of Landsat (ETM+) imagery, from 2005-2009, employed map the road network on the study area wide. Note: RGB for P182/R058 shows different hue of green due clouds were not mask out, as they were located outside the area the study area-wide

Table B.3. Landsat (ETM+) scenes used for road study are-wide database (2005-2008) by path/row.

	WRS-2 Path/Row							
	P181/R057	P182/R057	P182/058	P182/059	P183/058	P183/059	P184/057	P184/058
Date	207/05/10	2009/01/05	2008/0213	2008/0213	2009/01/05	2005/01/10	2008/12/27	2008/12/27
Sensor	ETM+	ETM+	ETM+	ETM+	ETM+	ETM+	ETM+	ETM+

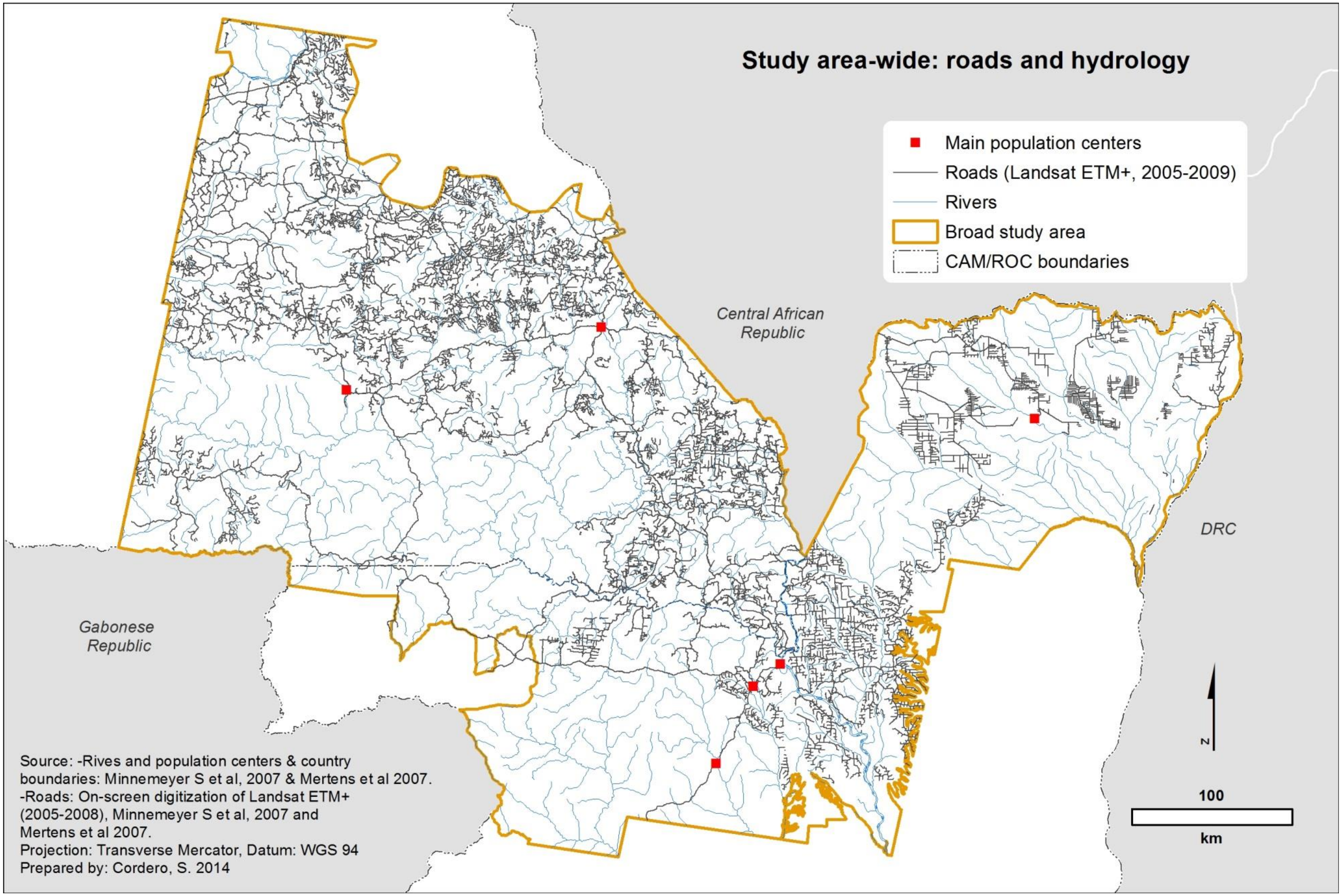

Figure B.2. Roads, rivers and larger population centers within the study area-wide

APPENDIX C.

Classification scheme

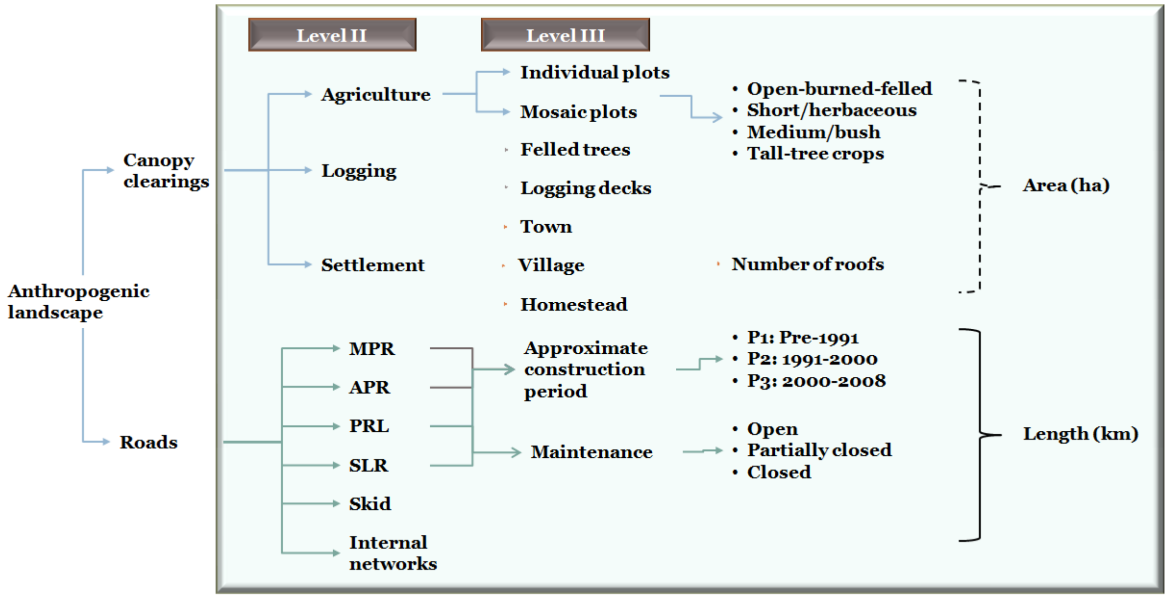

Figure C.1. Classification scheme summary. A hierarchical scheme was employed to describe different types of canopy clearings observed in the study area.

Table C.1. Classification scheme: canopy clearings types

Level I	Level II	Definition	Attributes
Agriculture	Individual plots	Canopy clearings of diverse size (e.g. 0.5, 1 ha). Covered by a uniform vegetation coverage including: burning fields, felled trees, open/bare soils, evidence of recently planted crops (combination of open/bare soils plus texture that looks like a grid of dots), herbaceous vegetation, scrubs vegetation). Clearing edges are surrounded by forest	- Vegetation coverage type - Area (units: m^2)
	Mosaic plots	At least two adjacent clearings with different vegetation coverage (e.g. burned fields and herbaceous vegetation)	
Settlements	City	Urban area, mix of larger density of houses, buildings, industrial development, roads.	- Number of roofs (n); roofs were digitized as an independent layer - Area (units: m^2)
	Town	Tended to occur near roads. Mix of houses, cropland. They are larger and more developed areas than villages.	
	Village	Settlements with a few houses (e.g. > 10 houses or roofs), not very urbanized, surrounded by farmland. Houses usually allocated along a road.	
	Logging camp	Buildings along or adjacent to extractive roads in a forest concession. Few houses used for field workers to sleep during forest operations. Non-permanent	
	Homesteads	Could occupy 1 ha, with few small buildings or houses, usually allocated in circular pattern. Nearby cropland usually present evidence of a diverse agricultural activity.	
Logging canopy gaps	Individual trees gaps	Usually ellipsoidal-shape canopy gaps (circa ~ 40-60 m of diameter). Distinctive from agricultural clearings by the presence of timber debris (e.g. canopies/branches or logs) and nearby logging network (e.g. skid roads, secondary logging roads.	- Area (units: m^2)
	Logging decks	Cleared areas along roads (usually square shaped). Used to temporal storage of timber logs. Diverse sizes	

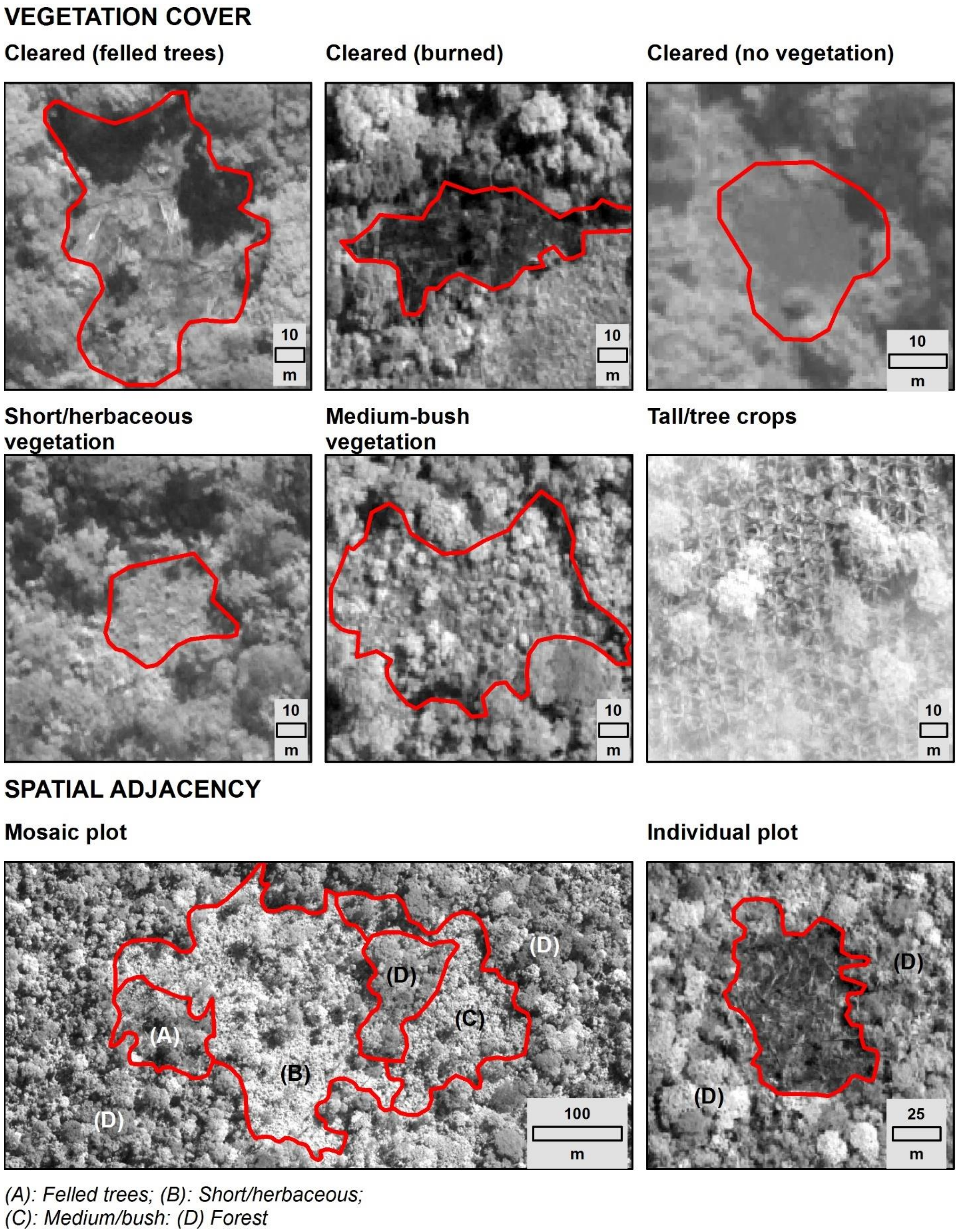

Figure C.2. Examples of agricultural clearings types (individual and mosaic plots) and attributes (vegetation coverage types), as observed in WV-1 satellite images

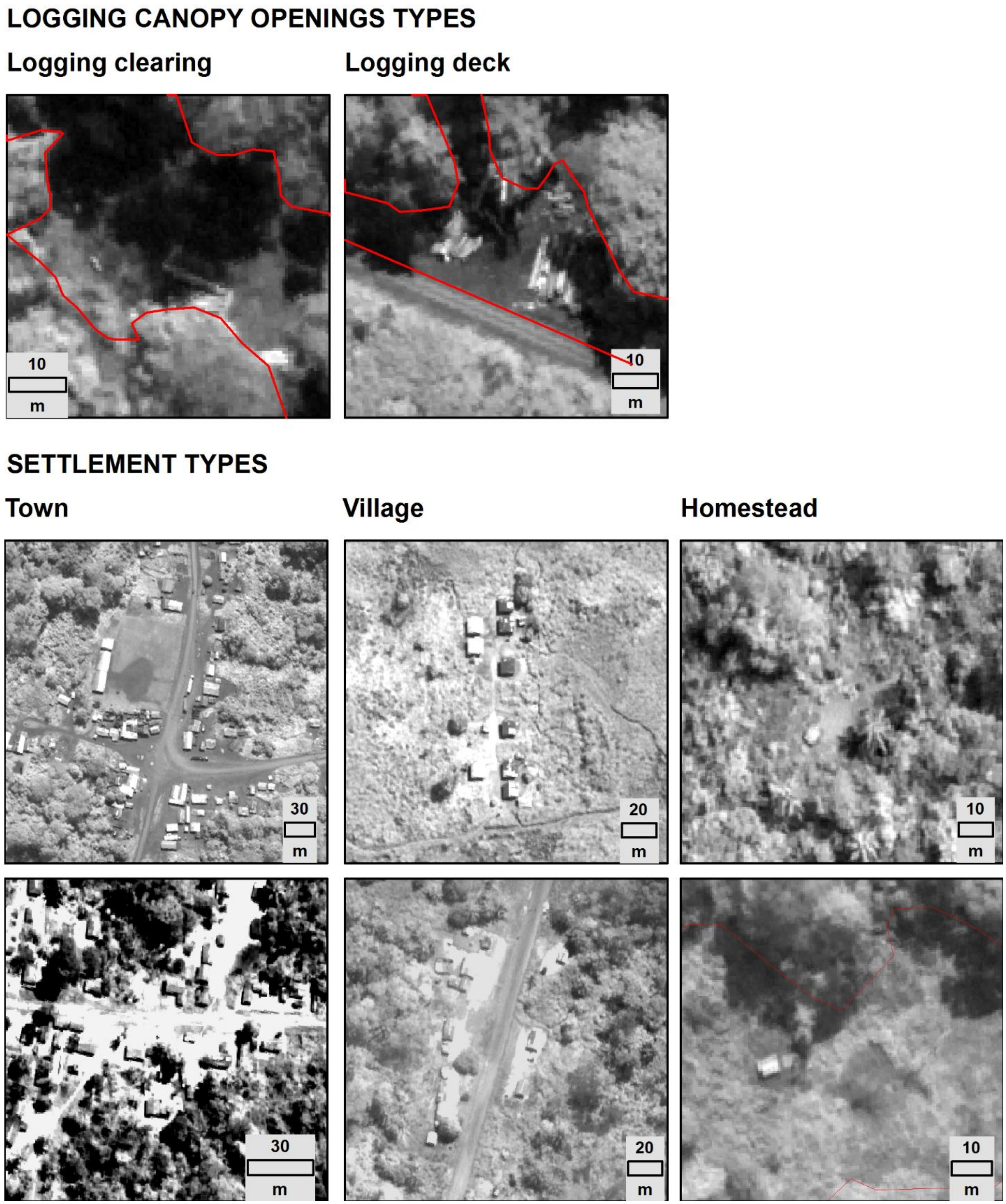

Figure C.3. Examples of logging clearings and settlement types, as observed in WV-1 satellite images

Table C.2. Classification scheme: road types

Level II	Code	Definition
Main public roads	**MPR**	Main public roads. Are routes that connect mayor cities and towns. Road-bed is wide and free of canopy coverage. Roads with the region are not-paved.
Auxiliary public roads	**APR**	Roads perpendicular or just adjacent to MPR, that are not related to logging Roads could have short, but they are usually and not as wide as the MPR
Primary logging roads	**PLR**	Open roads that generally occur within the limits logging concessions. Their function is to move logs from forest to market, therefore, usually connect to MPR. Road-beds are generally open, free of canopy coverage, and capable of sustain traffic of trucks and other heavy machinery. Roads are kept open (active) for more than one harvesting season. Other median size roads connect to it (it could look like a fish bone pattern). In some instances, visible presence of logging activities (felled trees or logging decks)
Secondary logging roads	**SLR**	Roads that connect to PLR. Their function is to move logs from the forest to a logging deck or a PLR. Road-bed tend to be more narrow than PLR. Roads are less permanent. Road-bed could be partially or completely covered by tree canopies, which suggest that the road was abandon. In the WV-imagery, when the roads are completely covered by canopy coverage, the canopies look almost white.
Internal network	**IN**	Very small roads, usually only visible within agricultural plots (free of canopy coverage). Usually find around settlements, connecting agricultural plots with settlements of to specific sections of the forest. These paths tend t be narrow (< 5 m–wide). In addition, some segments could be visible in the "in the middle of nowhere", far away from logging activities or main populated centers, associated to connectivity among small settlements.
Skid trails	**ST**	Very small roads, very subtle changes in the canopy. Usually connect felled trees with a secondary or main logging road.

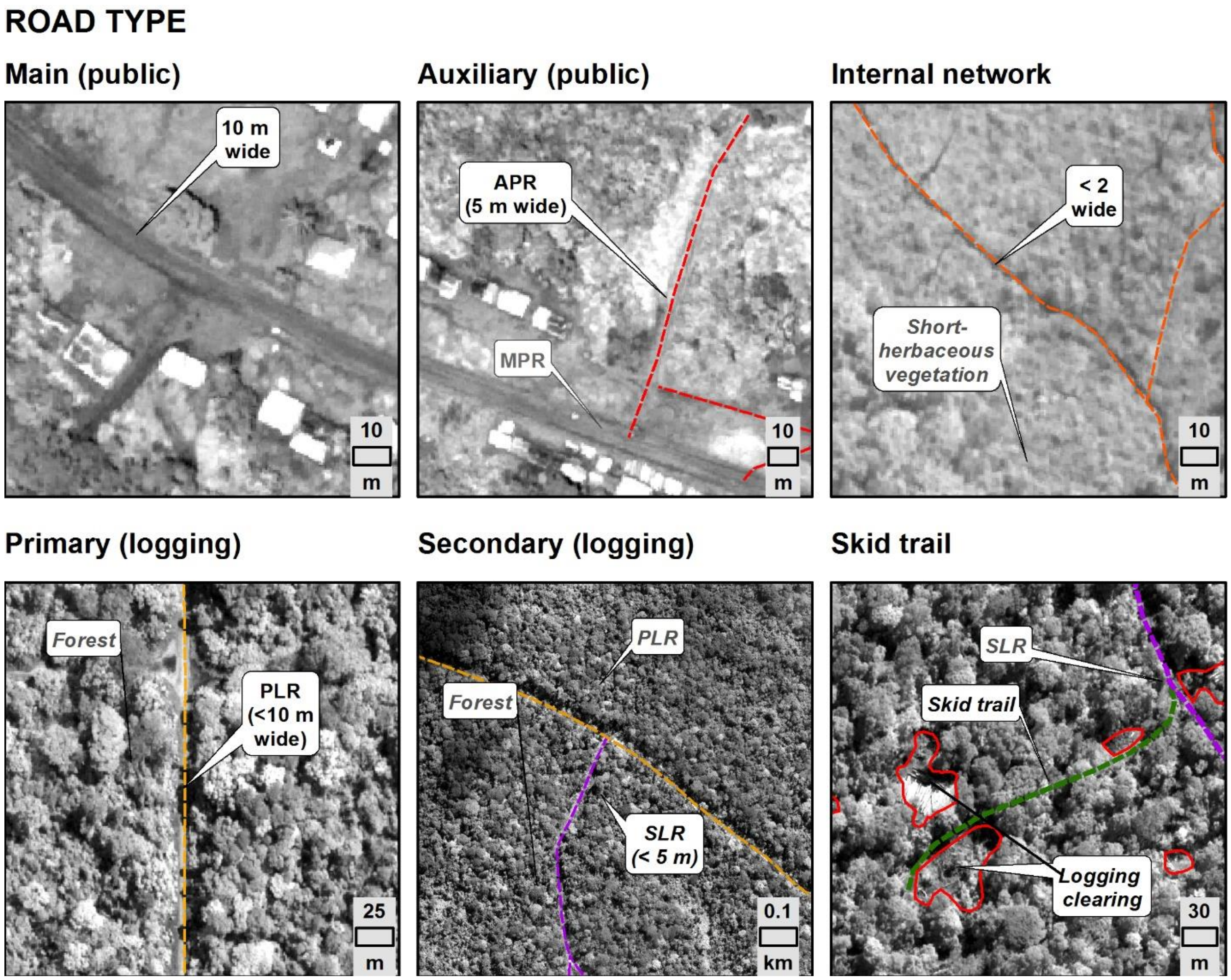

Figure C.4. Examples of the different road types as observed in WV-1 satellite images

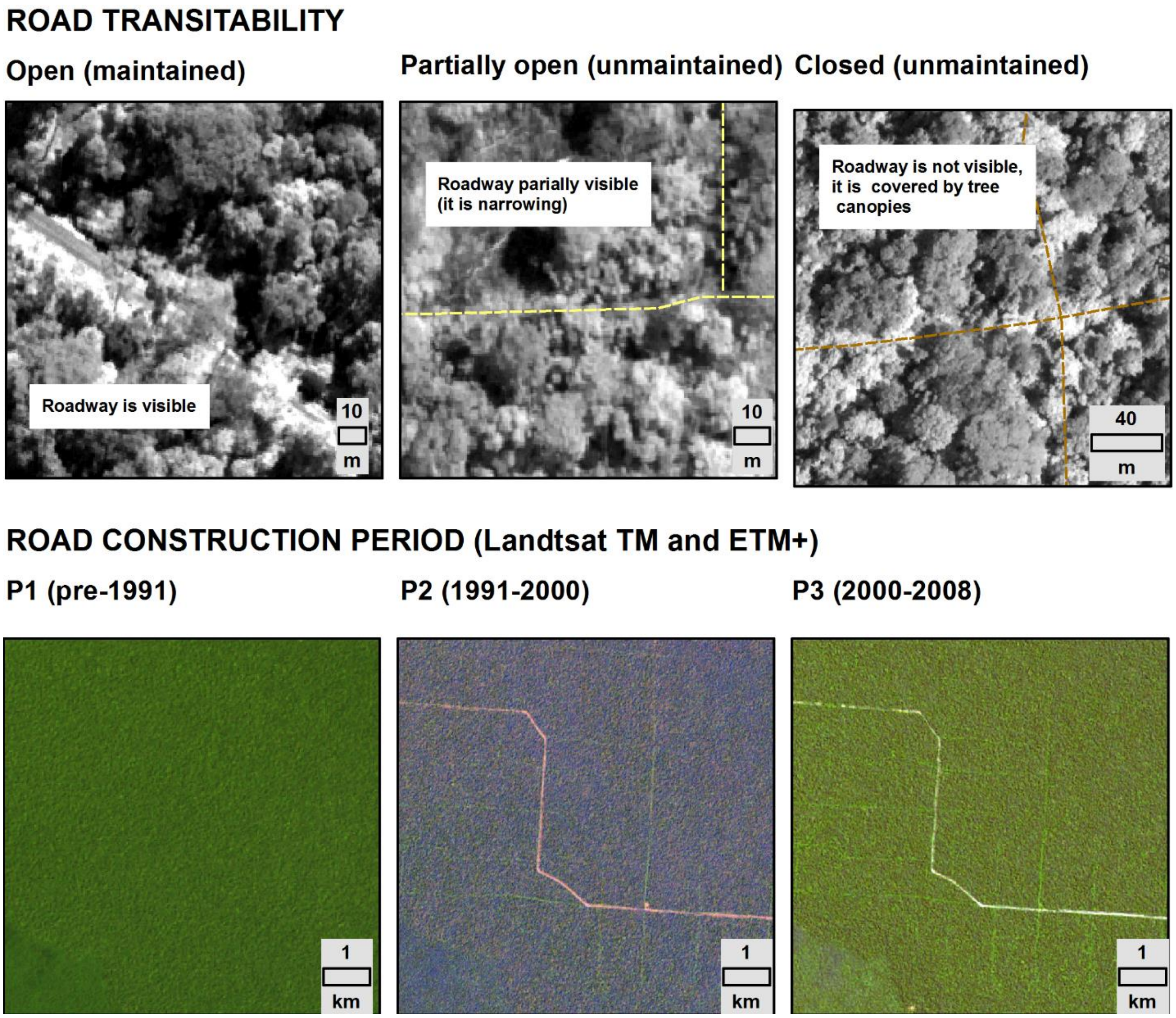

Figure C.5. Examples of the different road properties (transitability and construction period) as observed in WV-1 satellite images and Landsat (TM and ETM+)

APPENDIX D.

Spatial database summaries

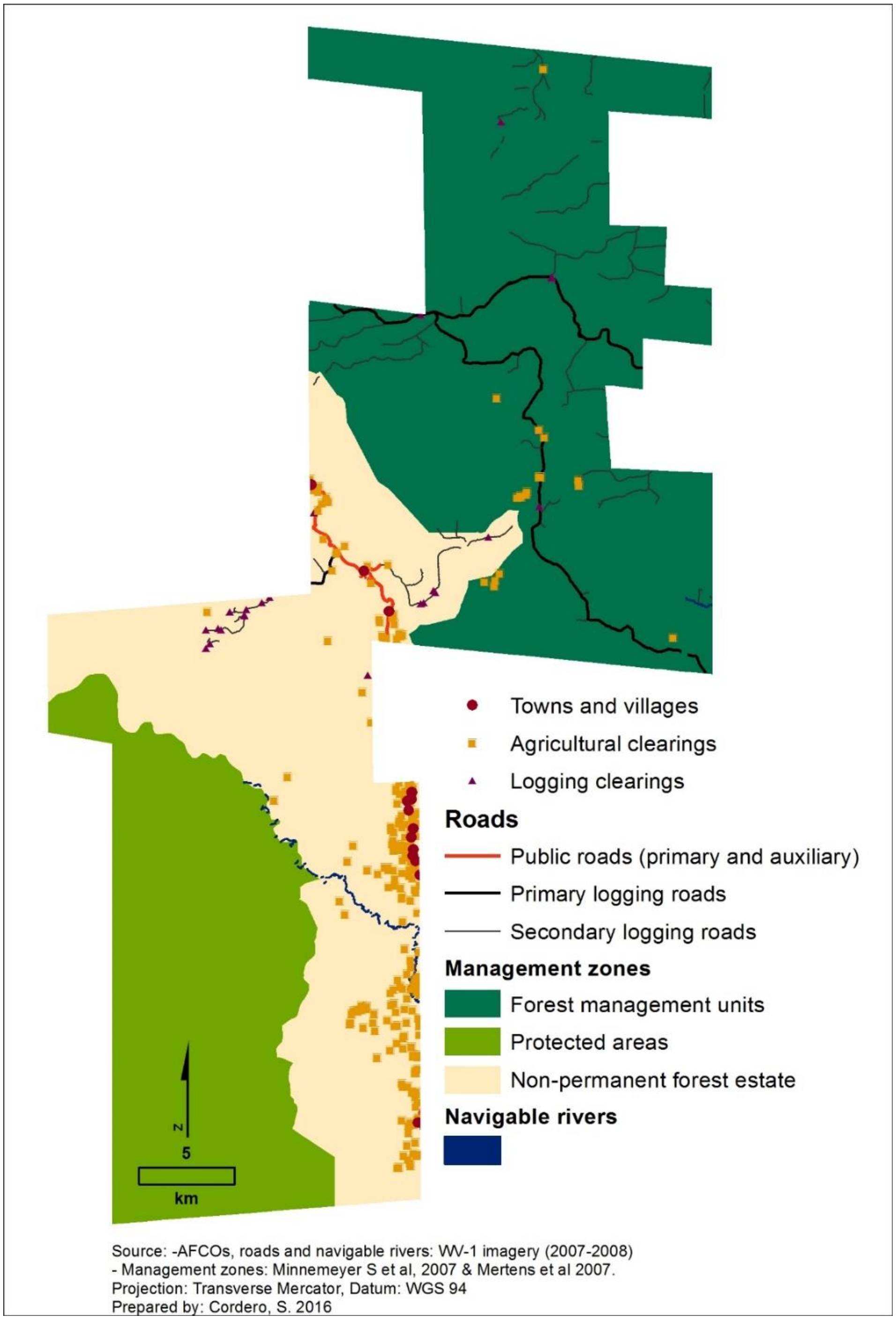

Figure D.1. Anthropogenic canopy clearings and transportation networks mapped with WV-1 imagery for Site 1

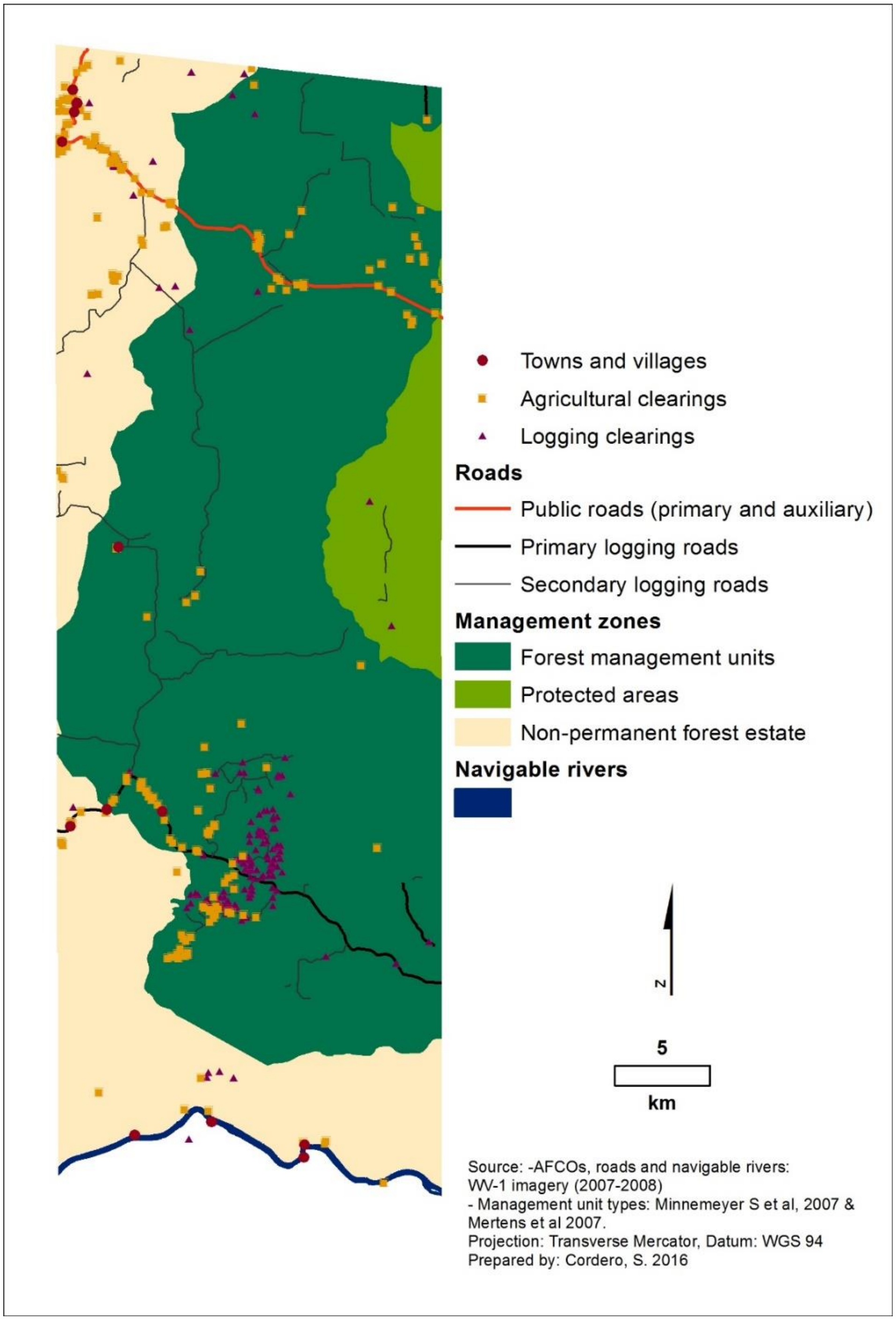

Figure D.2. Anthropogenic canopy clearings and transportation networks mapped with WV-1 imagery for Site 2

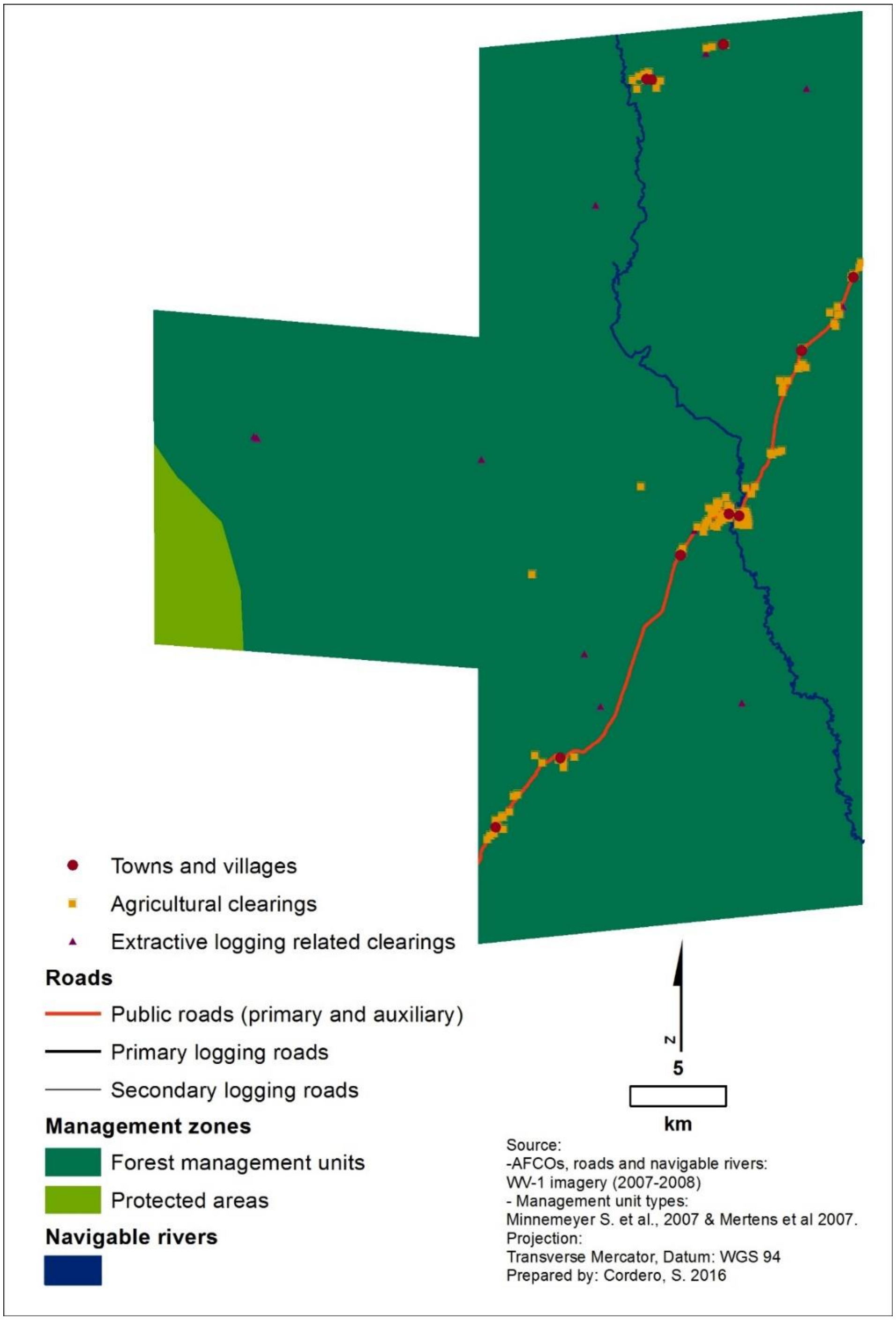

Figure D.3. Anthropogenic canopy clearings and transportation networks mapped with WV-1 imagery for Site 3

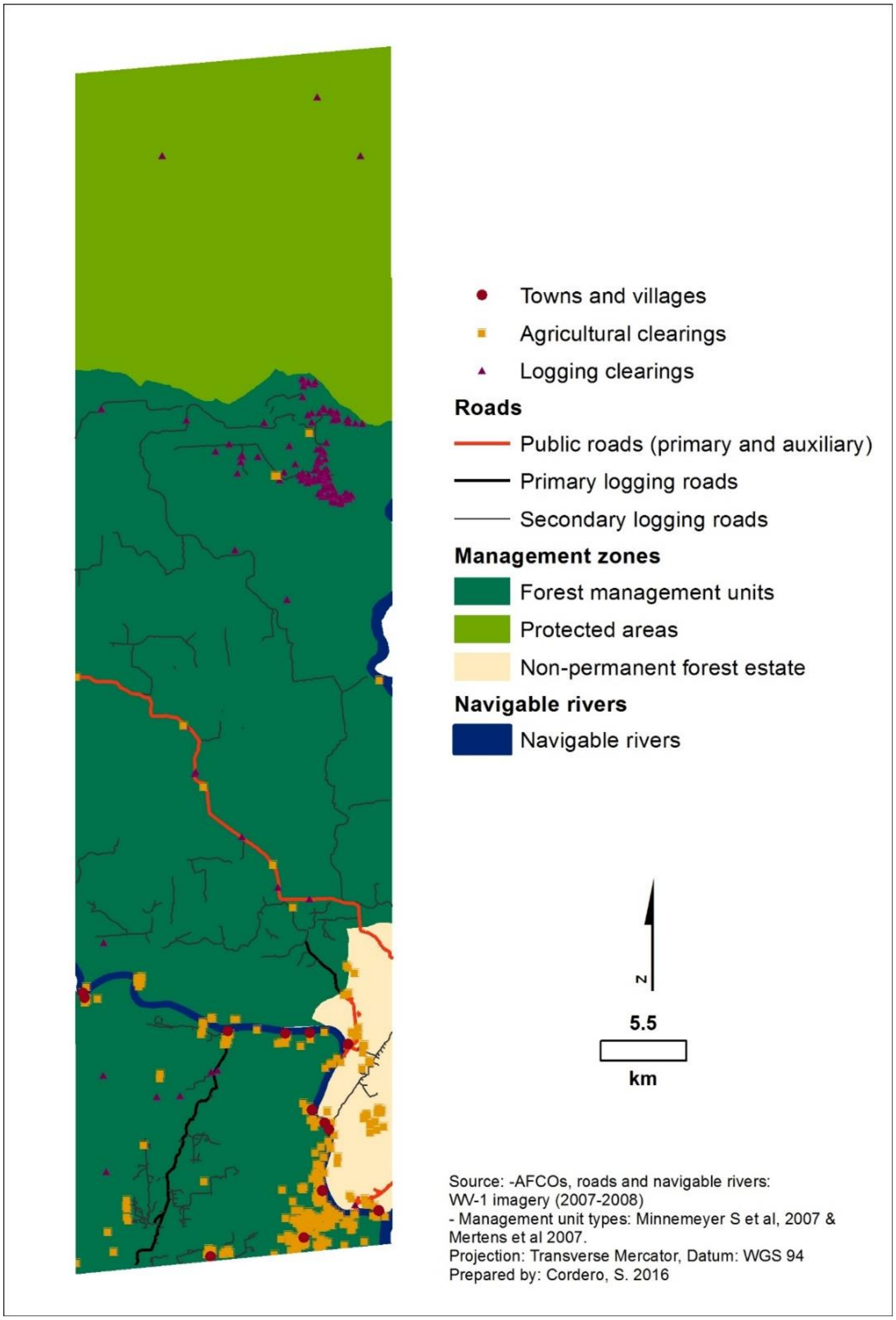

Figure D.4. Anthropogenic canopy clearings and transportation networks mapped with WV-1 imagery for Site 4

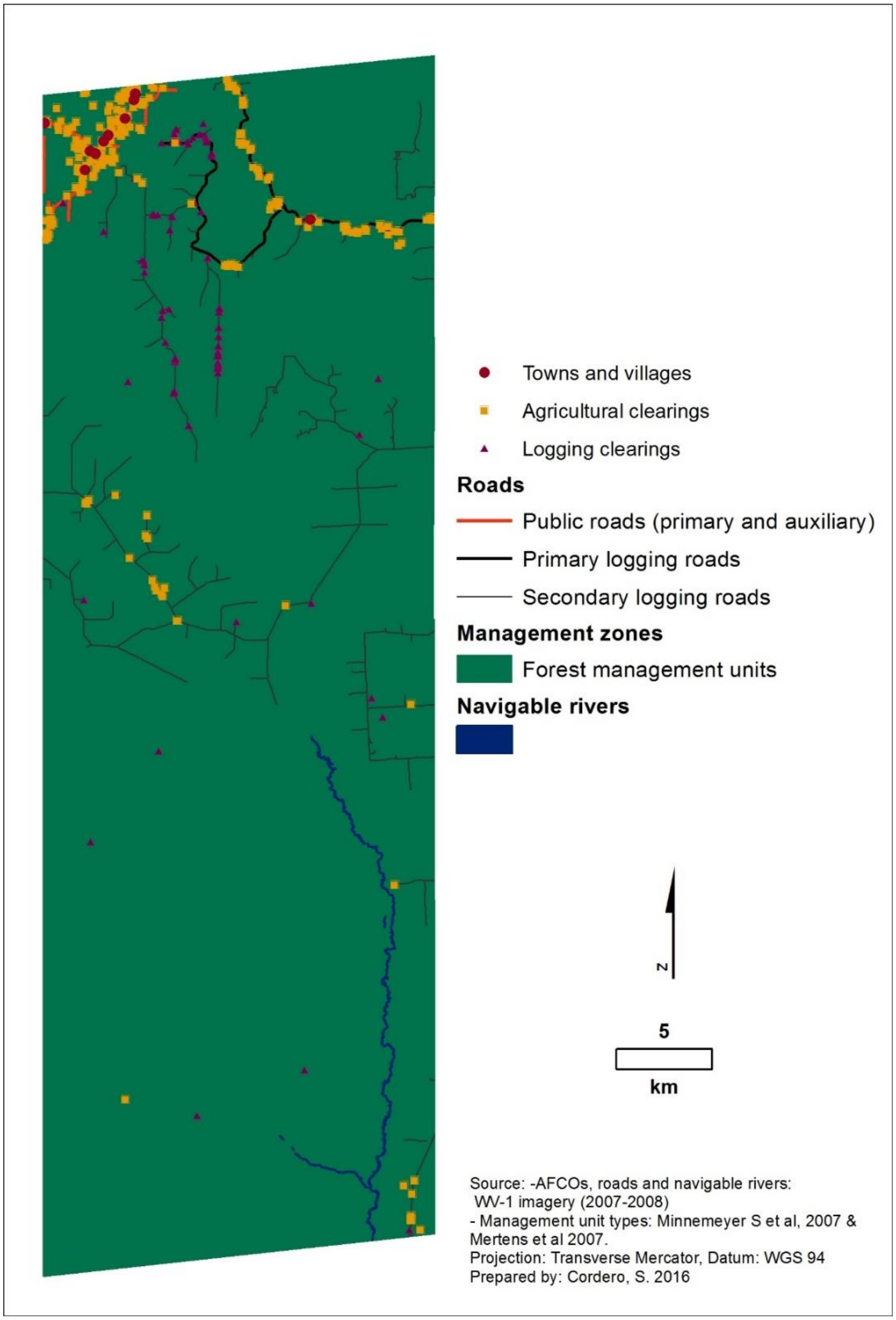

Figure D.5. Anthropogenic canopy clearings and transportation networks mapped with WV-1 imagery for Site 5

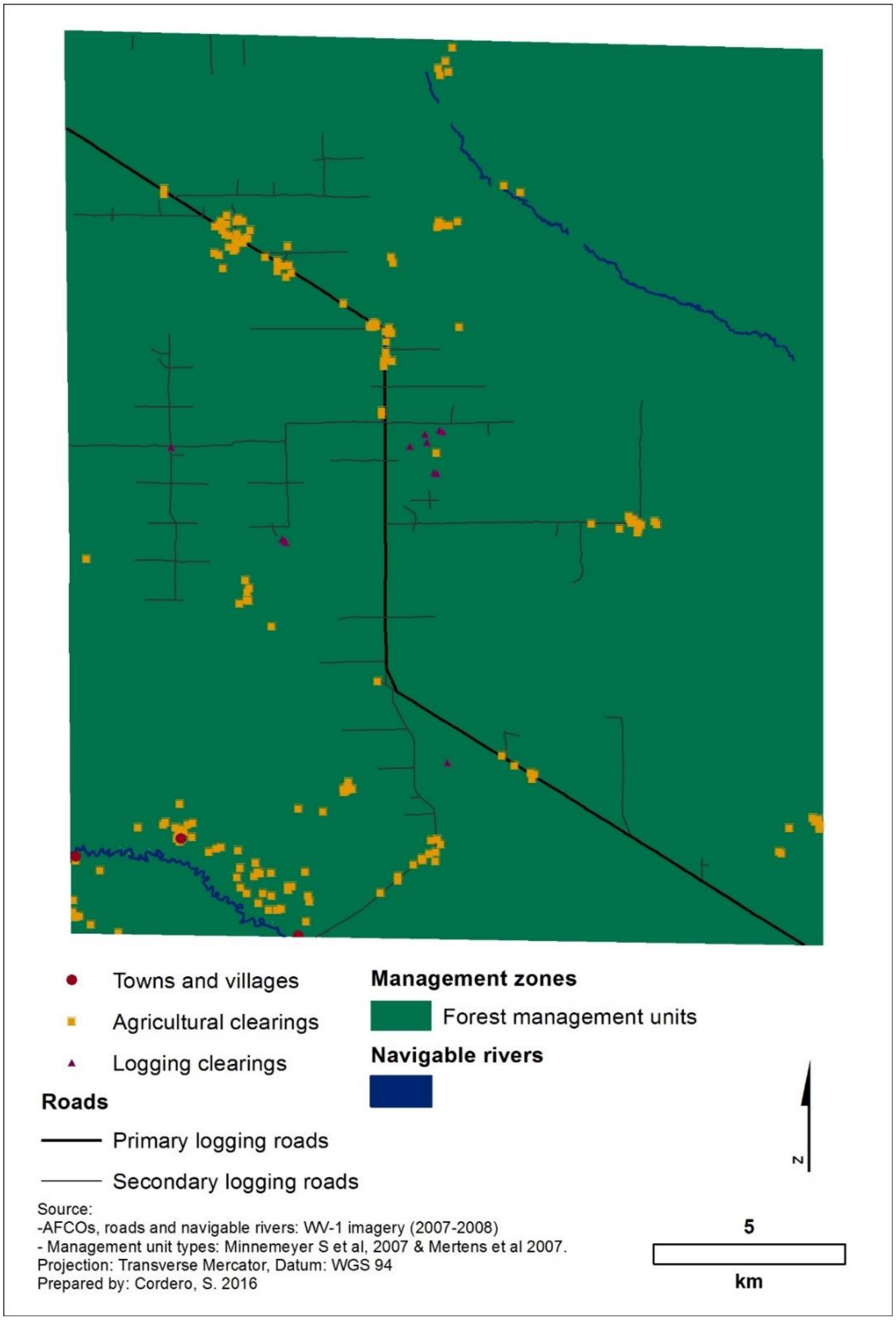

Figure D.6. Anthropogenic canopy clearings and transportation networks mapped with WV-1 imagery for Site 6

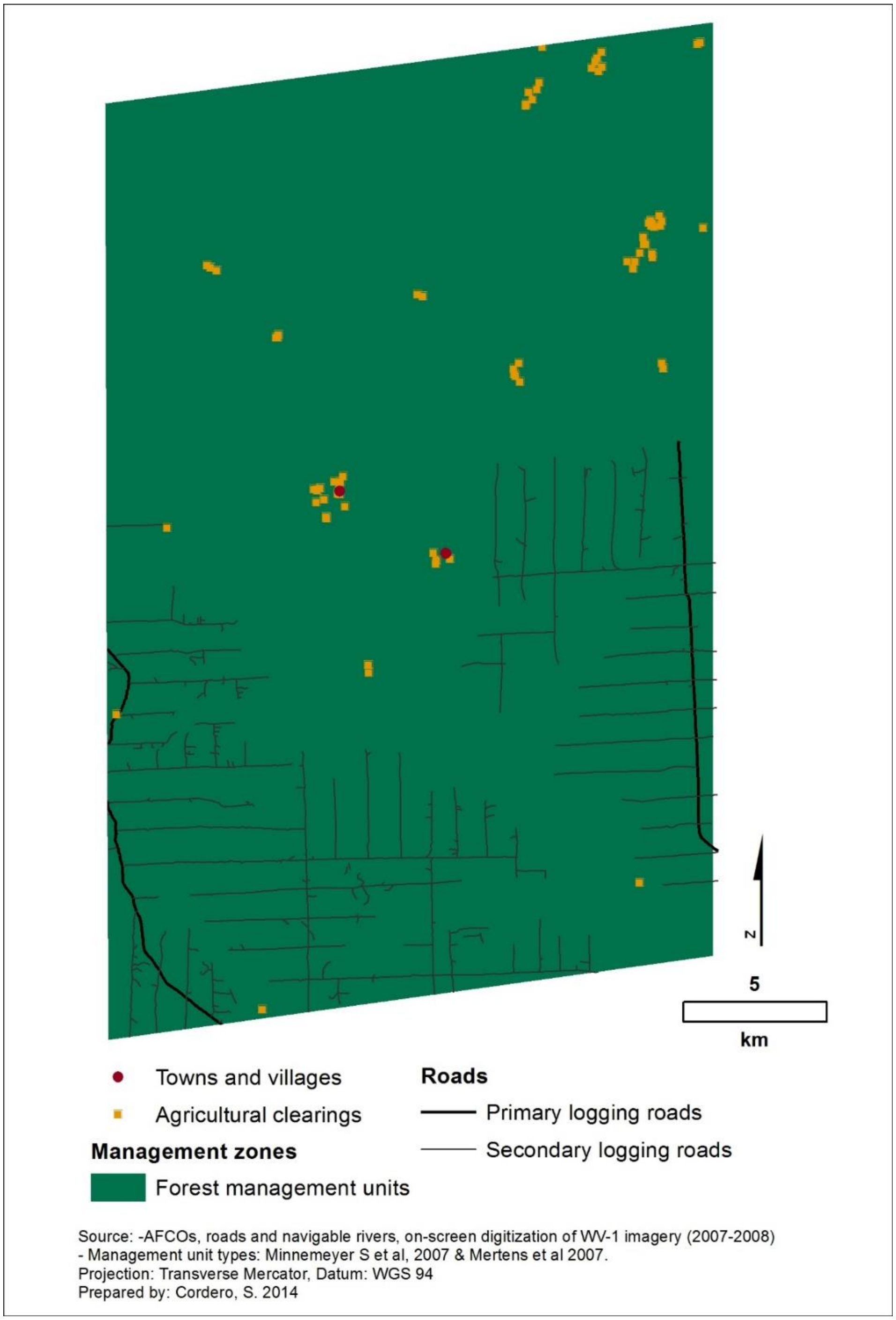

Figure D.7. Anthropogenic canopy clearings and transportation networks mapped with WV-1 imagery for Site 7

Table D.1. Plot size summary statistics for the set of agricultural plots (individual plots, mosaic plots and homesteads) employed in the analysis.

Site	Plot Type	N	Plot size (ha)				IQR	
			Min	Max	Mean	SD	Q1	Q3
1	Homestead	18.00	0.02	1.87	0.28	0.51	0.02	0.02
	Individual plot	158.00	0.02	14.40	0.88	1.72	0.02	0.02
	Mosaic plot	66.00	0.22	85.67	9.59	16.59	0.22	0.22
2	Homestead	27.00	0.03	2.56	0.55	0.66	0.03	0.03
	Individual plot	148.00	0.04	10.60	0.77	1.28	0.04	0.04
	Mosaic plot	21.00	0.26	8.12	3.04	2.43	0.26	0.26
3	Homestead	3.00	0.09	0.80	0.38	0.37	0.09	0.09
	Individual plot	76.00	0.09	32.59	1.57	3.84	0.09	0.09
	Mosaic plot	21.00	0.45	30.52	5.72	6.95	0.45	0.45
4	Homestead	26.00	0.03	2.29	0.37	0.53	0.03	0.03
	Individual plot	182.00	0.08	19.60	1.09	2.03	0.08	0.08
	Mosaic plot	47.00	0.29	309.05	13.37	45.86	0.29	0.29
5	Homestead	14.00	0.02	0.46	0.22	0.16	0.02	0.02
	Individual plot	152.00	0.07	13.08	0.98	1.52	0.07	0.07
	Mosaic plot	58.00	0.16	28.02	5.19	5.94	0.16	0.16
6	Homestead	17.00	0.16	1.07	0.45	0.27	0.16	0.16
	Individual plot	129.00	0.06	5.38	0.75	0.83	0.06	0.06
	Mosaic plot	29.00	0.36	128.78	8.82	23.74	0.36	0.36
7	Homestead	15.00	0.01	0.41	0.23	0.15	0.01	0.01
	Individual plot	45.00	0.17	2.54	0.68	0.64	0.17	0.17
	Mosaic plot	12.00	1.06	29.03	7.82	9.34	1.06	1.06

Table D.2. Frequency distribution of the number of agricultural clearings and distance to the nearest transportation based on road types

Site	Road type	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	>3	Total
1	MPR	0.26	0.08	0.05	0.00	0.00	0.00	0.00	0.39
	APR	0.10	0.05	0.02	0.01	0.00	0.00	0.00	0.18
	PLR	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.05
	SLR	0.02	0.00	0.01	0.00	0.01	0.00	0.00	0.04
	Navigable rivers	0.10	0.10	0.05	0.03	0.01	0.03	0.02	0.34
Total		**0.14**	**0.12**	**0.06**	**0.04**	**0.02**	**0.03**	**0.02**	**1.00**
2	MPR	0.33	0.05	0.03	0.00	0.00	0.00	0.00	0.40
	APR	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01
	PLR	0.15	0.02	0.01	0.00	0.01	0.00	0.00	0.18
	SLR	0.23	0.08	0.03	0.03	0.01	0.00	0.00	0.38
	Navigable rivers	0.03	0.00	0.00	0.01	0.00	0.01	0.00	0.04
Total		**0.41**	**0.10**	**0.04**	**0.03**	**0.02**	**0.01**	**0.00**	**1.00**
	MPR	0.78	0.05	0.00	0.00	0.00	0.00	0.02	0.85
	Navigable rivers	0.04	0.03	0.04	0.01	0.00	0.00	0.03	0.15
Total		**0.82**	**0.08**	**0.04**	**0.01**	**0.00**	**0.00**	**0.05**	**2.42**
	MPR	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.04
	APR	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.05
	PLR	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.04
	SLR	0.11	0.01	0.03	0.03	0.05	0.02	0.00	0.26
	Navigable rivers	0.31	0.09	0.06	0.05	0.07	0.03	0.00	0.61
Total		**0.44**	**0.11**	**0.09**	**0.09**	**0.13**	**0.05**	**0.01**	**1.00**
	MPR	0.39	0.08	0.00	0.00	0.01	0.00	0.00	0.48
	APR	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.07
	PLR	0.27	0.01	0.00	0.00	0.00	0.00	0.00	0.28
	SLR	0.16	0.01	0.00	0.00	0.00	0.00	0.00	0.17
	Navigable rivers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total		**0.43**	**0.02**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**1.00**
	PLR	0.27	0.02	0.00	0.01	0.00	0.03	0.00	0.33
	SLR	0.20	0.05	0.07	0.02	0.01	0.00	0.00	0.34
	Navigable rivers	0.06	0.14	0.07	0.06	0.00	0.00	0.00	0.33
Total		**0.54**	**0.20**	**0.14**	**0.09**	**0.01**	**0.03**	**0.00**	**2.00**
	PLR	0.01	0.00	0.00	0.00	0.00	0.03	0.28	0.32
	SLR	0.01	0.03	0.00	0.01	0.04	0.04	0.54	0.68
Total		**0.03**	**0.03**	**0.00**	**0.01**	**0.04**	**0.07**	**0.82**	**2.34**

Table D.3. Frequency distribution of the number of agricultural clearings and distance to the nearest transportation based on road approximate construction period

Site	Period	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	>3	Total
1	P1	0.31	0.11	0.05	0.01	0.00	0.00	0.00	0.49
	P2	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01
	P3	0.07	0.04	0.02	0.00	0.01	0.00	0.00	0.15
	Navigable rivers	0.10	0.10	0.05	0.03	0.01	0.03	0.02	0.34
Total		**0.50**	**0.25**	**0.12**	**0.05**	**0.02**	**0.04**	**0.02**	**1.00**
2	P1	0.43	0.07	0.01	0.01	0.01	0.00	0.00	0.53
	P2	0.11	0.03	0.03	0.01	0.01	0.00	0.00	0.17
	P3	0.17	0.06	0.02	0.01	0.01	0.00	0.00	0.26
	Navigable rivers	0.03	0.00	0.00	0.01	0.00	0.01	0.00	0.04
Total		**0.74**	**0.15**	**0.06**	**0.03**	**0.02**	**0.01**	**0.00**	**1.00**
3	P1	0.78	0.05	0.00	0.00	0.00	0.00	0.02	0.85
	Navigable rivers	0.04	0.03	0.04	0.01	0.00	0.00	0.03	0.15
Total		**0.82**	**0.08**	**0.04**	**0.01**	**0.00**	**0.00**	**0.05**	**1.00**
4	P1	0.09	0.00	0.02	0.01	0.00	0.00	0.00	0.12
	P2	0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.04
	P3	0.11	0.01	0.02	0.01	0.05	0.02	0.00	0.24
	Navigable rivers	0.31	0.09	0.06	0.05	0.07	0.03	0.00	0.61
Total		**0.53**	**0.11**	**0.09**	**0.09**	**0.13**	**0.05**	**0.01**	**1.00**
5	P1	0.59	0.08	0.00	0.00	0.01	0.00	0.00	0.69
	P2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	P3	0.21	0.01	0.00	0.00	0.00	0.00	0.00	0.22
	Navigable rivers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total		**0.81**	**0.09**	**0.00**	**0.00**	**0.01**	**0.00**	**0.00**	**0.92**
6	P3	0.47	0.06	0.07	0.03	0.01	0.03	0.00	0.67
	Navigable rivers	0.06	0.14	0.07	0.06	0.00	0.00	0.00	0.33
Total		**0.54**	**0.20**	**0.14**	**0.09**	**0.01**	**0.03**	**0.00**	**1.00**
7	P2	0.01	0.03	0.00	0.00	0.00	0.04	0.58	0.67
	P3	0.01	0.00	0.00	0.01	0.04	0.03	0.24	0.33
Total		**0.03**	**0.03**	**0.00**	**0.01**	**0.04**	**0.07**	**0.82**	**1.00**

Table D.4. Frequency distribution of the number of agricultural clearings and distance to the nearest transportation based on road maintenance

Site	Maintenance	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	>3	Total
1	Maintained	0.36	0.13	0.06	0.00	0.00	0.00	0.00	0.55
	Unmaintained	0.05	0.02	0.01	0.01	0.01	0.00	0.00	0.11
	Navigable rivers	0.10	0.10	0.05	0.03	0.01	0.03	0.02	0.34
Total		**0.50**	**0.25**	**0.12**	**0.05**	**0.02**	**0.04**	**0.02**	**1.00**
2	Maintained	0.69	0.12	0.05	0.01	0.01	0.00	0.00	0.88
	Unmaintained	0.02	0.03	0.01	0.02	0.01	0.00	0.00	0.08
	Navigable rivers	0.03	0.00	0.00	0.01	0.00	0.01	0.00	0.04
Total		**0.74**	**0.15**	**0.06**	**0.03**	**0.02**	**0.01**	**0.00**	**1.00**
3	Maintained	0.78	0.05	0.00	0.00	0.00	0.00	0.02	0.85
	Navigable rivers	0.04	0.03	0.04	0.01	0.00	0.00	0.03	0.15
Total		**0.82**	**0.08**	**0.04**	**0.01**	**0.00**	**0.00**	**0.05**	**1.00**
4	Maintained	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.11
	Unmaintained	0.11	0.02	0.04	0.03	0.05	0.02	0.01	0.28
	Navigable rivers	0.31	0.09	0.06	0.05	0.07	0.03	0.00	0.61
Total		**0.53**	**0.11**	**0.09**	**0.09**	**0.13**	**0.05**	**0.01**	**1.00**
5	Maintained	0.87	0.10	0.00	0.00	0.01	0.00	0.00	0.98
	Unmaintained	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.02
	Navigable rivers	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total		**0.88**	**0.10**	**0.00**	**0.00**	**0.01**	**0.00**	**0.00**	**1.00**
6	Maintained	0.37	0.03	0.01	0.02	0.00	0.03	0.00	0.45
	Unmaintained	0.11	0.03	0.06	0.01	0.01	0.00	0.00	0.23
	Navigable rivers	0.06	0.14	0.07	0.06	0.00	0.00	0.00	0.33
Total		**0.54**	**0.20**	**0.14**	**0.09**	**0.01**	**0.03**	**0.00**	**1.00**
7	Maintained	0.01	0.00	0.00	0.00	0.00	0.00	0.04	0.06
	Unmaintained	0.01	0.03		0.01	0.04	0.07	0.78	0.94
Total		**0.03**	**0.03**	**0.00**	**0.01**	**0.04**	**0.07**	**0.82**	**1.00**

Table D.5. Frequency distribution of the size of agricultural plots (ha) per plot type in relationship to their nearest transportation

Site	Plot type	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	>3	Total
1	Homestead	0.000	0.002	0.004	0.000	0.000	0.000	0.000	0.007
	Individual plot	0.096	0.050	0.021	0.003	0.003	0.004	0.001	0.178
	Mosaic plot	0.524	0.233	0.026	0.019	0.000	0.008	0.005	0.815
Total		**0.620**	**0.286**	**0.050**	**0.021**	**0.003**	**0.013**	**0.006**	**1.000**
2	Homestead	0.054	0.023	0.000	0.000	0.001	0.000	0.000	0.077
	Individual plot	0.406	0.157	0.022	0.005	0.001	0.001	0.000	0.591
	Mosaic plot	0.303	0.000	0.022	0.006	0.000	0.000	0.000	0.331
Total		**0.763**	**0.180**	**0.044**	**0.011**	**0.001**	**0.001**	**0.000**	**1.000**
3	Homestead	0.005	0.000	0.000	0.000	0.000	0.000	0.000	0.005
	Individual plot	0.404	0.031	0.008	0.002	0.000	0.000	0.051	0.497
	Mosaic plot	0.297	0.146	0.022	0.000	0.000	0.000	0.034	0.499
Total		**0.706**	**0.177**	**0.030**	**0.002**	**0.000**	**0.000**	**0.085**	**1.000**
4	Homestead	0.010	0.000	0.001	0.000	0.001	0.000	0.000	0.012
	Individual plot	0.104	0.055	0.026	0.023	0.016	0.007	0.005	0.237
	Mosaic plot	0.266	0.055	0.376	0.016	0.030	0.009	0.000	0.752
Total		**0.380**	**0.110**	**0.403**	**0.039**	**0.047**	**0.016**	**0.005**	**1.000**
5	Homestead	0.007	0.000	0.000	0.000	0.000	0.000	0.000	0.007
	Individual plot	0.291	0.031	0.000	0.002	0.005	0.000	0.001	0.330
	Mosaic plot	0.613	0.050	0.000	0.000	0.000	0.000	0.000	0.663
Total		**0.911**	**0.081**	**0.000**	**0.002**	**0.005**	**0.000**	**0.001**	**1.000**
6	Homestead	0.015	0.001	0.001	0.001	0.000	0.003	0.000	0.021
	Individual plot	0.146	0.064	0.038	0.017	0.001	0.004	0.000	0.269
	Mosaic plot	0.121	0.449	0.097	0.044	0.000	0.000	0.000	0.710
Total		**0.281**	**0.514**	**0.135**	**0.061**	**0.001**	**0.007**	**0.000**	**1.000**
7	Homestead	0.000	0.003	0.000	0.000	0.000	0.003	0.021	0.026
	Individual plot	0.003	0.005	0.000	0.000	0.009	0.032	0.190	0.238
	Mosaic plot	0.010	0.000	0.000	0.191	0.000	0.021	0.513	0.735
Total		**0.013**	**0.007**	**0.000**	**0.191**	**0.009**	**0.056**	**0.724**	**1.000**

Table D.6. Road length relative frequency per site according with the different road properties evaluated (trype, transitability and construction period)

Site	Road type	Transitability	Construction period			Total
			P1	P2	P3	
1	**MPR**	Open	0.09	0.00	0.00	0.09
	APR	Open	0.01	0.00	0.02	0.02
		Closed	0.00	0.00	0.00	0.00
	PLR	Open	0.00	0.15	0.15	0.29
	SLR	Open	0.00	0.01	0.04	0.05
		Partially closed	0.00	0.05	0.00	0.05
		Closed	0.00	0.30	0.19	0.49
Total			**0.09**	**0.51**	**0.40**	**1.00**
2	**MPR**	Open	0.05	0.09	0.00	0.14
	APR	Open	0.00	0.00	0.00	0.00
	PLR	Open	0.12	0.01	0.02	0.15
	SLR	Open	0.22	0.00	0.19	0.41
		Partially closed	0.11	0.10	0.02	0.23
		Closed	0.01	0.05	0.01	0.08
Total			**0.51**	**0.25**	**0.23**	**1.00**
3	**MPR**	Open	1.00	0	0	0
Total			**1**	**0**	**0**	**0**
4	**MPR**	Open	0.09	0.01	0.01	0.11
		Partially closed	0.00	0.00	0.00	0.00
		Closed	0.00	0.00	0.00	0.00
	APR	Open	0.00	0.00	0.02	0.02
		Partially closed	0.00	0.00	0.00	0.00
		Closed	0.00	0.00	0.00	0.00
	PLR	Open	0.00	0.00	0.00	0.00
		Closed	0.04	0.01	0.01	0.06
	SLR	Open	0.09	0.00	0.11	0.20
		Partially closed	0.06	0.03	0.02	0.12
		Closed	0.31	0.10	0.09	0.49
Total			**0.59**	**0.15**	**0.26**	**1.00**
5	**MPR**	Open	0.05	0.00	0.00	0.05
	APR	Open	0.00	0.00	0.04	0.04
	PLR	Open	0.07	0.00	0.05	0.12
	SLR	Open	0.03	0.00	0.48	0.50
		Partially closed	0.01	0.00	0.00	0.01
		Closed	0.19	0.07	0.02	0.28
Total			**0.34**	**0.07**	**0.59**	**1.00**

Site	Road type	Transitability	Construction period			Total
			P1	P2	P3	
6	**PLR**	Open	0.00	0.00	0.24	0.24
	SLR	Open	0.00	0.00	0.05	0.05
		Partially closed	0.00	0.00	0.45	0.45
		Closed	0.00	0.00	0.26	0.26
Total			**0.00**	**0.00**	**1.00**	**1.00**
7	**PLR**	Open	0.00	0.01	0.00	0.01
		Partially closed	0.00	0.03	0.00	0.03
		Closed	0.00	0.05	0.00	0.05
	SLR	Partially closed	0.00	0.00	0.02	0.02
		Closed	0.00	0.44	0.45	0.89
Total			**0.00**	**0.54**	**0.46**	**1.00**

Table D.7. Internal networks and skid trials length relative frequency per site.

Site	Internal network	Skid trail	Total (per site)
1	0.99	0.01	1.00
2	0.97	0.03	1.00
3	1.00	0.00	1.00
4	0.80	0.20	1.00
5	0.92	0.08	1.00
6	1.00	0.00	1.00
7	1.00	0.00	1.00

Table D.8. Frequency distribution of the number of agricultural plots, per plot type in relationship to their nearest settlement (villages and towns)

Site	Plot type	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	>3	Total
1	Homestead	0.01	0.00	0.00	0.00	0.00	0.01	0.05	0.07
	Individual plot	0.14	0.08	0.10	0.05	0.02	0.02	0.25	0.65
	Mosaic pot	0.07	0.06	0.03	0.02	0.01	0.00	0.08	0.27
Total		**0.21**	**0.14**	**0.13**	**0.07**	**0.03**	**0.03**	**0.38**	**1.00**
2	Homestead	0.03	0.03	0.02	0.02	0.00	0.00	0.05	0.14
	Individual plot	0.12	0.06	0.03	0.04	0.02	0.06	0.43	0.76
	Mosaic pot	0.01	0.02	0.01	0.01	0.01	0.02	0.05	0.11
Total		**0.16**	**0.10**	**0.05**	**0.07**	**0.02**	**0.08**	**0.53**	**1.00**
3	Homestead	0.00	0.01	0.00	0.00	0.01	0.00	0.01	0.03
	Individual plot	0.34	0.20	0.04	0.07	0.06	0.00	0.05	0.76
	Mosaic pot	0.08	0.08	0.03	0.01	0.01	0.00	0.00	0.21
Total		**0.42**	**0.29**	**0.07**	**0.08**	**0.08**	**0.00**	**0.06**	**1.00**
4	Homestead	0.02	0.02	0.02	0.04	0.00	0.00	0.02	0.10
	Individual plot	0.09	0.17	0.17	0.07	0.05	0.02	0.14	0.71
	Mosaic pot	0.05	0.04	0.03	0.04	0.01	0.00	0.01	0.18
Total		**0.16**	**0.22**	**0.22**	**0.15**	**0.05**	**0.03**	**0.16**	**1.00**
5	Homestead	0.01	0.01	0.01	0.00	0.00	0.00	0.03	0.06
	Individual plot	0.13	0.15	0.02	0.04	0.01	0.04	0.29	0.68
	Mosaic pot	0.10	0.05	0.03	0.02	0.01	0.00	0.06	0.26
Total		**0.23**	**0.21**	**0.05**	**0.07**	**0.02**	**0.04**	**0.38**	**1.00**
6	Homestead	0.01	0.00	0.00	0.00	0.00	0.00	0.09	0.10
	Individual plot	0.05	0.05	0.05	0.05	0.01	0.01	0.53	0.74
	Mosaic pot	0.01	0.01	0.02	0.03	0.01	0.00	0.09	0.17
Total		**0.06**	**0.06**	**0.07**	**0.07**	**0.02**	**0.01**	**0.71**	**1.00**
7	Homestead	0.06	0.01	0.01	0.00	0.00	0.00	0.13	0.21
	Individual plot	0.04	0.07	0.00	0.00	0.00	0.00	0.51	0.63
	Mosaic pot	0.03	0.01	0.01	0.00	0.00	0.00	0.11	0.17
Total		**0.13**	**0.10**	**0.03**	**0.00**	**0.00**	**0.00**	**0.75**	**1.00**

Table D.9. Frequency distribution of the size of agricultural plots (ha) per plot type in relationship to their nearest settlement (villages and towns)

Site	Plot type	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	>3	Total
1	Homestead	0.000	0.000	0.000	0.000	0.001	0.000	0.005	0.007
	Individual plot	0.045	0.015	0.029	0.011	0.004	0.007	0.068	0.178
	Mosaic pot	0.310	0.251	0.040	0.018	0.006	0.002	0.188	0.815
Total		**0.355**	**0.266**	**0.069**	**0.030**	**0.012**	**0.009**	**0.261**	**1.000**
2	Homestead	0.012	0.023	0.009	0.008	0.000	0.000	0.024	0.077
	Individual plot	0.108	0.025	0.020	0.066	0.005	0.058	0.309	0.591
	Mosaic pot	0.056	0.074	0.007	0.025	0.041	0.039	0.089	0.331
Total		**0.176**	**0.122**	**0.036**	**0.099**	**0.046**	**0.097**	**0.422**	**1.000**
3	Homestead	0.000	0.000	0.000	0.000	0.001	0.000	0.003	0.005
	Individual plot	0.149	0.201	0.019	0.042	0.024	0.000	0.061	0.497
	Mosaic pot	0.133	0.213	0.054	0.025	0.075	0.000	0.000	0.499
Total		**0.282**	**0.415**	**0.073**	**0.067**	**0.100**	**0.000**	**0.064**	**1.000**
4	Homestead	0.004	0.002	0.003	0.002	0.000	0.000	0.001	0.012
	Individual plot	0.035	0.067	0.049	0.022	0.016	0.004	0.043	0.237
	Mosaic pot	0.213	0.062	0.047	0.034	0.381	0.000	0.015	0.752
Total		**0.251**	**0.131**	**0.099**	**0.058**	**0.397**	**0.005**	**0.058**	**1.000**
5	Homestead	0.002	0.001	0.001	0.001	0.000	0.000	0.002	0.007
	Individual plot	0.075	0.051	0.005	0.047	0.011	0.012	0.130	0.330
	Mosaic pot	0.202	0.248	0.062	0.049	0.010	0.000	0.092	0.663
Total		**0.278**	**0.301**	**0.067**	**0.097**	**0.021**	**0.012**	**0.225**	**1.000**
6	Homestead	0.000	0.000	0.000	0.000	0.000	0.000	0.021	0.021
	Individual plot	0.018	0.025	0.027	0.014	0.005	0.007	0.172	0.269
	Mosaic pot	0.362	0.027	0.017	0.155	0.015	0.000	0.133	0.710
Total		**0.380**	**0.052**	**0.045**	**0.169**	**0.020**	**0.007**	**0.326**	**1.000**
7	Homestead	0.003	0.003	0.002	0.000	0.000	0.000	0.018	0.026
	Individual plot	0.009	0.033	0.000	0.000	0.000	0.000	0.196	0.238
	Mosaic pot	0.418	0.018	0.017	0.000	0.000	0.000	0.282	0.735
Total		**0.431**	**0.055**	**0.019**	**0.000**	**0.000**	**0.000**	**0.495**	**1.000**

Table D.10. Frequency distribution of the number and type settlements in relationship to nearest transportation based on road type

Site	Settlement type	Road Type	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	>3	Total
1	Town	Public	0.21	0.00	0.00	0.00	0.00	0.00	0.21
	Village	Public	0.79	0.00	0.00	0.00	0.00	0.00	0.79
Total			**1.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**1.00**
2	Town	Navigable rivers	0.08	0.00	0.00	0.00	0.00	0.00	0.08
	Village	Public	0.33	0.00	0.00	0.00	0.00	0.00	0.33
		Logging	0.33	0.00	0.00	0.00	0.00	0.00	0.33
		Navigable rivers	0.25	0.00	0.00	0.00	0.00	0.00	0.25
Total			**1.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**1.00**
3	Town	Public	0.10	0.00	0.00	0.00	0.00	0.00	0.10
	Village	Public	0.20	0.00	0.00	0.00	0.10	0.30	0.60
		Navigable rivers	0.00	0.10	0.10	0.00	0.00	0.10	0.30
Total			**0.30**	**0.10**	**0.10**	**0.00**	**0.10**	**0.40**	**1.00**
4	Village	Public	0.07	0.00	0.00	0.00	0.00	0.00	0.07
		Logging	0.14	0.00	0.00	0.00	0.00	0.00	0.14
		Navigable rivers	0.71	0.00	0.00	0.00	0.07	0.00	0.79
Total			**0.93**	**0.00**	**0.00**	**0.00**	**0.07**	**0.00**	**1.00**
5	Town	Public	0.10	0.00	0.00	0.00	0.00	0.00	0.10
	Village	Public	0.90	0.00	0.00	0.00	0.00	0.00	0.90
Total			**1.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**1.00**
6	Village	Logging	0.63	0.00	0.00	0.00	0.00	0.00	0.63
		Navigable rivers	0.25	0.13	0.00	0.00	0.00	0.00	0.38
Total			**0.88**	**0.13**	**0.00**	**0.00**	**0.00**	**0.00**	**1.00**
7	Village	Logging	0.00	0.00	0.00	0.50	0.00	0.50	1.00
Total			**0.00**	**0.00**	**0.00**	**0.50**	**0.00**	**0.50**	**1.00**

Table D.11. Frequency distribution of the number and type settlements in relationship to nearest transportation based on road approximate construction period

Site	Settlement type	Construction period	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	>3	Total
1	Town	P1	0.21	0.00	0.00	0.00	0.00	0.00	0.21
	Village	P1	0.79	0.00	0.00	0.00	0.00	0.00	0.79
Total			**1.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**1.00**
2	Town	Navigable rivers	0.08	0.00	0.00	0.00	0.00	0.00	0.08
	Village	P1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		Navigable rivers	0.67	0.00	0.00	0.00	0.00	0.00	0.67
Total			**0.75**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.75**
3	Town	P1	0.10	0.00	0.00	0.00	0.00	0.00	0.10
	Village	P1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		Navigable rivers	0.20	0.00	0.00	0.00	0.10	0.30	0.60
Total			**0.30**	**0.00**	**0.00**	**0.00**	**0.10**	**0.30**	**0.70**
4	Village	P1	0.07	0.00	0.00	0.00	0.00	0.00	0.07
		P3	0.14	0.00	0.00	0.00	0.00	0.00	0.14
		Navigable rivers	0.71	0.00	0.00	0.00	0.07	0.00	0.79
Total			**0.93**	**0.00**	**0.00**	**0.00**	**0.07**	**0.00**	**1.00**
5	Town	P1	0.10	0.00	0.00	0.00	0.00	0.00	0.10
	Village	P1	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total			**0.10**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.10**
6	Village	P3	0.63	0.00	0.00	0.00	0.00	0.00	0.63
		Navigable rivers	0.25	0.13	0.00	0.00	0.00	0.00	0.38
Total			**0.88**	**0.13**	**0.00**	**0.00**	**0.00**	**0.00**	**1.00**
7	Village	P3	0.00	0.00	0.00	0.50	0.00	0.50	1.00
Total			**0.00**	**0.00**	**0.00**	**0.50**	**0.00**	**0.50**	**1.00**

Table D.12. Frequency distribution of the number and type settlements in relationship to nearest transportation based on road maintenance

Site	Settlement type	Road Maintenance	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	>3	Total
1	Town	Maintained	0.21	0.00	0.00	0.00	0.00	0.00	0.21
	Village	Maintained	0.79	0.00	0.00	0.00	0.00	0.00	0.79
Total			**1.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**1.00**
2	Town	Navigable rivers	0.08	0.00	0.00	0.00	0.00	0.00	0.08
	Village	Maintained	0.58	0.00	0.00	0.00	0.00	0.00	0.58
		Unmaintained	0.08	0.00	0.00	0.00	0.00	0.00	0.08
		Navigable rivers	0.25	0.00	0.00	0.00	0.00	0.00	0.25
Total			**1.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.92**
3	Town	Maintained	0.10	0.00	0.00	0.00	0.00	0.00	0.10
	Village	Maintained	0.20	0.00	0.00	0.00	0.10	0.30	0.60
		Navigable rivers	0.00	0.10	0.10	0.00	0.00	0.10	0.30
Total			**0.30**	**0.10**	**0.10**	**0.00**	**0.10**	**0.40**	**1.00**
4	Village	Maintained	0.14	0.00	0.00	0.00	0.00	0.00	0.14
		Unmaintained	0.07	0.00	0.00	0.00	0.00	0.00	0.07
		Navigable rivers	0.71	0.00	0.00	0.00	0.07	0.00	0.79
Total			**0.93**	**0.00**	**0.00**	**0.00**	**0.07**	**0.00**	**1.00**
5	Town	Maintained	0.10	0.00	0.00	0.00	0.00	0.00	0.10
	Village	Maintained	0.90	0.00	0.00	0.00	0.00	0.00	0.90
Total			**1.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**1.00**
6	Village	Maintained	0.50	0.00	0.00	0.00	0.00	0.00	0.50
		Unmaintained	0.13	0.00	0.00	0.00	0.00	0.00	0.13
		Navigable rivers	0.25	0.13	0.00	0.00	0.00	0.00	0.38
Total			**1.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**1.00**
7	Village	Unmaintained	0.00	0.00	0.00	0.50	0.00	0.50	1.00
Total			**0.00**	**0.00**	**0.00**	**0.50**	**0.00**	**0.50**	**1.00**

APPENDIX E.

Gibbs spatial point pattern analysis supplementary data

Table E.1. Spatial point pattern quadrat count test for inhomogeneity employing four different grid sizes

Site	Grid size (m)	X²	p-value
1	250 x 250	26676.0	0.0040
1	500 x 500	11445.0	0.0020
1	1000 x 1000	7164.8	0.0020
1	2000 x 2000	4241.9	0.0020
2	250 x 250	25993.0	0.0060
2	500 x 500	10252.0	0.0020
2	1000 x 1000	4496.6	0.0020
2	2000 x 2000	2075.1	0.0020
3	250 x 250	25054.0	0.0040
3	500 x 500	10150.0	0.0020
3	1000 x 1000	6093.7	0.0020
3	2000 x 2000	3789.2	0.0020
4	250 x 250	35085.0	0.0020
4	500 x 500	14989.0	0.0020
4	1000 x 1000	7847.1	0.0020
4	2000 x 2000	5173.5	0.0020
5	250 x 250	30844.0	0.0020
5	500 x 500	13280.0	0.0020
5	1000 x 1000	6826.8	0.0020
5	2000 x 2000	4714.6	0.0020
6	250 x 250	12816.0	0.0020
6	500 x 500	5641.9	0.0020
6	1000 x 1000	2916.7	0.0020
6	2000 x 2000	1090.8	0.0020
7	250 x 250	17504.0	0.0020
7	500 x 500	5611.0	0.0060
7	1000 x 1000	2940.7	0.0020
7	2000 x 2000	880.8	0.0020

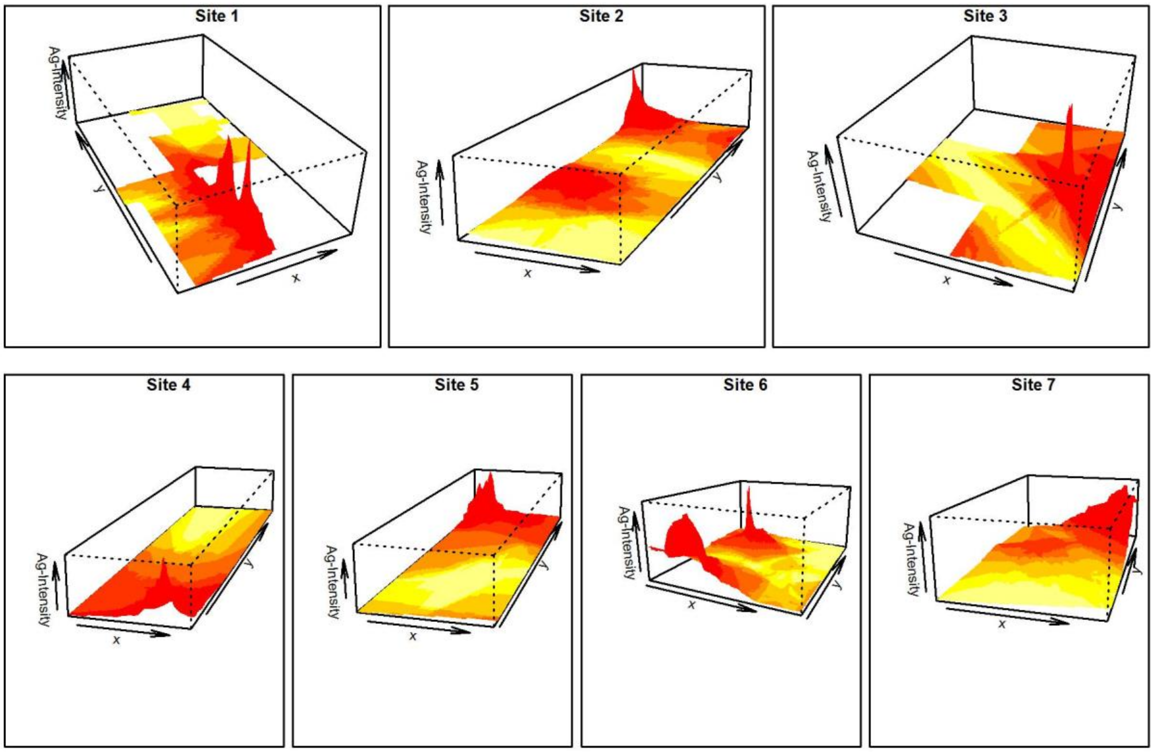

Figure E.1. Case sites agricultural pattern’s intensity surfaces. Surfaces allow to identify zones in where the patter is inhomogeneity along the window of observation (w).

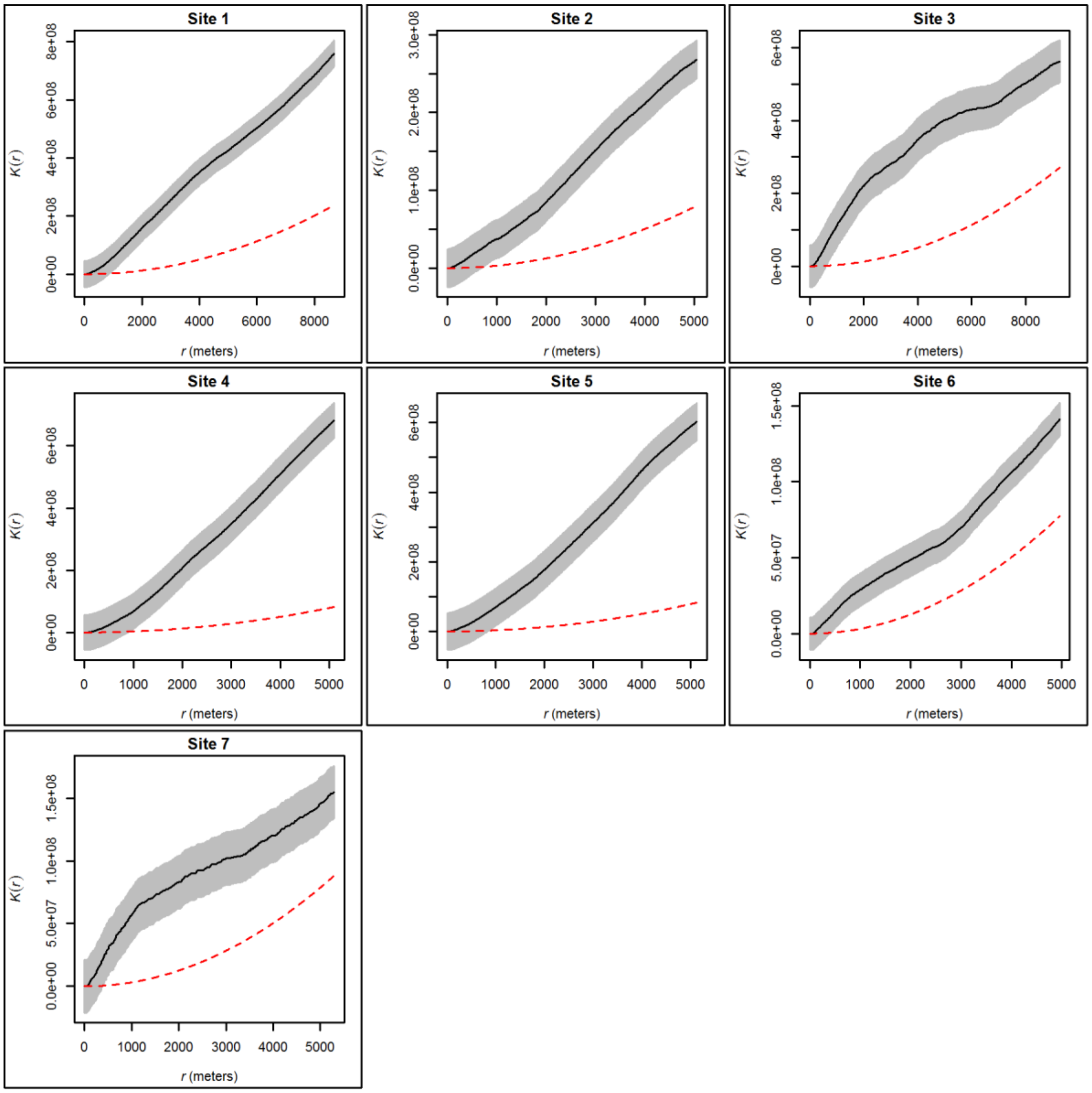

Figure E.2. Case sites results for Ripley's K-function. Red dotted line indicates theoretical pattern under CSR, black solid lined indicate estimated K-function agricultural pattern. Grey bands indicate 95% confidence bands (based on Loh's bootstrap). If estimated K values are above the red dotted line, the pattern is aggregated, if values are below the red dotted line, pattern is disperse.

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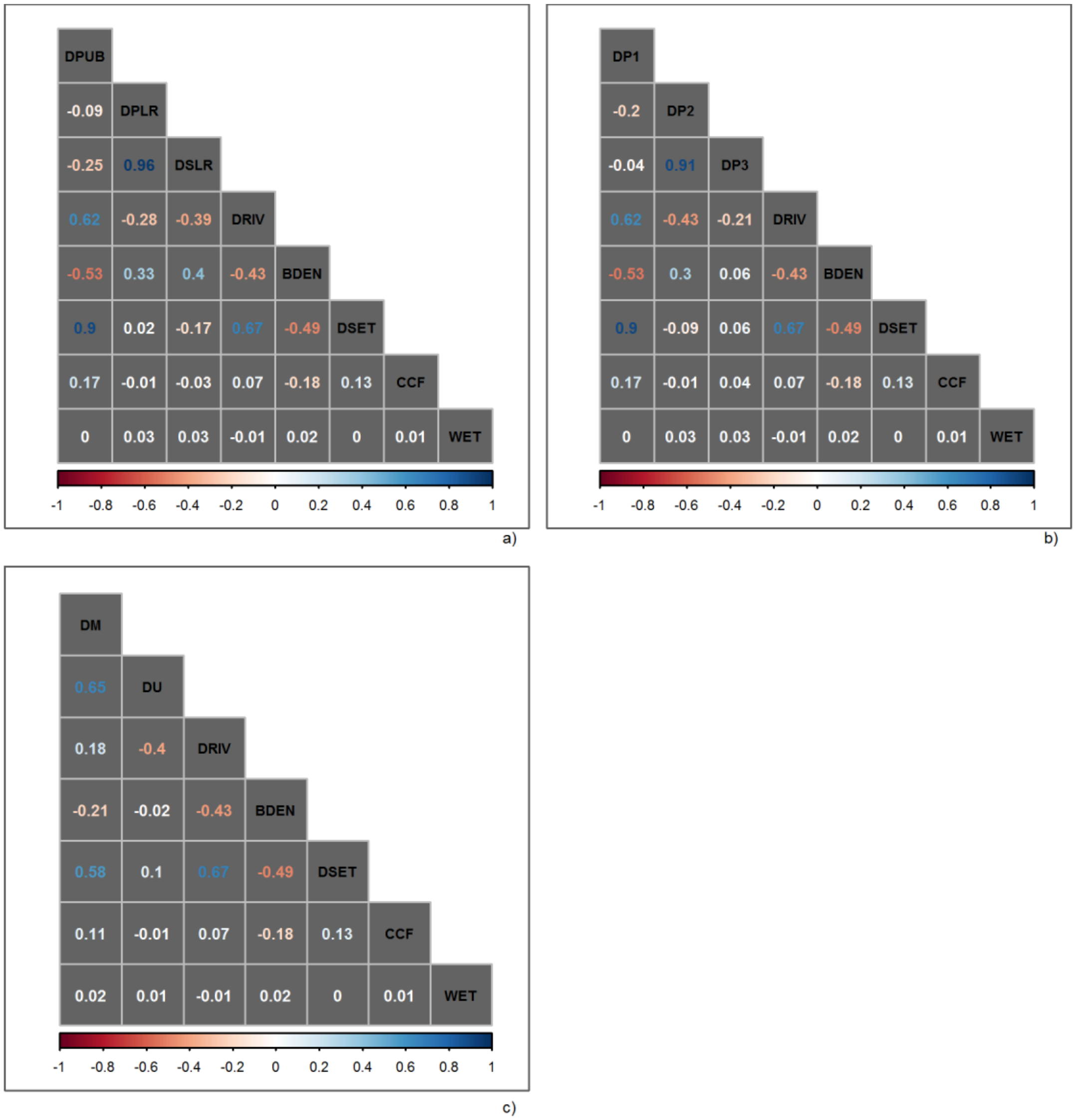

Figure E.3. Pearson correlation coefficient (r) plots for Site 1 grouped by road properties: a) road type, b) road proximate construction period and c) road maintenance. It was considered that collinearity was present if │r│ > 0.7.

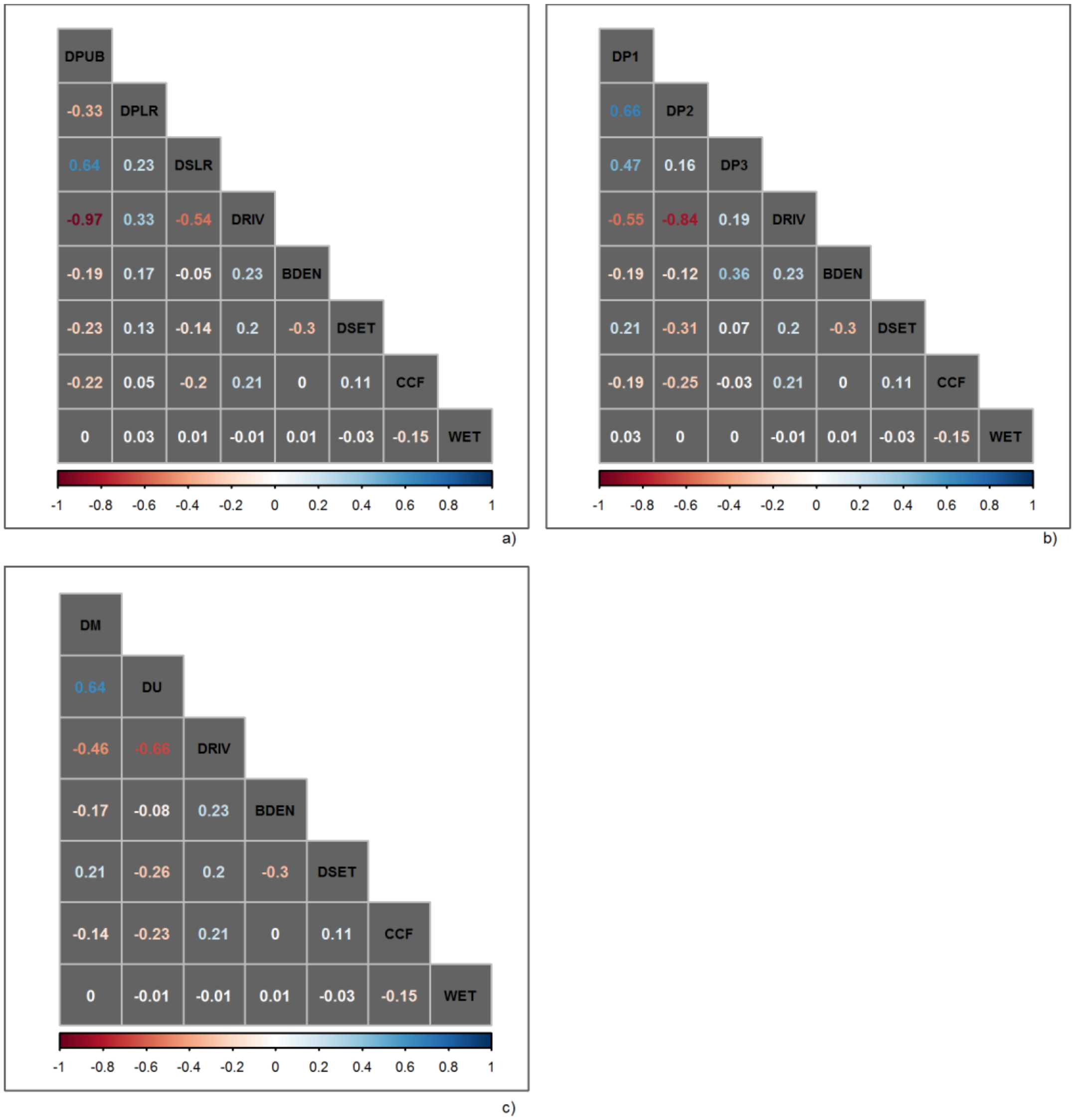

Figure E.4. Pearson correlation coefficient (*r*) plots for Site 2 grouped by road properties: a) road type, b) road proximate construction period and c) road maintenance. It was considered that collinearity was present if $|r| > 0.7$.

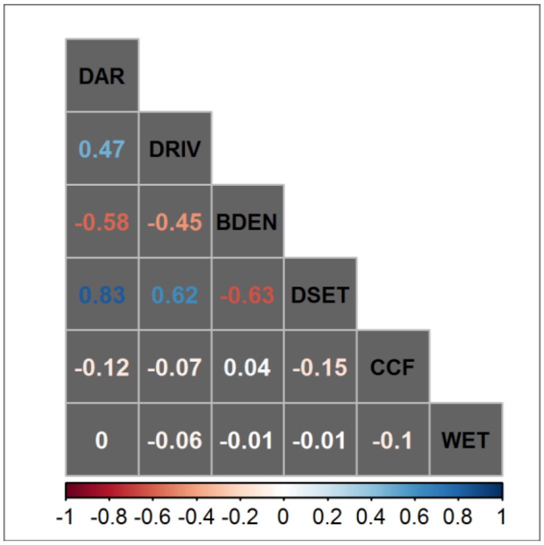

Figure E.5. Pearson correlation coefficient (*r*) plots for Site 3 grouped by road properties: a) road type, b) road proximate construction period and c) road maintenance. It was considered that collinearity was present if $|r| > 0.7$.

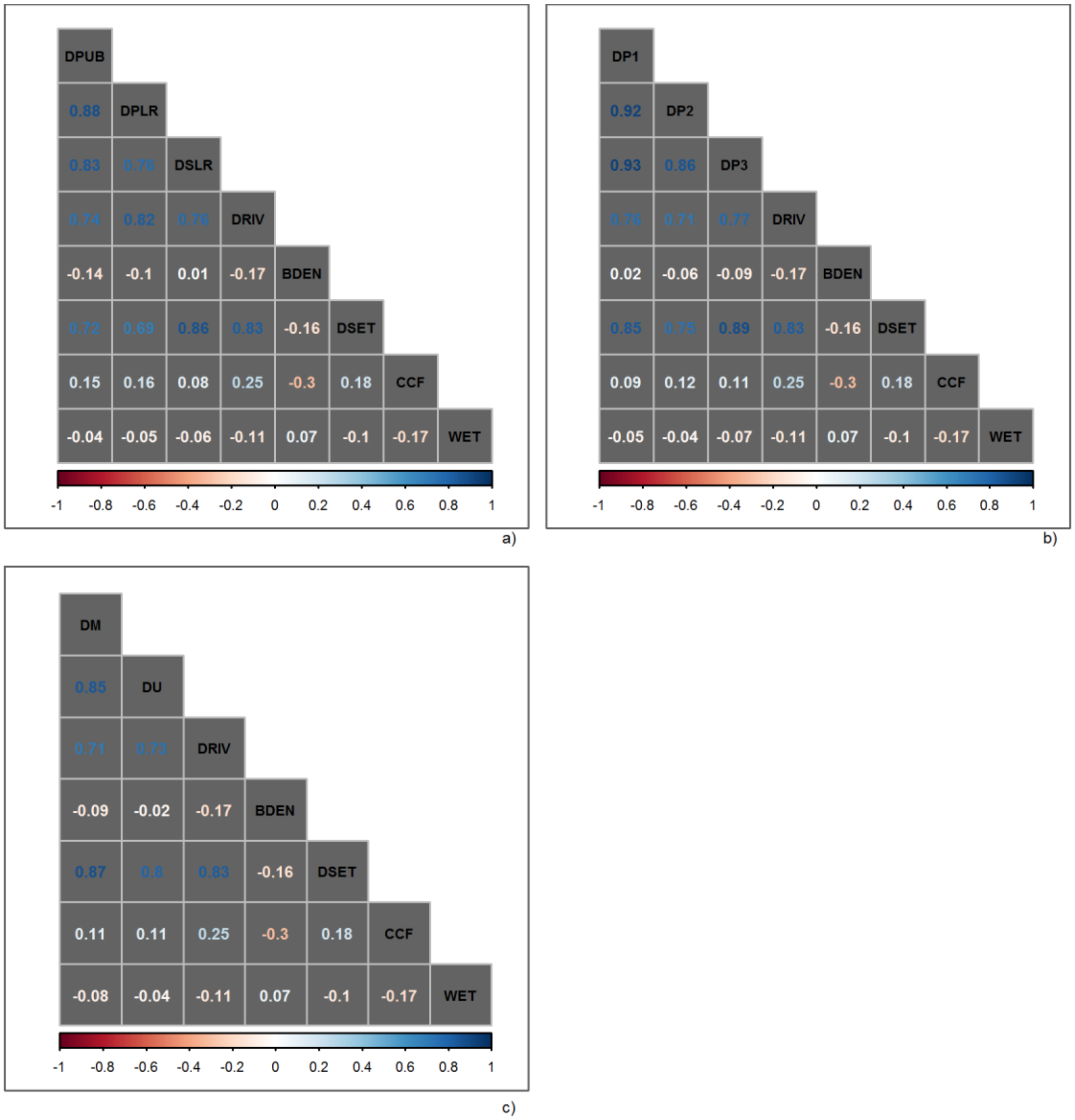

Figure E.6. Pearson correlation coefficient (*r*) plots for Site 4 grouped by road properties: a) road type, b) road proximate construction period and c) road maintenance. It was considered that collinearity was present if $|r| > 0.7$.

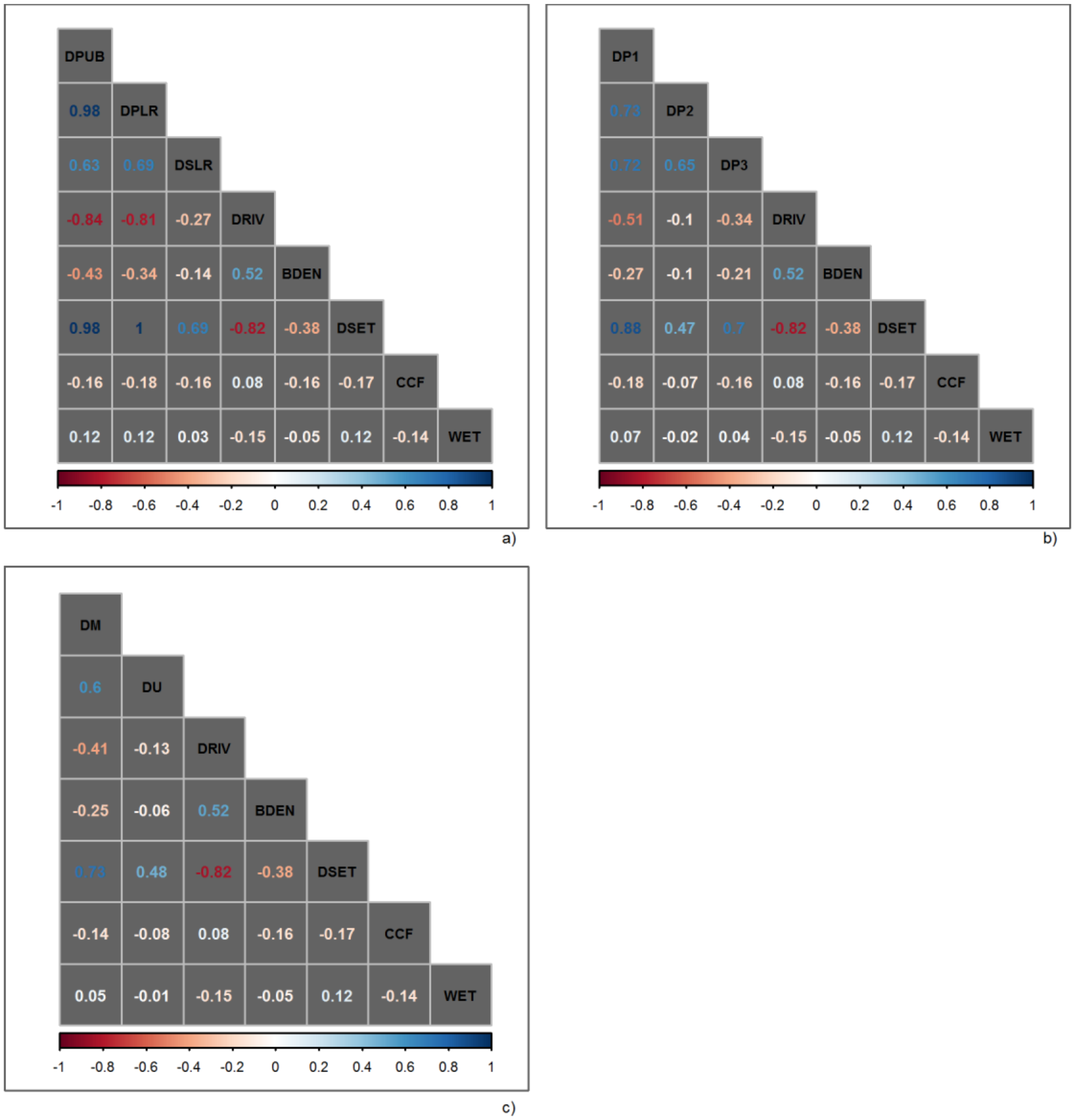

Figure E.7. Pearson correlation coefficient (*r*) plots for Site 5 grouped by road properties: a) road type, b) road proximate construction period and c) road maintenance. It was considered that collinearity was present if $|r| > 0.7$.

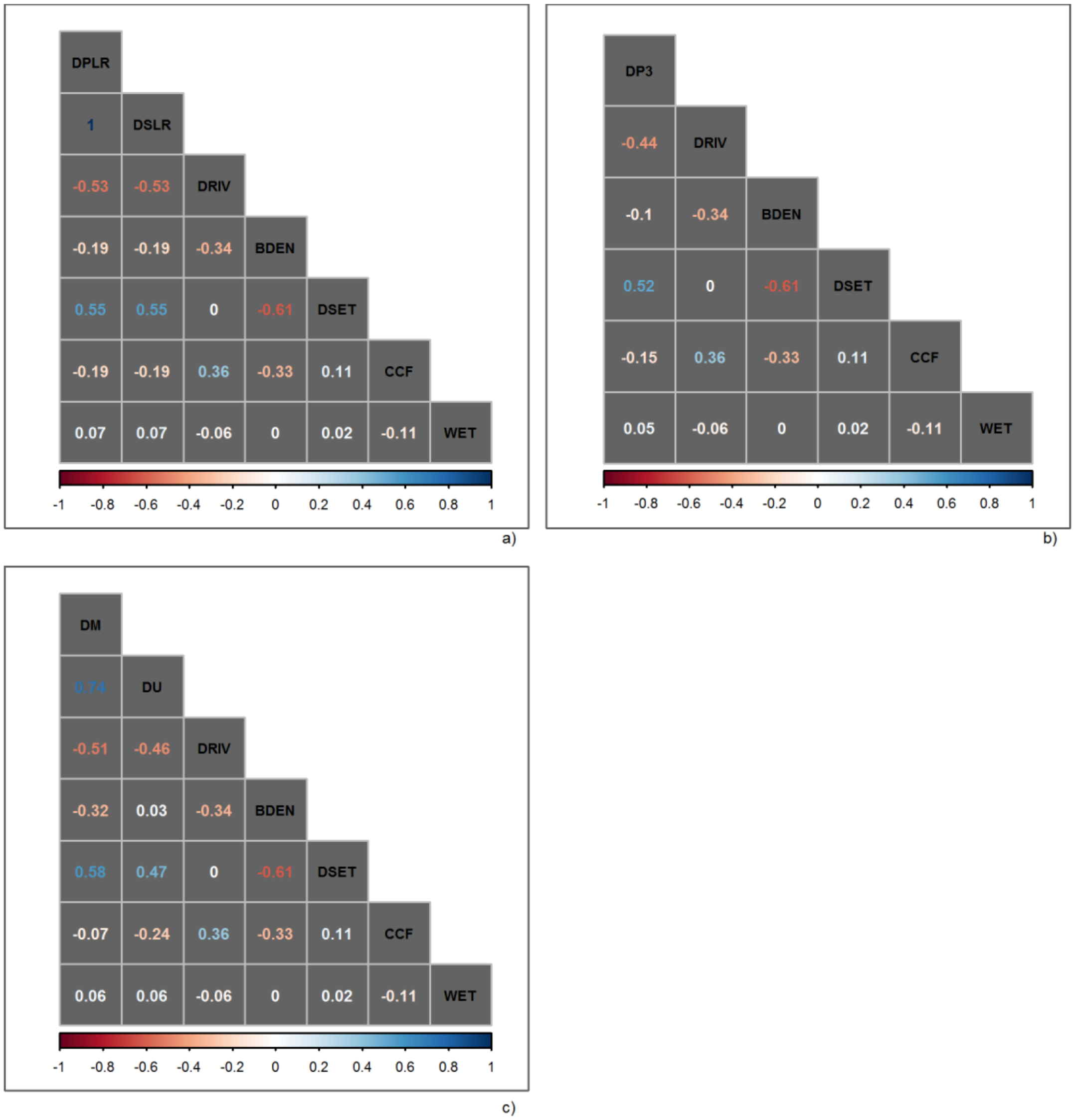

Figure E.8. Pearson correlation coefficient (*r*) plots for Site 6 grouped by road properties: a) road type, b) road proximate construction period and c) road maintenance. It was considered that collinearity was present if $|r| > 0.7$.

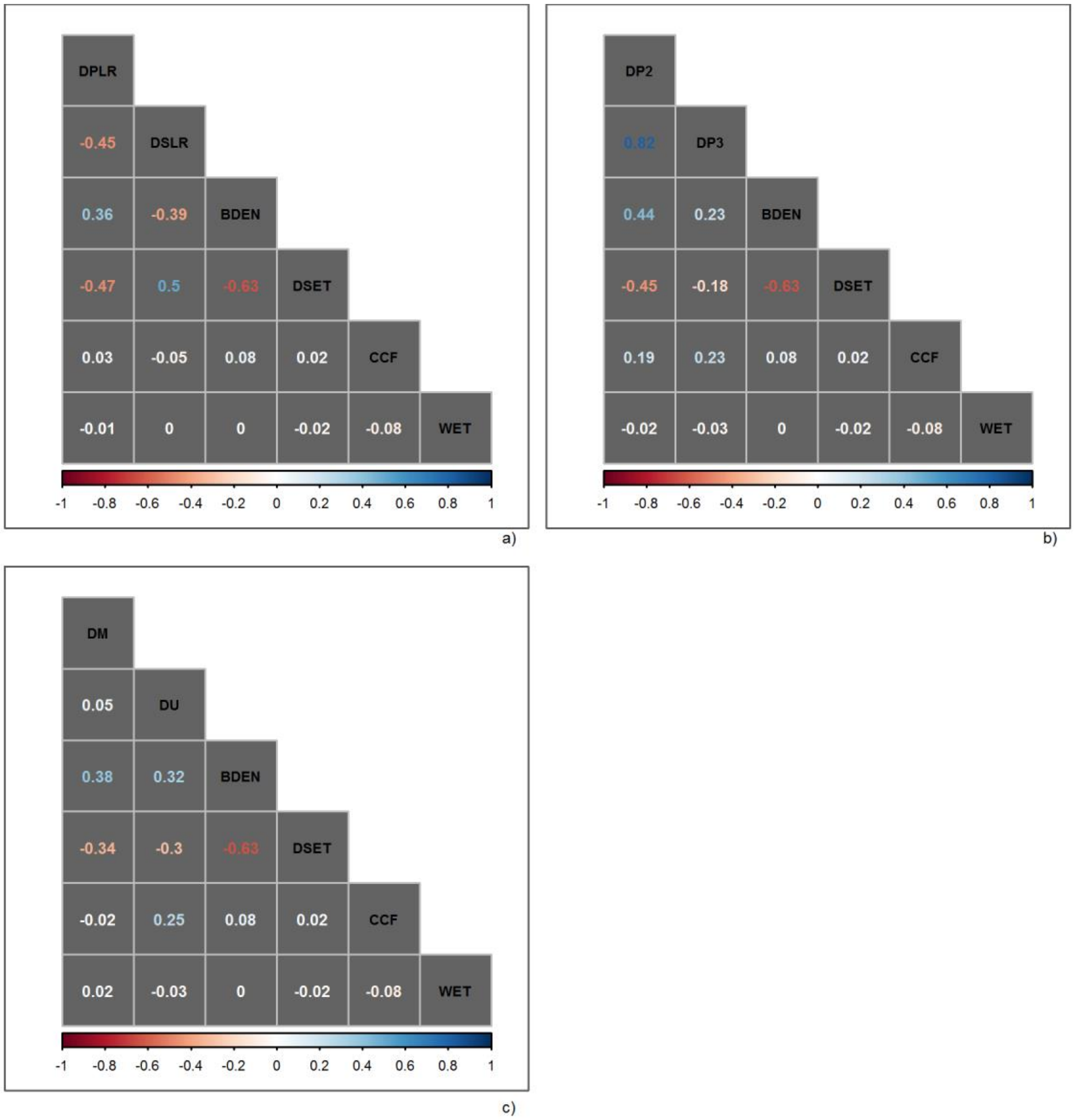

Figure E.9. Pearson correlation coefficient (*r*) plots for Site 7 grouped by road properties: a) road type, b) road proximate construction period and c) road maintenance. It was considered that collinearity was present if $|r| > 0.7$.

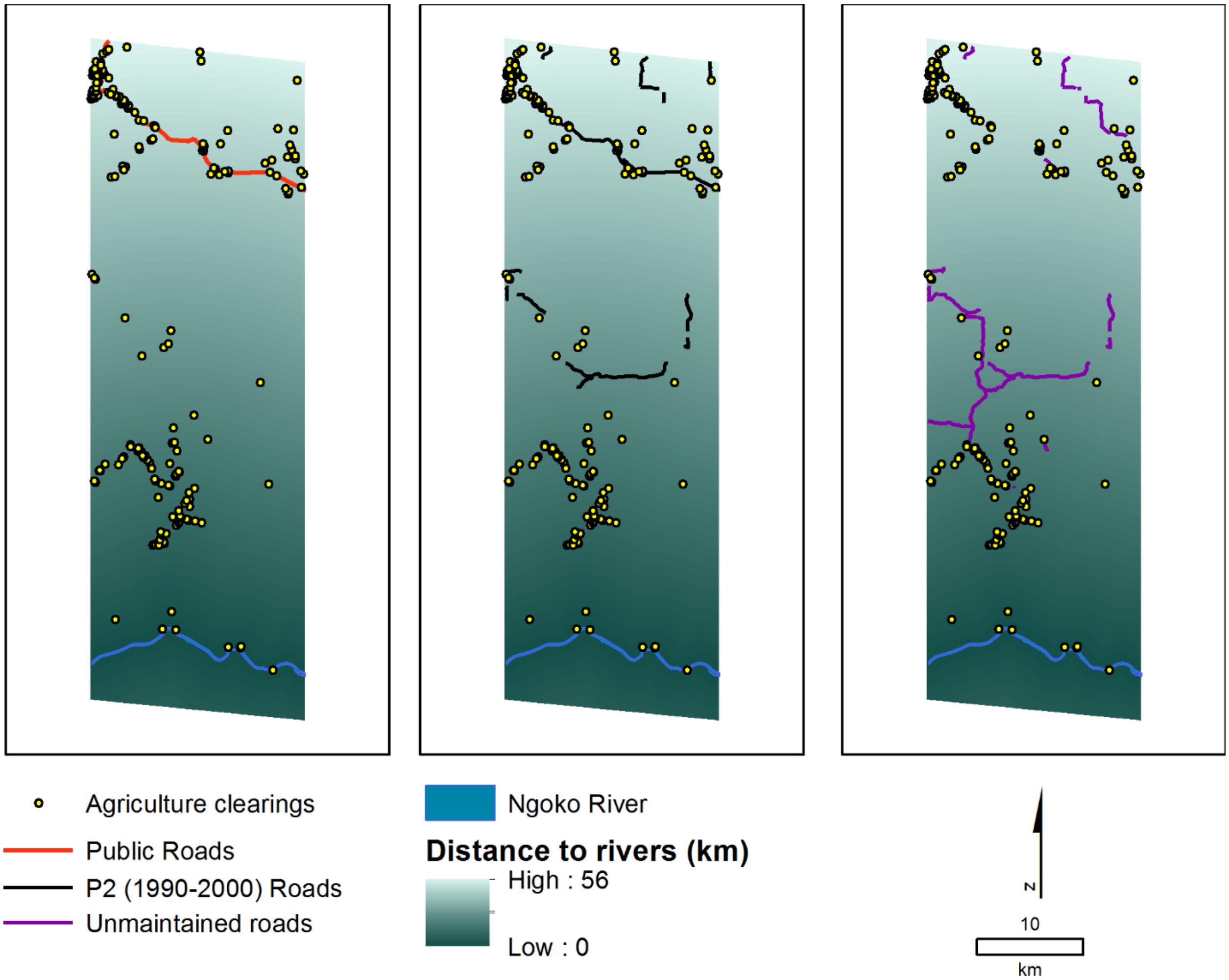

Figure E.10. For S2, collinearity was present among 1) variable distance to public roads and distance to rivers ($|r|$ = 0.97), 2) variable distance to roads build during P2 and distance to rivers ($|r|$ = 0.8) and 3) variable distance to unmaintained and distance to rivers ($|r|$ = 0.7). When the distance to rivers dataset was visually overlaid with the road segments with the conflicted characteristics, it was observed that the collinearity was due the position (south) and direction (east-west) of the river mirrored the opposite position of the road segments (north) and followed the same direction (east-west).

Table E.2. Model independent variables summary statistics by case site

Site	Explanatory variable	Variable	Units	Min	Max	Mean	SD	IQR	
								0.25	0.75
1	Distance to rivers	R	km	0.00	35.90	11.33	8.02	4.95	16.08
1	Distance to settlements	S	km	0.00	23.99	8.03	5.50	3.68	11.19
1	Topographic Wetness Index	W		10.17	26.84	13.00	2.07	11.79	13.22
1	Continuous forest fields *	C	%	4.48	84.36	73.74	3.64	73.28	75.24
1	Population density *	B	N/km²	0.00	11.69	0.84	1.71	0.01	0.88
1	Distance to all roads	A	km	0.00	17.07	4.09	4.23	0.77	6.53
1	Distance to Public Roads	T1	km	0.00	30.13	10.60	6.44	5.48	14.63
1	Distance to PLR	T2	km	0.00	35.05	11.00	9.56	2.94	17.52
1	Distance to SLR	T3	km	0.00	30.99	8.20	9.05	1.15	14.43
1	Distance to roads built Pre-1991	P1	km	0.00	30.13	10.67	6.43	5.55	14.69
1	Distance to roads built between 1992-2000	P2	km	0.00	36.72	11.08	10.27	2.16	18.77
1	Distance to roads built after 2000	P3	km	0.00	24.32	5.76	5.50	1.55	8.53
1	Distance to maintained roads	M1	km	0.00	17.11	5.30	4.22	0.00	0.00
1	Distance to unmaintained roads	M2	km	0.00	19.54	5.77	5.24	0.00	0.00
2	Distance to rivers	R	km	0.00	56.03	24.81	16.74	9.20	39.40
2	Distance to settlements	S	km	0.00	16.97	4.94	3.17	2.52	6.57
2	Topographic Wetness Index	W		9.68	31.65	13.47	2.30	12.04	14.04
2	Continuous forest fields *	C	%	0.00	83.92	75.94	5.81	75.60	77.80
2	Population density *	B	N/km²	0.00	9.23	0.23	0.77	0.00	0.15
2	Distance to all roads	A	km	0.00	16.75	3.14	3.50	0.78	3.93
2	Distance to Public Roads	T1	km	0.00	51.30	21.59	15.39	7.01	35.04
2	Distance to PLR	T2	km	0.00	22.76	10.18	5.77	5.27	15.01
2	Distance to SLR	T3	km	0.00	16.75	3.44	3.44	1.05	4.39
2	Distance to roads built Pre-1991	P1	km	0.00	21.18	5.06	4.47	1.53	7.58
2	Distance to roads built between 1992-2000	P2	km	0.00	32.93	9.16	8.99	2.21	15.33
2	Distance to roads built after 2000	P3	km	0.00	19.70	6.30	4.19	2.75	9.39
2	Distance to maintained roads	M1	km	0.00	16.75	4.00	3.60	1.17	5.82
2	Distance to unmaintained roads	M2	km	0.00	24.86	6.18	5.62	2.07	8.33
3	Distance to rivers	R	km	0.00	28.87	8.77	6.85	3.16	13.34
3	Distance to settlements	S	km	0.00	29.21	8.97	6.45	4.08	12.55
3	Topographic Wetness Index	W		10.35	28.91	13.62	2.24	12.23	14.18
3	Continuous forest fields *	C	%	0.00	79.92	75.50	3.15	75.00	77.04
3	Population density *	B	N/km²	0.00	0.79	0.14	0.17	0.01	0.19
3	Distance to all roads	A	km	0.00	30.28	9.83	6.81	4.06	14.46
4	Distance to rivers	R	km	0.00	34.30	11.36	8.15	4.63	16.72
4	Distance to settlements	S	km	0.00	25.46	7.15	5.33	3.33	9.06
4	Topographic Wetness Index	W		10.05	31.73	13.66	2.21	12.27	14.22
4	Continuous forest fields *	C	%	0.00	84.76	75.56	7.52	75.92	77.68
4	Population density *	B	N/km²	0.00	66.53	0.35	2.49	0.00	0.07
4	Distance to all roads	A	km	0.00	3.71	0.22	0.40	0.00	0.38
4	Distance to Public Roads	T1	km	0.00	44.67	14.51	11.71	4.68	22.78
4	Distance to PLR	T2	km	0.00	57.90	23.07	17.46	6.80	38.19
4	Distance to SLR	T3	km	0.00	23.10	4.28	5.52	0.76	4.54
4	Distance to roads built Pre-1991	P1	km	0.00	25.76	4.88	5.97	0.94	5.99

Site	Explanatory variable	Variable	Units	Min	Max	Mean	SD	IQR	
								0.25	0.75
4	Distance to roads built between 1992-2000	P2	km	0.00	36.60	9.53	9.12	2.67	15.01
4	Distance to roads built after 2000	P3	km	0.00	23.10	5.05	5.27	1.56	6.13
4	Distance to maintained roads	M1	km	0.00	23.10	5.20	5.25	1.62	6.51
4	Distance to unmaintained roads	M2	km	0.00	29.80	6.05	7.18	0.96	9.22
5	Distance to rivers	R	km	0.00	36.38	13.34	9.90	5.14	20.50
5	Distance to settlements	S	km	0.00	54.96	23.98	16.58	8.03	38.50
5	Topographic Wetness Index	W		10.38	28.19	13.96	2.28	12.50	14.64
5	Continuous forest fields *	C	%	4.60	169.80	75.02	3.49	74.40	76.88
5	Population density *	B	N/km²	0.00	3.17	0.13	0.46	0.00	0.00
5	Distance to all roads	A	km	0.00	19.67	4.13	4.94	0.60	6.36
5	Distance to Public Roads	T1	km	0.00	55.97	26.37	15.47	13.10	39.62
5	Distance to PLR	T2	km	0.00	53.67	22.76	16.01	7.31	36.76
5	Distance to SLR	T3	km	0.00	19.67	4.22	4.90	0.72	6.36
5	Distance to roads built Pre-1991	P1	km	0.00	32.56	9.22	8.25	2.05	15.05
5	Distance to roads built between 1992-2000	P2	km	0.00	22.67	7.60	5.03	3.54	11.07
5	Distance to roads built after 2000	P3	km	0.00	19.67	4.87	4.94	0.99	7.83
5	Distance to maintained roads	M1	km	0.00	20.56	5.35	5.18	0.93	8.89
5	Distance to unmaintained roads	M2	km	0.00	19.74	6.39	5.08	1.98	10.00
6	Distance to rivers	R	km	0.00	14.13	5.61	3.25	2.85	8.28
6	Distance to settlements	S	km	0.00	10.22	3.05	1.81	1.74	3.96
6	Topographic Wetness Index	W		10.67	29.06	14.09	2.09	12.69	14.89
6	Continuous forest fields *	C	%	14.00	80.36	75.09	2.63	74.64	76.40
6	Population density *	B	N/km²	0.00	0.74	0.17	0.16	0.05	0.27
6	Distance to all roads	A	km	0.00	10.33	1.98	2.00	0.48	2.93
6	Distance to PLR	T2	km	0.00	13.60	4.42	3.04	1.86	6.60
6	Distance to SLR	T3	km	0.00	10.33	2.04	1.97	0.57	2.94
6	Distance to roads built after 2000	P3	km	0.00	10.33	1.98	2.00	0.48	2.93
6	Distance to maintained roads	M1	km	0.00	13.60	3.83	3.03	1.36	5.73
6	Distance to unmaintained roads	M2	km	0.00	10.33	2.15	2.05	0.60	3.12
7	Distance to settlements	S	km	0.00	15.80	4.78	2.82	2.59	6.50
7	Topographic Wetness Index	W		10.70	26.95	14.04	2.02	12.69	14.82
7	Continuous forest fields *	C	%	29.84	80.13	75.60	1.60	75.00	76.56
7	Population density *	B	N/km²	0.00	0.63	0.09	0.13	0.01	0.13
7	Distance to all roads	A	km	0.00	15.66	3.88	4.44	0.33	6.91
7	Distance to PLR	T2	km	0.00	14.95	6.26	3.49	3.54	8.83
7	Distance to SLR	T3	km	0.00	11.97	3.30	3.43	0.33	6.32
7	Distance to roads built between 1992-2000	P2	km	0.00	10.77	3.53	3.08	0.60	6.07
7	Distance to roads built after 2000	P3	km	0.00	15.66	4.05	4.37	0.54	6.97
7	Distance to maintained roads	M1	km	0.00	23.87	12.07	5.72	7.35	16.88
7	Distance to unmaintained roads	M2	km	0.00	11.97	3.28	3.42	0.33	6.30

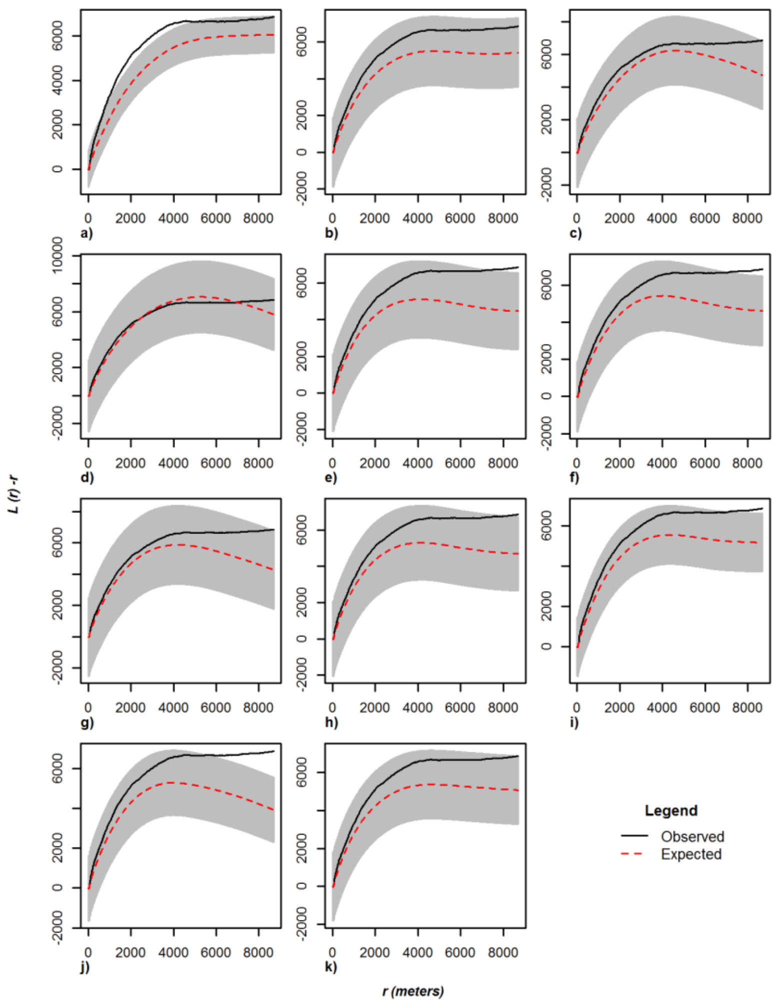

Figure E.11. Site 1: L-summary function. Grey shaded area indicates upper and lower critical bands. Black solid-lines indicate tendency of the fitted-output, dotted red line indicates the n-envelope estimated mean. Showing simulations sets as follow: a) Base + NI, Base, b) Base + I, c) Base+I+DARO, d) Base+I+PUB, e) Base+I+PLOG, f) Base+I+SLOG, g) Base+I+PER1, h) Base+I+PER2, i) Base+I+PER3, j) Base+I+MNTD, k) Base+I+ UMNTD.

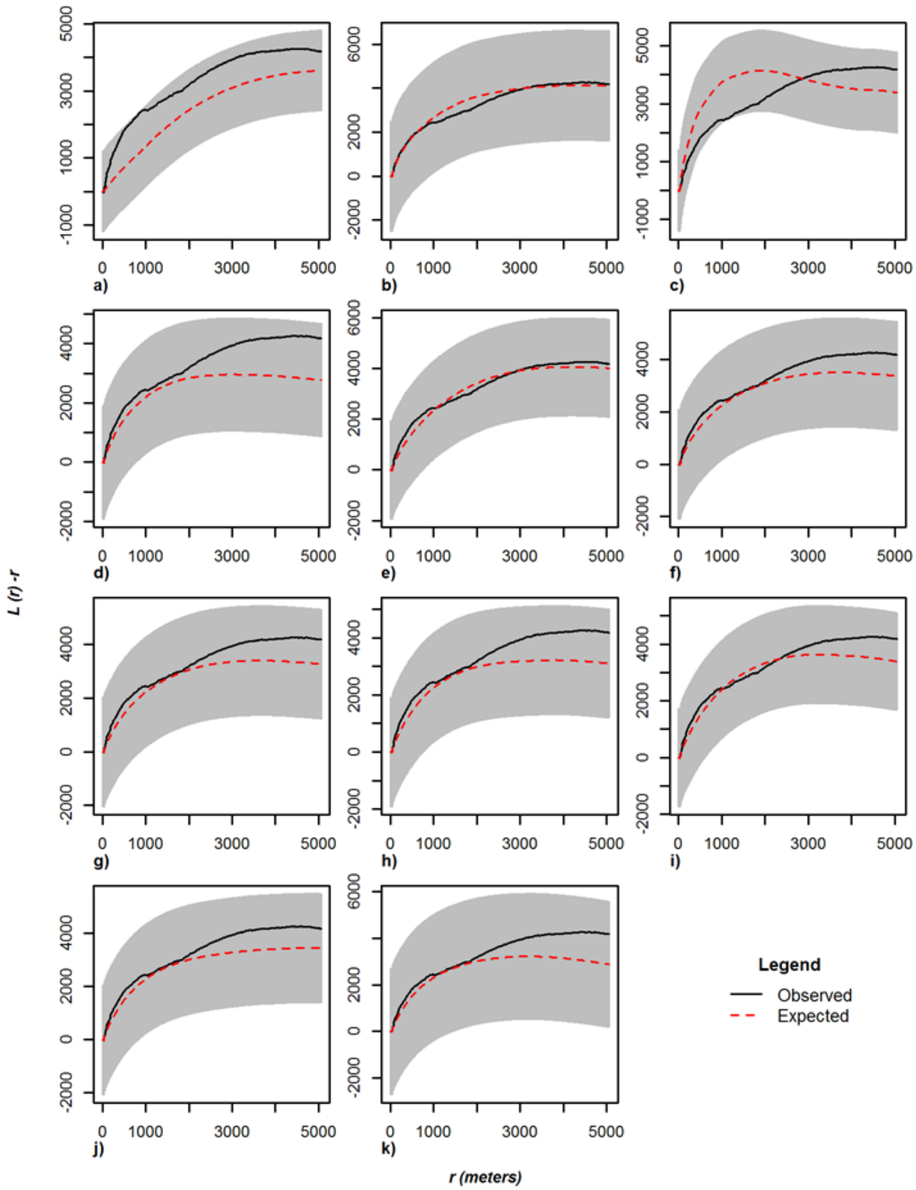

Figure E.12. Site 2: L-summary function. Grey shaded area indicates upper and lower critical bands. Black solid-lines indicate tendency of the fitted-output, dotted red line indicates the n-envelope estimated mean. Showing simulations sets as follow: a) Base + NI, Base, b) Base + I, c) Base+I+DARO, d) Base+I+PUB, e) Base+I+PLOG, f) Base+I+SLOG, g) Base+I+PER1, h) Base+I+PER2, i) Base+I+PER3, j) Base+I+MNTD, k) Base+I+ UMNTD.

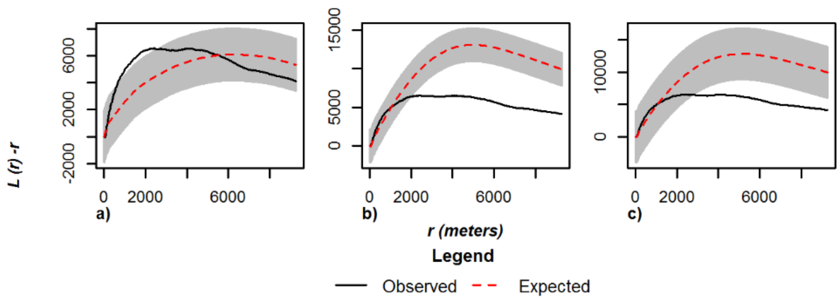

Figure E.13. Site 3: L-summary function. Grey shaded area indicates upper and lower critical bands. Black solid-lines indicate tendency of the fitted-output, dotted red line indicates the n-envelope estimated mean. Showing simulations sets as follow: a) Base + NI, Base, b) Base + I, c) Base+I+DARO

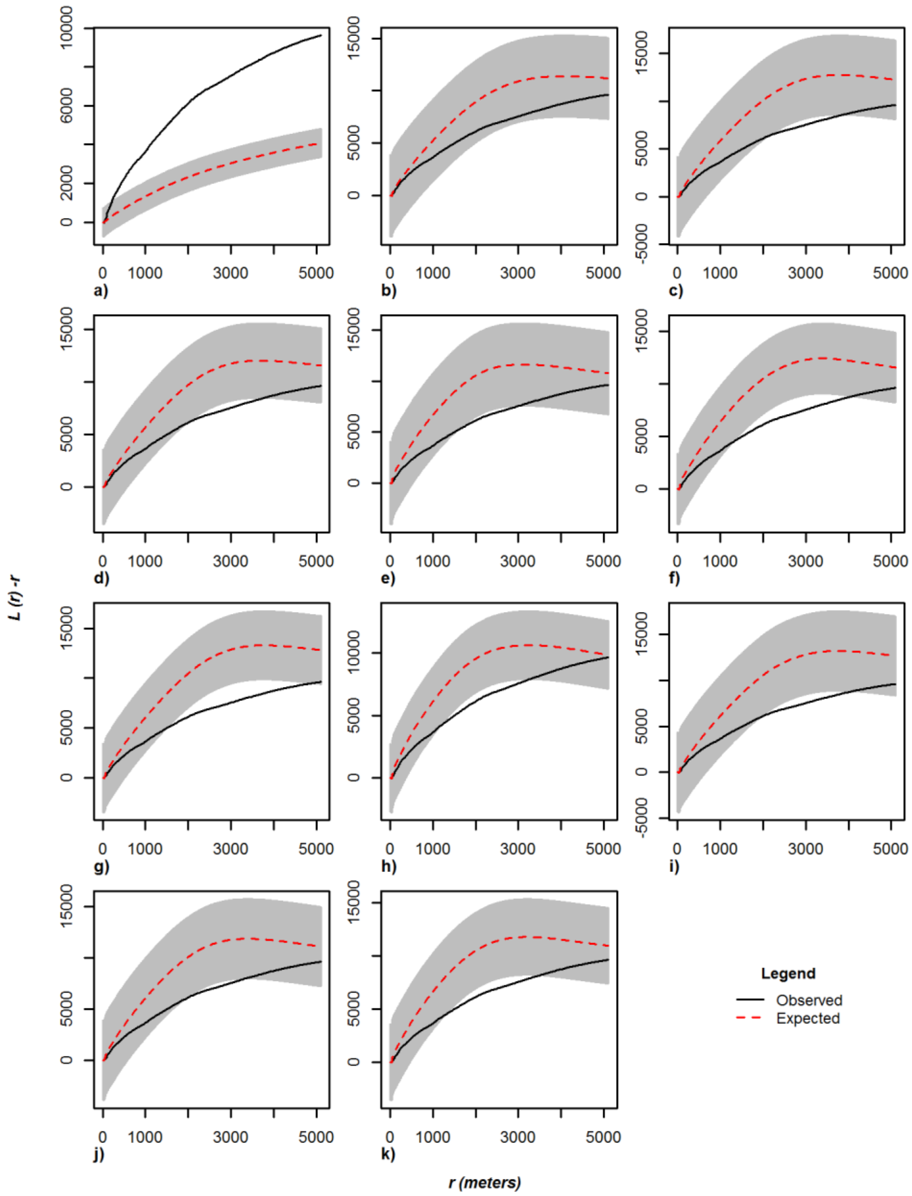

Figure E.14. Site 4: L-summary function. Grey shaded area indicates upper and lower critical bands. Black solid-lines indicate tendency of the fitted-output, dotted red line indicates the n-envelope estimated mean. Showing simulations sets as follow: a) Base + NI, Base, b) Base + I, c) Base+I+DARO, d) Base+I+PUB, e) Base+I+PLOG, f) Base+I+SLOG, g) Base+I+PER1, h) Base+I+PER2, i) Base+I+PER3, j) Base+I+MNTD, k) Base+I+ UMNTD.

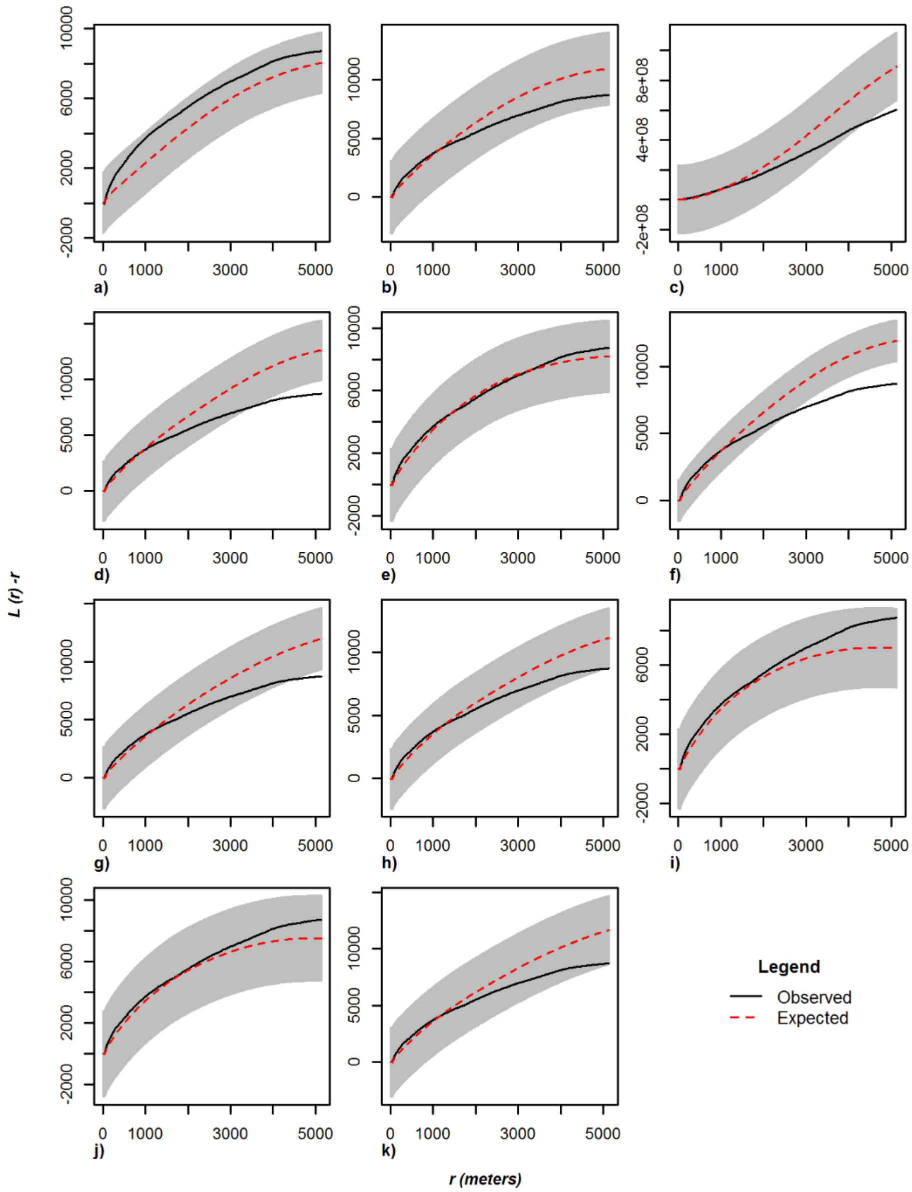

Figure E.15. Site 5: L-summary function. Grey shaded area indicates upper and lower critical bands. Black solid-lines indicate tendency of the fitted-output, dotted red line indicates the n-envelope estimated mean. Showing simulations sets as follow: a) Base + NI, Base, b) Base + I, c) Base+I+DARO, d) Base+I+PUB, e) Base+I+PLOG, f) Base+I+SLOG, g) Base+I+PER1, h) Base+I+PER2, i) Base+I+PER3, j) Base+I+MNTD, k) Base+I+ UMNTD.

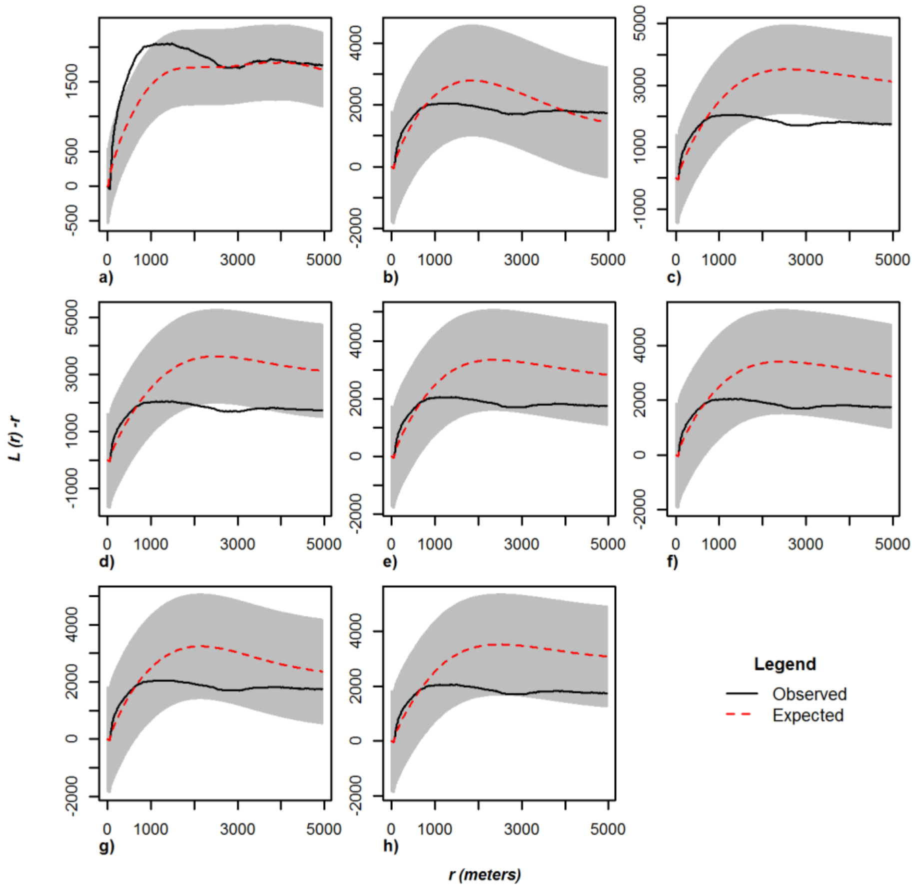

Figure E.16. S6 *L-summary function*. Grey shaded area indicates upper critical bands. Black solid-lines indicate tendency of the fitted-output, dotted red line indicates the n-envelope estimated mean. Showing simulations sets as follow: a) Base + NI, Base, b) Base + I, c) Base+I+DARO, d) Base+I+PLOG, e) Base+I+SLOG, f) Base+I+PER3, g) Base+I+MNTD, h) Base+I+ UMNTD.

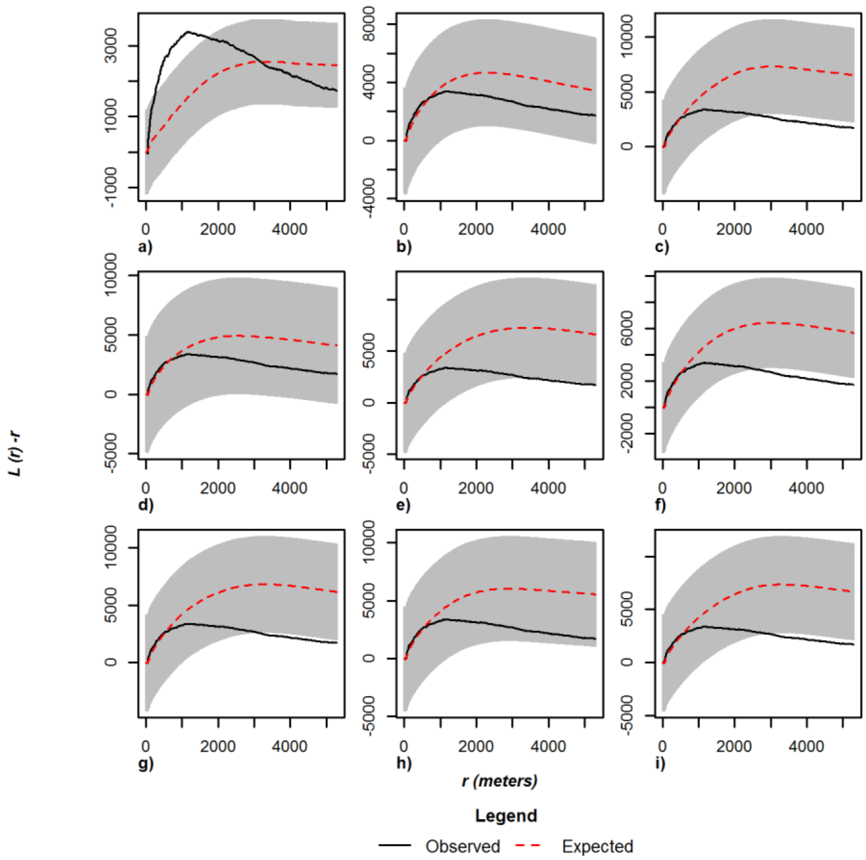

Figure E.17. S7 L-summary function. Grey shaded area indicates upper and lower critical bands. Black solid-lines indicate tendency of the fitted-output, dotted red line indicates the n-envelope estimated mean. Showing simulations sets as follow: a) Base + NI, Base, b) Base + I, c) Base+I+DARO, d) Base+I+PLOG, e) Base+I+SLOG, f) Base+I+PER2, g) Base+I+PER3, h) Base+I+MNTD, i) Base+I+ UMNTD.

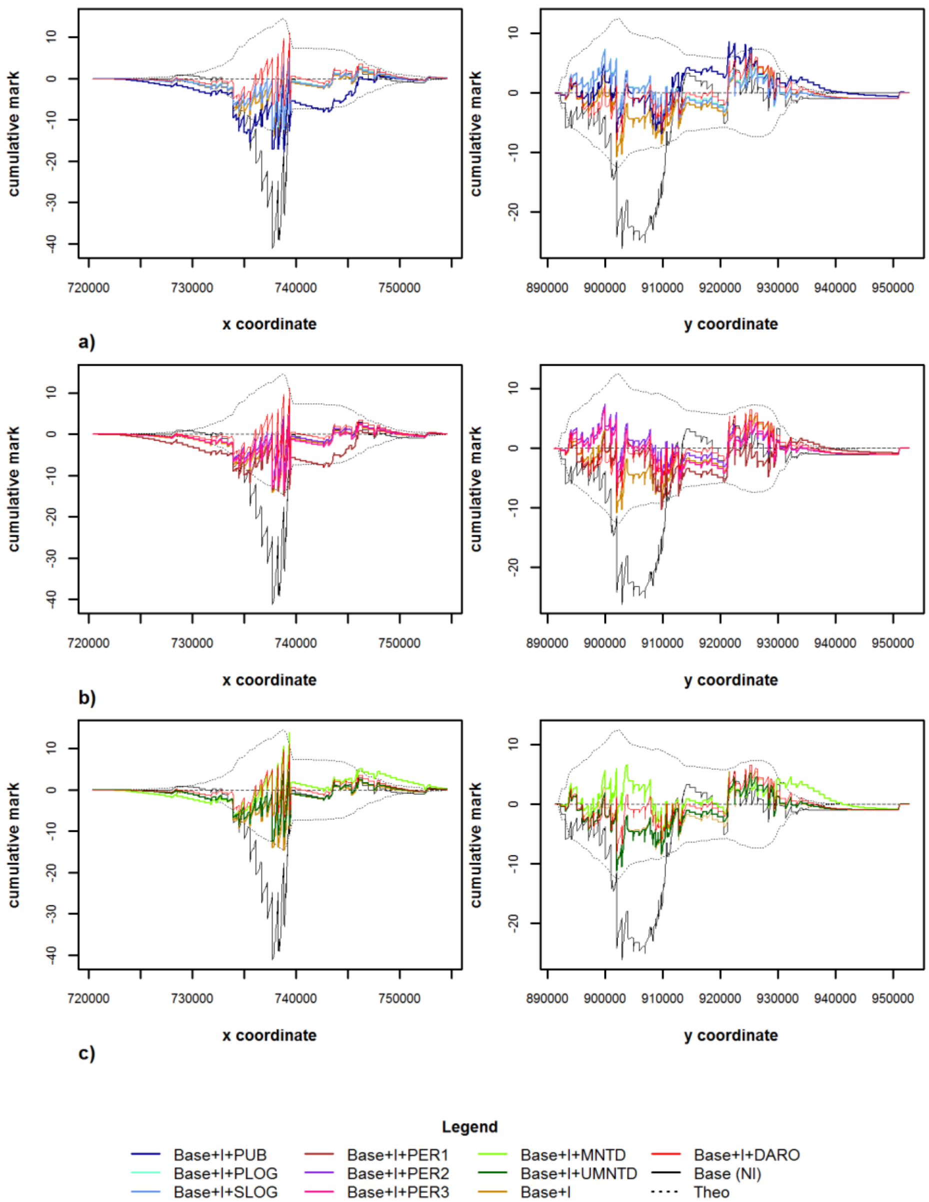

Figure E.18. Site 1, residuals lurking assessment of the trend. Simulations grouped by road property classes. a) road types, b) road construction period, c) road maintenance. Each plot illustrated the road sub-property plus Base+I, Base+I+DARO and Base (NI).

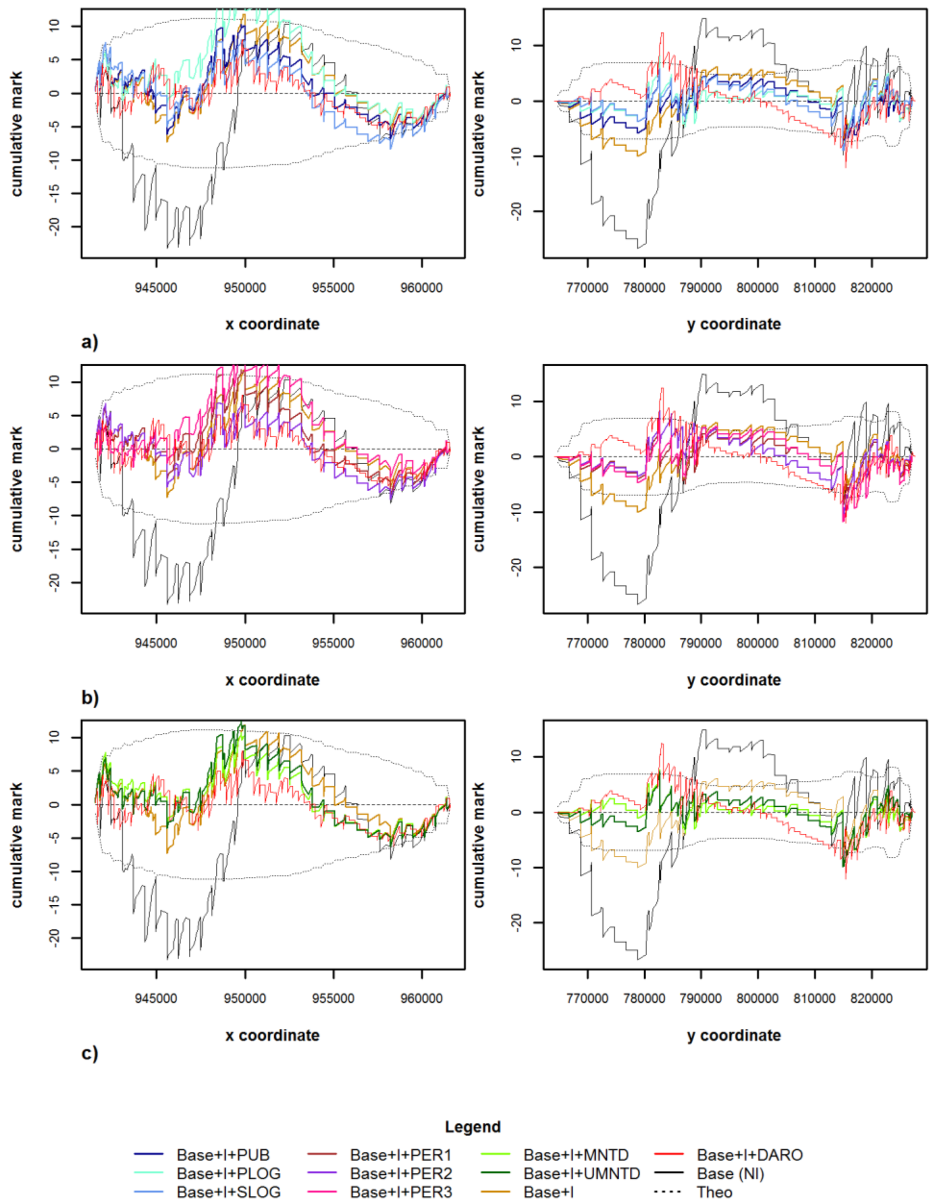

Figure E.19. Site 2, residuals lurking assessment of the trend. Simulations grouped by road property classes. a) road types, b) road construction period, c) road maintenance. Each plot illustrated the road sub-property plus Base+I, Base+I+DARO and Base (NI).

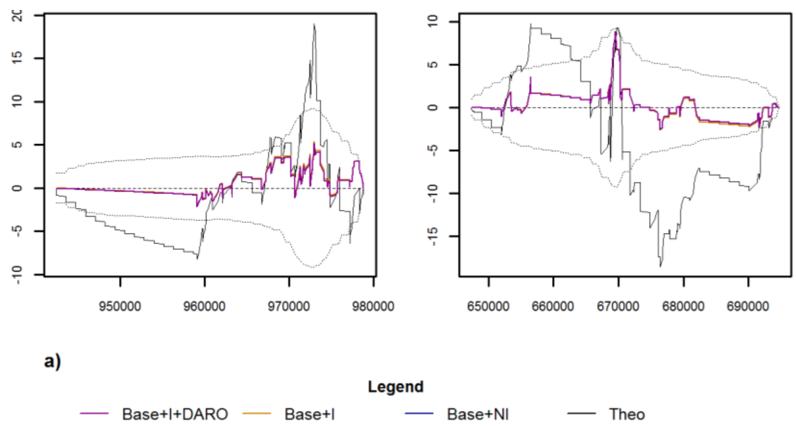

Figure E.20. Site 3, residuals lurking assessment of the trend.

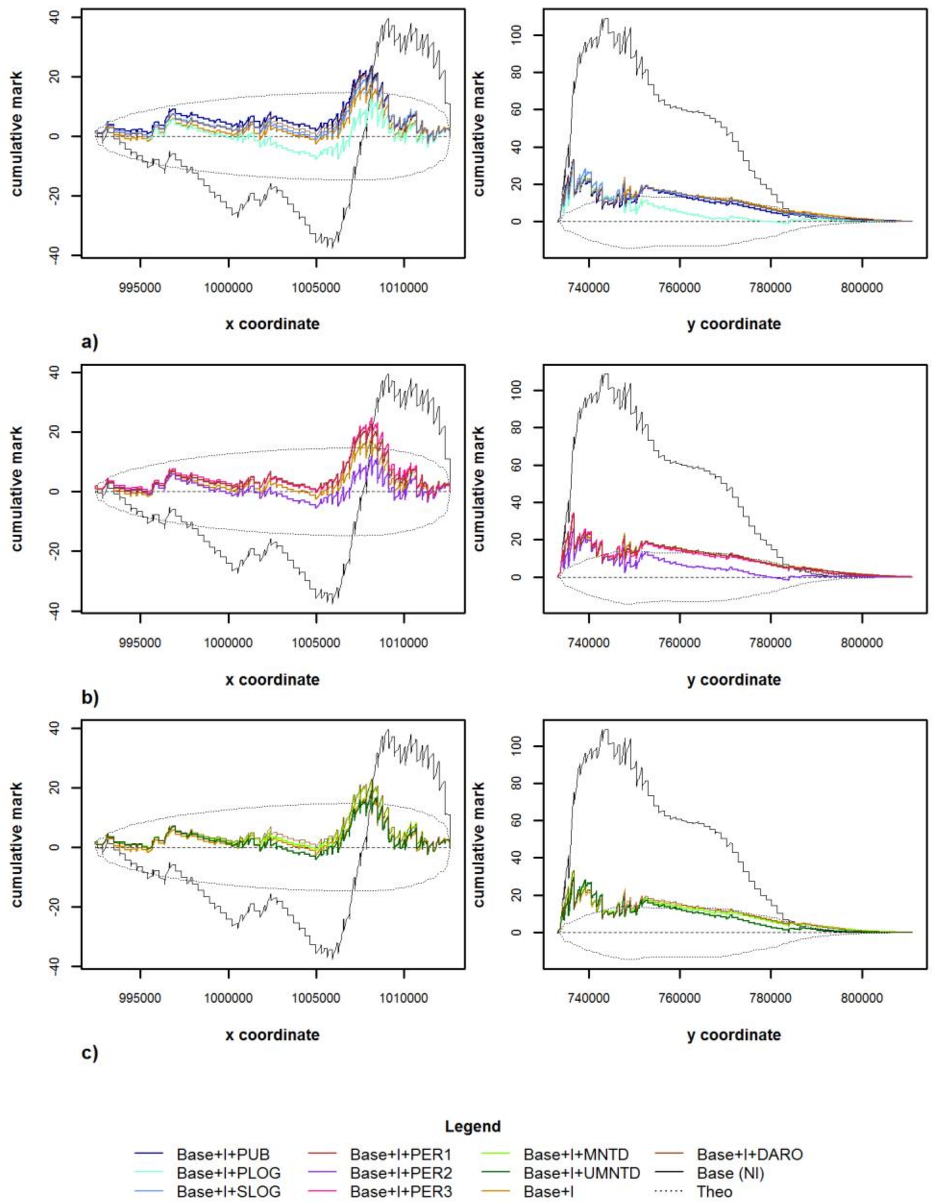

Figure E.21. Site 4, residuals lurking assessment of the trend. Simulations grouped by road property classes. a) road types, b) road construction period, c) road maintenance. Each plot illustrated the road sub-property plus Base+I, Base+I+DARO and Base (NI).

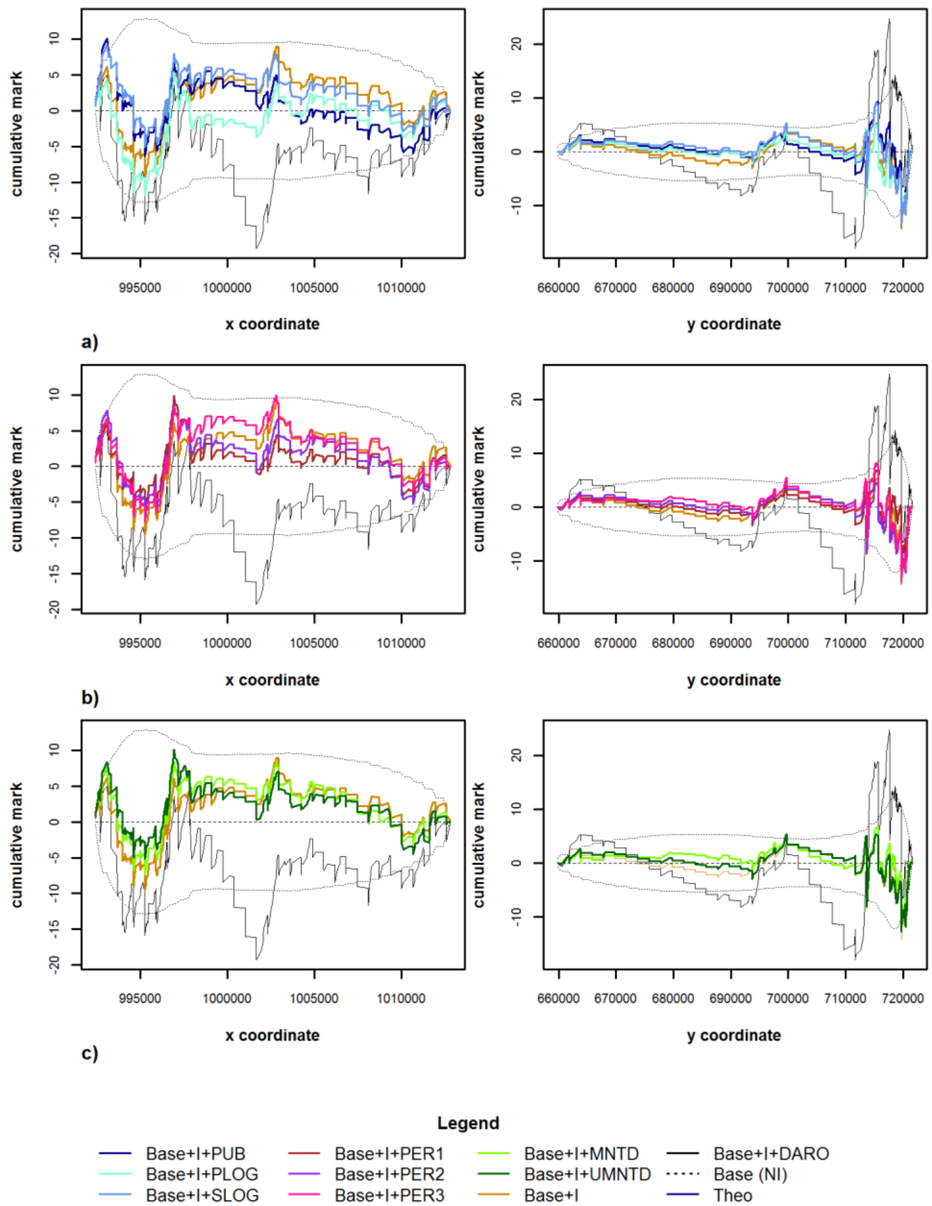

Figure E.22. Site 5, residuals lurking assessment of the trend. Simulations grouped by road property classes. a) road types, b) road construction period, c) road maintenance. Each plot illustrated the road sub-property plus Base+I, Base+I+DARO and Base (NI).

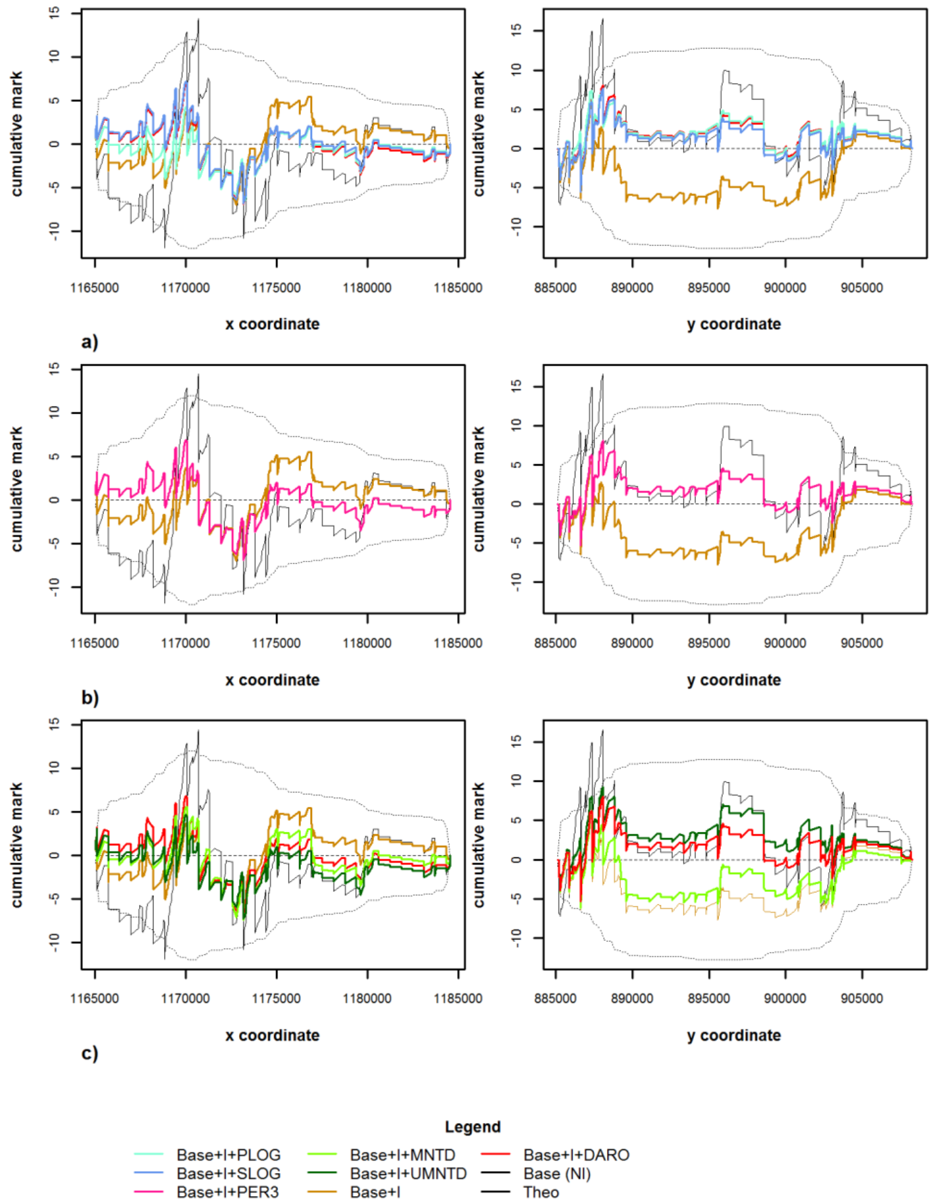

Figure E.23. Site 6, residuals lurking assessment of the trend. Simulations grouped by road property classes. a) road types, b) road construction period, c) road maintenance. Each plot illustrated the road sub-property plus Base+I, Base+I+DARO and Base (NI).

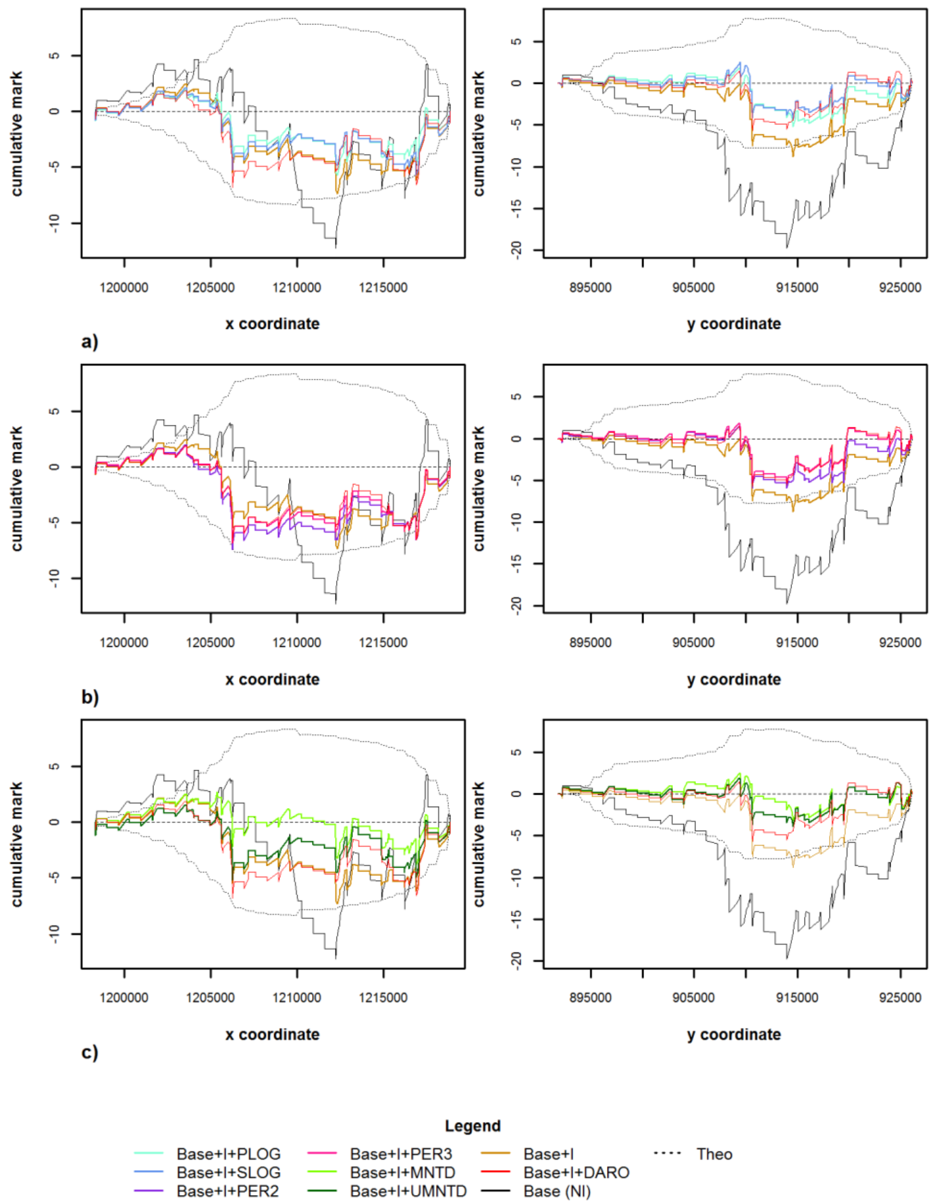

Figure E.24. Site 7, residuals lurking assessment of the trend. Simulations grouped by road property classes. a) road types, b) road construction period, c) road maintenance. Each plot illustrated the road sub-property plus Base+I, Base+I+DARO and Base (NI).

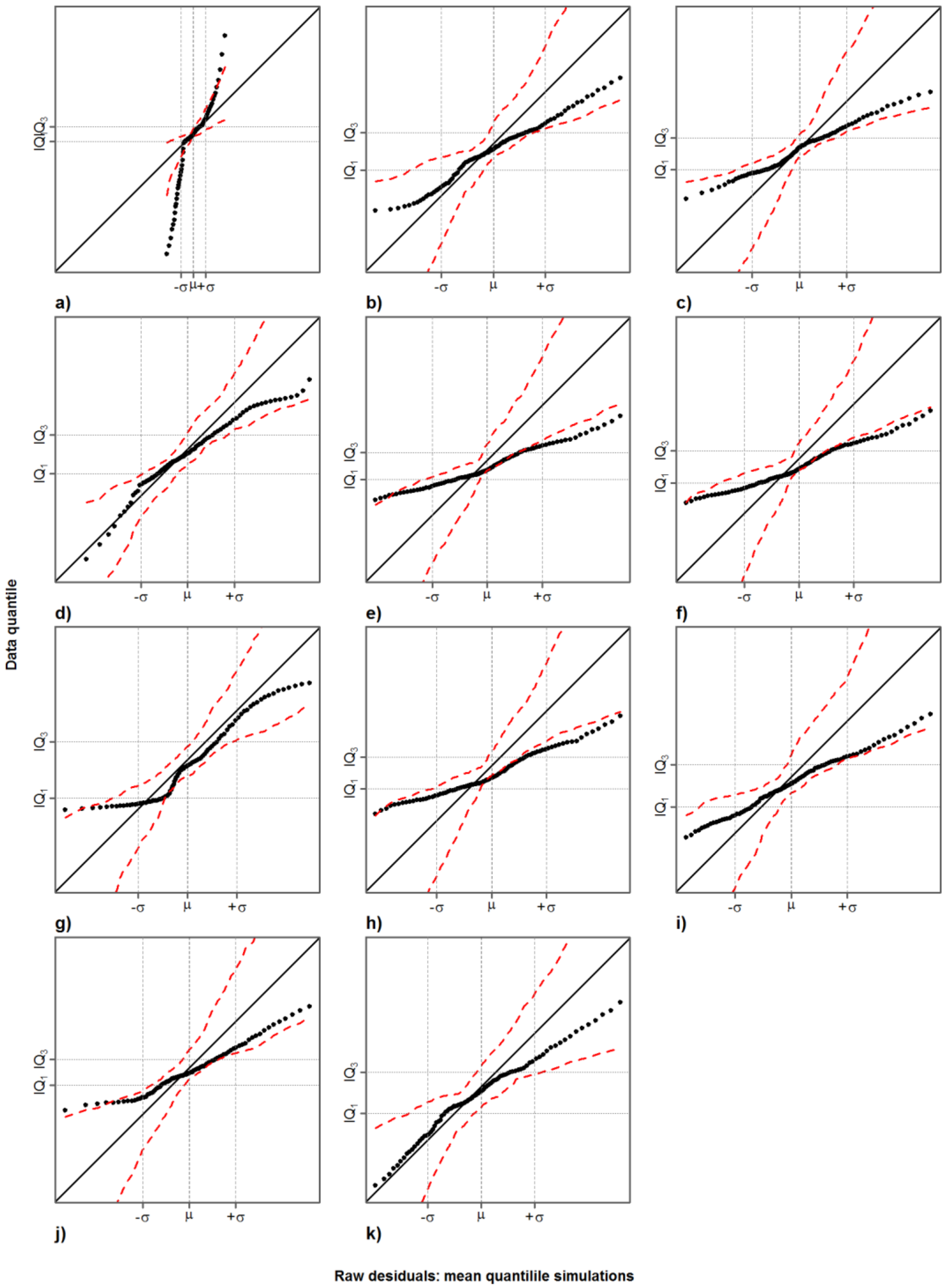

Figure E.25. Site 1 residual Q-Q plot test for the assessment of the simulation interaction component. Red dotted lines show confidence intervals, solid black line shows the ideal distribution of the residuals, dots indicated observed residuals. Showing set of simulations as follow: a) Base + NI, Base, b) Base + I, c) Base+I+DARO, d) Base+I+PUB, e) Base+I+PLOG, f) Base+I+SLOG, g) Base+I+PER1, h) Base+I+PER2, i) Base+I+PER3, j) Base+I+MNTD, k) Base+I+ UMNTD.

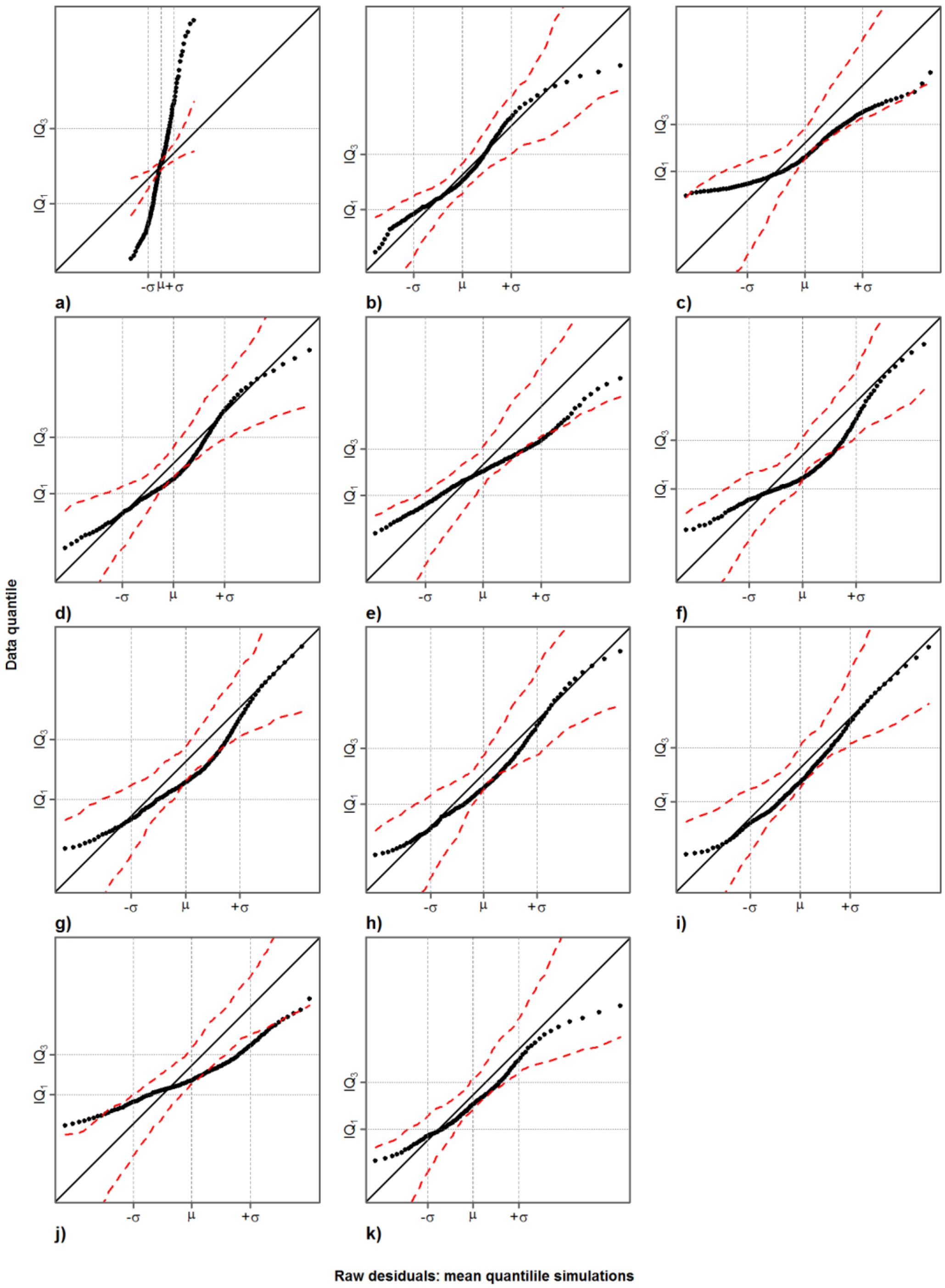

Figure E.26. Site 2 residual Q-Q plot test for the assessment of the simulation interaction component. Red dotted lines show confidence intervals, solid black line shows the ideal distribution of the residuals, dots indicated observed residuals. Showing set of simulations as follow: a) Base + NI, Base, b) Base + I, c) Base+I+DARO, d) Base+I+PUB, e) Base+I+PLOG, f) Base+I+SLOG, g) Base+I+PER1, h) Base+I+PER2, i) Base+I+PER3, j) Base+I+MNTD, k) Base+I+ UMNTD.

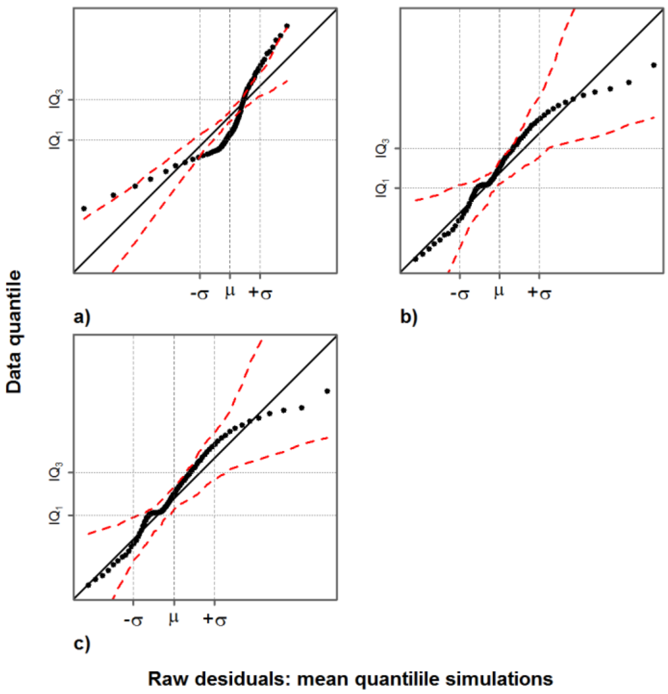

Figure E.27. Site 3 residual Q-Q plot test for the assessment of the simulation interaction component. Red dotted lines show confidence intervals, solid black line shows the ideal distribution of the residuals, dots indicated observed residuals. Showing set of simulations as follow: a) Base + NI, Base, b) Base + I, c) Base+I+DARO.

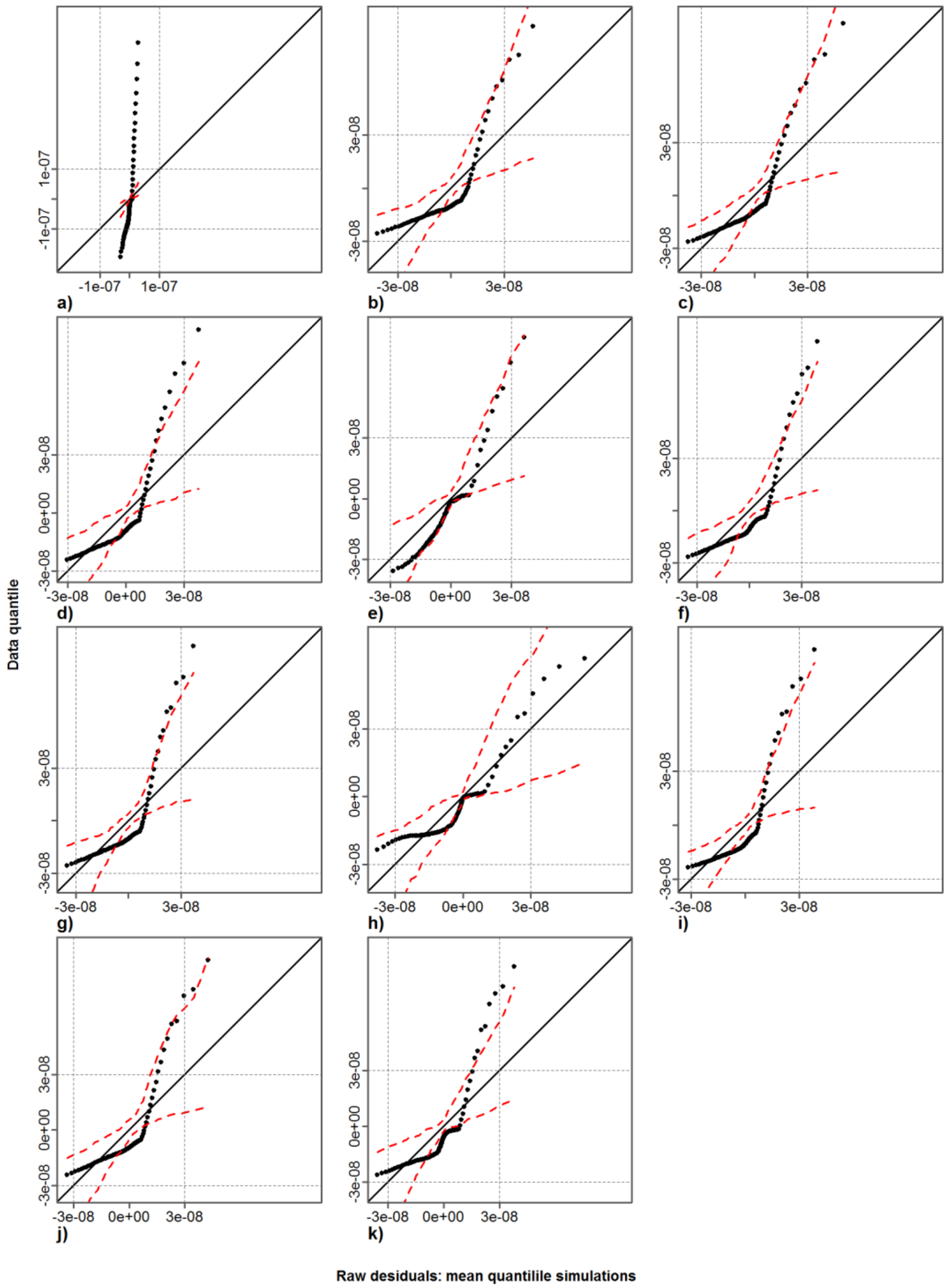

Figure E.28. Site 4 residual QQplot test for the assessment of the simulation interaction component. Showing simulations as follow: a) Base + NI, Base, b) Base + I, c) Base+I+DARO, d) Base+I+PUB, e) Base+I+PLOG, f) Base+I+SLOG, g) Base+I+PER1, h) Base+I+PER2, i) Base+I+PER3, j) Base+I+MNTD, k) Base+I+ UMNTD.

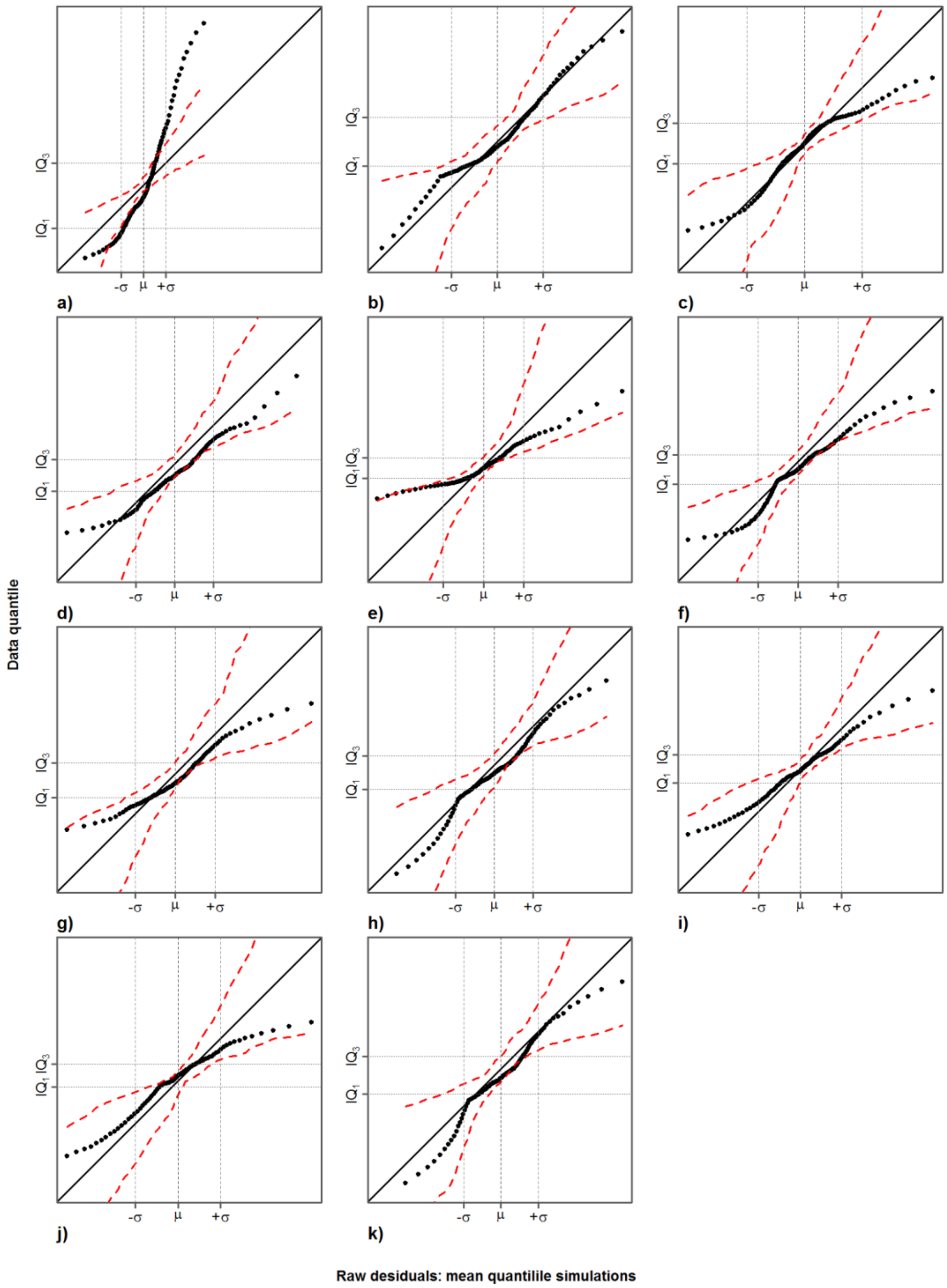

Figure E.29. Site 5 residual QQplot test for the assessment of the simulation interaction component. Showing simulations as follow: a) Base + NI, Base, b) Base + I, c) Base+I+DARO, d) Base+I+PUB, e) Base+I+PLOG, f) Base+I+SLOG, g) Base+I+PER1, h) Base+I+PER2, i) Base+I+PER3, j) Base+I+MNTD, k) Base+I+ UMNTD.

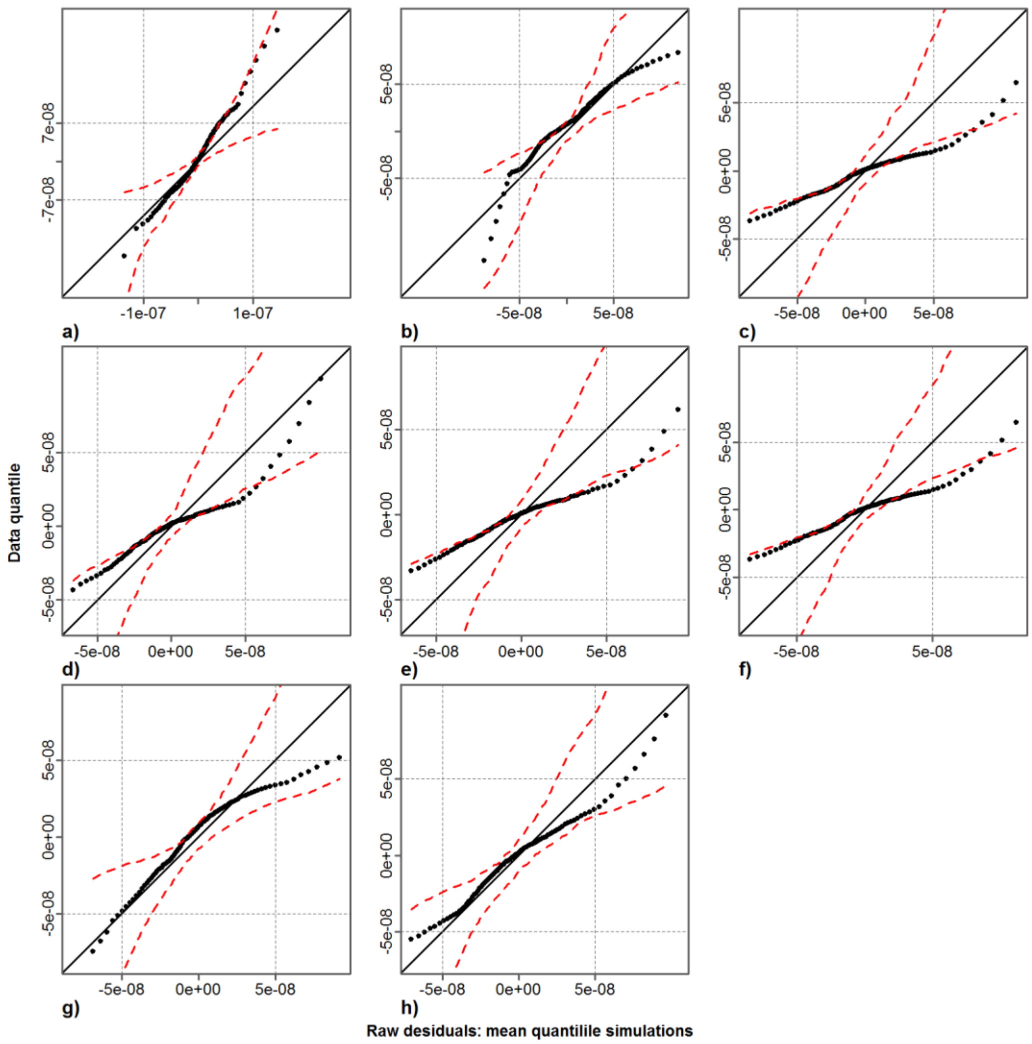

Figure E.30. Site 6 residual QQplot test for the assessment of the simulation interaction component. Showing simulations as follow: a) Base + NI, Base, b) Base + I, c) Base+I+DARO, d) Base+I+PLOG, e) Base+I+SLOG, f) Base+I+PER3, g) Base+I+MNTD, h) Base+I+ UMNTD.

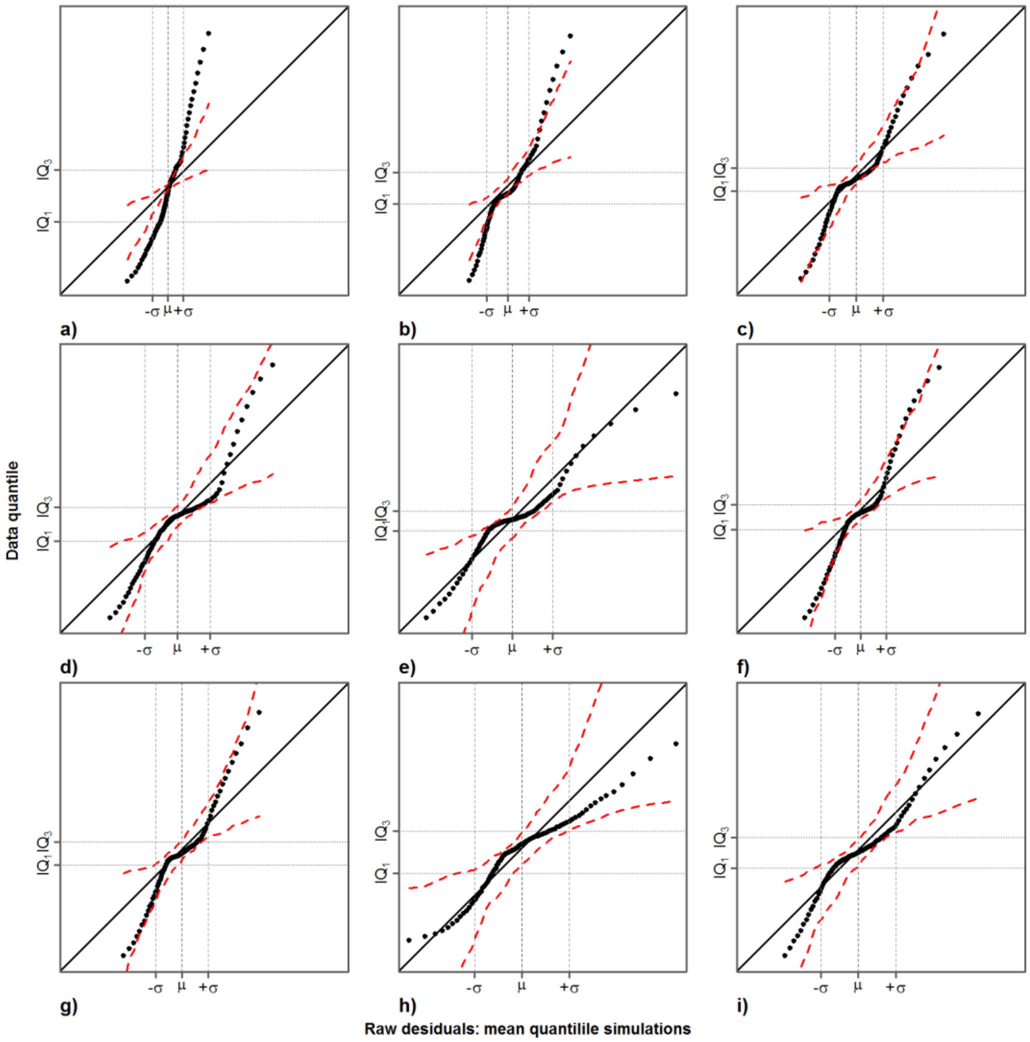

Figure E.31. Site 7 residual QQplot test for the assessment of the simulation interaction component. Showing simulations as follow: a) Base + NI, Base, b) Base + I, c) Base+I+DARO, d) Base+I+PLOG, e) Base+I+SLOG, f) Base+I+PER2, g) Base+I+PER3, h) Base+I+MNTD, i) Base+I+ UMNTD.

Table E.3. Fitted outputs for the best simulations per case site.

Site	Simulation	Variable	Estimate	S.E.	CI95.lo	CI95.hi	Ztest	Zval
1	Base+I+DARO	(Intercept)	-14.24	0.70	-15.62	-12.86	***	-20.24
		R	-0.05	0.02	-0.08	-0.01	*	-2.42
		B	-0.01	0.03	-0.07	0.04		-0.48
		C	-0.02	0.01	-0.04	-0.01	***	-3.58
		W	0.05	0.03	0.00	0.10		1.95
		S	-0.23	0.04	-0.31	-0.15	***	-5.50
		A	-0.16	0.06	-0.27	-0.04	**	-2.66
		Interaction	3.74	0.30	3.15	4.34	***	12.36
2	Base+I+ MNTD	(Intercept)	-15.13	0.96	-17.01	-13.25	***	-15.77
		R	0.00	0.00	-0.01	0.00		-0.69
		B	0.03	0.03	-0.03	0.09		0.93
		C	-0.03	0.01	-0.05	-0.01	**	-2.77
		W	0.05	0.03	-0.01	0.10		1.69
		S	-0.04	0.03	-0.10	0.02		-1.44
		D	0.26	0.51	-0.73	1.25		0.51
		M1	-0.17	0.04	-0.24	-0.10	***	-4.52
		Interaction	4.22	0.31	3.62	4.83	***	13.61
3	Base+I	(Intercept)	-18.59	0.96	-20.48	-16.70	***	-19.28
		R	-0.02	0.02	-0.06	0.02		-1.11
		B	0.99	0.52	-0.03	2.02		1.91
		C	-0.02	0.01	-0.03	0.00		-1.89
		W	0.03	0.03	-0.04	0.10		0.83
		Interaction	6.40	0.58	5.27	7.54	***	11.04
5	Base+I+DARO	(Intercept)	-16.34	0.65	-17.62	-15.07	***	-25.13
		R	0.01	0.01	0.00	0.03		1.57
		B	0.08	0.06	-0.04	0.21		1.29
		C	-0.02	0.00	-0.03	-0.01	***	-3.61
		W	0.00	0.03	-0.06	0.07		0.13
		A	-0.36	0.07	-0.49	-0.23	***	-5.42
		Interaction	4.78	0.34	4.11	5.44	***	14.13
6	Base+I	(Intercept)	-15.78	0.91	-17.56	-14.00	***	-17.38
		R	0.03	0.02	-0.02	0.07		1.20
		B	-0.07	0.41	-0.88	0.73		-0.18
		C	-0.02	0.01	-0.04	0.00		-1.88
		W	0.05	0.03	-0.02	0.11		1.42
		S	-0.38	0.08	-0.54	-0.22	***	-4.70
		Interaction	5.17	0.29	4.60	5.74	***	17.75
7	Base+I	(Intercept)	-14.95	1.32	-17.54	-12.36	***	-11.30
		B	0.48	0.54	-0.57	1.54		0.90
		C	-0.03	0.02	-0.07	0.00	*	-2.00
		W	-0.06	0.06	-0.18	0.06		-1.00
		S	0.00	0.08	-0.15	0.14		-0.04
		Interaction	6.12	0.62	4.90	7.34	***	9.84

Table E.4. Summary of AIC values per set simulations (based on different variable combinations) and measure of the strength of the simulation sets based Akaike weights (ω).

Site	Model	Variables tested	AIC	Δ_i	Relative likelihood	ω_i
1	Base +I+ DARO	RBCWSA	6583.0	0	1.000	0.65
	Base +I+ PER2	RBCWSDP2	6587.0	3.99	0.140	0.09
	Base +I	RBCWS	6587.3	4.33	0.110	0.07
	Base +I+ SLOG	RBCWSDT3	6587.7	4.68	0.100	0.06
	Base +I+ PLOG	RBCWSDT2	6588.0	4.99	0.080	0.05
	Base +I+ UMNTD	RBCWSDM2	6588.7	5.69	0.060	0.04
	Base +I+ PER3	RBCWSDP3	6589.0	5.94	0.050	0.03
	Base +I+ PUB	RBCWDT1	6595.7	12.72	0.000	0
	Base +I+ PER1	RBCWDP1	6597.4	14.36	0.000	0
	Base +I+ MNTD	RBCWDM1	6605.7	22.65	0.000	0
	Base (NI)	RBCWS.NI	6791.2	208.15	0.000	0
2	Base +I+ MNTD	RBCWSDM1	5774.3	0.00	1.000	0.96
	Base +I+ DARO	RBCWSA	5781.5	7.29	0.026	0.03
	Base +I+ UMNTD	RBCWSDM2	5783.3	9.05	0.011	0.01
	Base +I+ PER1	RBCWSDP1	5790.7	16.48	0.000	0.00
	Base +I+ PLOG	RBCWSDT2	5791.7	17.39	0.000	0.00
	Base +I+ PUB	RBCWSDT1	5792.0	17.77	0.000	0.00
	Base +I+ SLOG	RBCWSDT3	5792.7	18.40	0.000	0.00
	Base +I+ PER2	RBCWSDP2	5793.7	19.42	0.000	0.00
	Base +I+ PER3	RBCWSDP3	5794.3	19.99	0.000	0.00
	Base+I	RBCWS	5794.9	20.66	0.000	0.00
	Base (NI)	RBCWNI	6167.9	393.60	0.000	0.00
3	Base +I	RBCW	2843.9	0.0	1.000	0.618
	Base +I+ DARO	RBCWA	2844.9	1.0	0.618	0.382
	Base (NI)	RBCW.NI	3103.2	259.2	0.000	0.000
5	Base +I+ DARO	RBCWA	6212.5	0.00	1.000	0.45
	Base +I+ MNTD	RBCWDM1	6213.2	0.68	0.711	0.32
	Base +I+ PUB	RBCWDT1	6215.3	2.76	0.251	0.11
	Base +I+ PER3	RBCWDP3	6216.0	3.47	0.177	0.08
	Base +I+ SLOG	RBCWDT3	6219.0	6.46	0.040	0.02
	Base +I+ PLOG	RBCWDT2	6221.2	8.71	0.013	0.01
	Base +I	RBCW	6223.1	10.56	0.005	0.00
	Base +I+ PER2	RBCWDP2	6223.1	10.61	0.005	0.00
	Base +I+ UMNTD	RBCWDM2	6223.6	11.13	0.004	0.00
	Base +I+ PER1	RBCWDP1	6224.9	12.42	0.002	0.00
	Base (NI)	RBCW.NI	6616.0	403.50	0.000	0.00
6	Base+I	RBCWS	4663.7	0.00	1.000	0.51
	Base +I+ MNTD	RBCWSDM1	4664.4	0.75	0.688	0.35
	Base +I+ PER3	RBCWSP3	4668.8	5.11	0.078	0.04
	Base +I+ DARO	RBCWSA	4668.8	5.11	0.078	0.04
	Base +I+ UMNTD	RBCWSDM2	4669.3	5.64	0.060	0.03
	Base +I+ SLOG	RBCWSDT3	4669.8	6.15	0.046	0.02
	Base +I+ PLOG	RBCWSDT2	4671.0	7.32	0.026	0.01
	Base (NI)	RBCWS.NI	4938.8	275.12	0.000	0.00

Site	Model	Variables tested	AIC	Δ_i	Relative likelihood	ω_i
7	Base +I	BCWS	2036.1	0.00	1.000	0.30
	Base +I+ SLOG	BCWSDT3	2036.9	0.80	0.669	0.20
	Base +I+ MNTD	BCWSDM1	2037.1	0.99	0.608	0.18
	Base +I+ PLOG	BCWSDT2	2037.7	1.53	0.465	0.14
	Base +I+ DARO	BCWSA	2039.5	3.32	0.190	0.06
	Base +I+ PER3	BCWSDP3	2039.9	3.73	0.155	0.05
	Base +I+ PER2	BCWSDP2	2040.3	4.14	0.126	0.04
	Base +I+ UMNTD	BCWSDM2	2041.0	4.85	0.088	0.03
	Base (NI)	BCWS.NI	2227.5	191.32	0.000	0.00

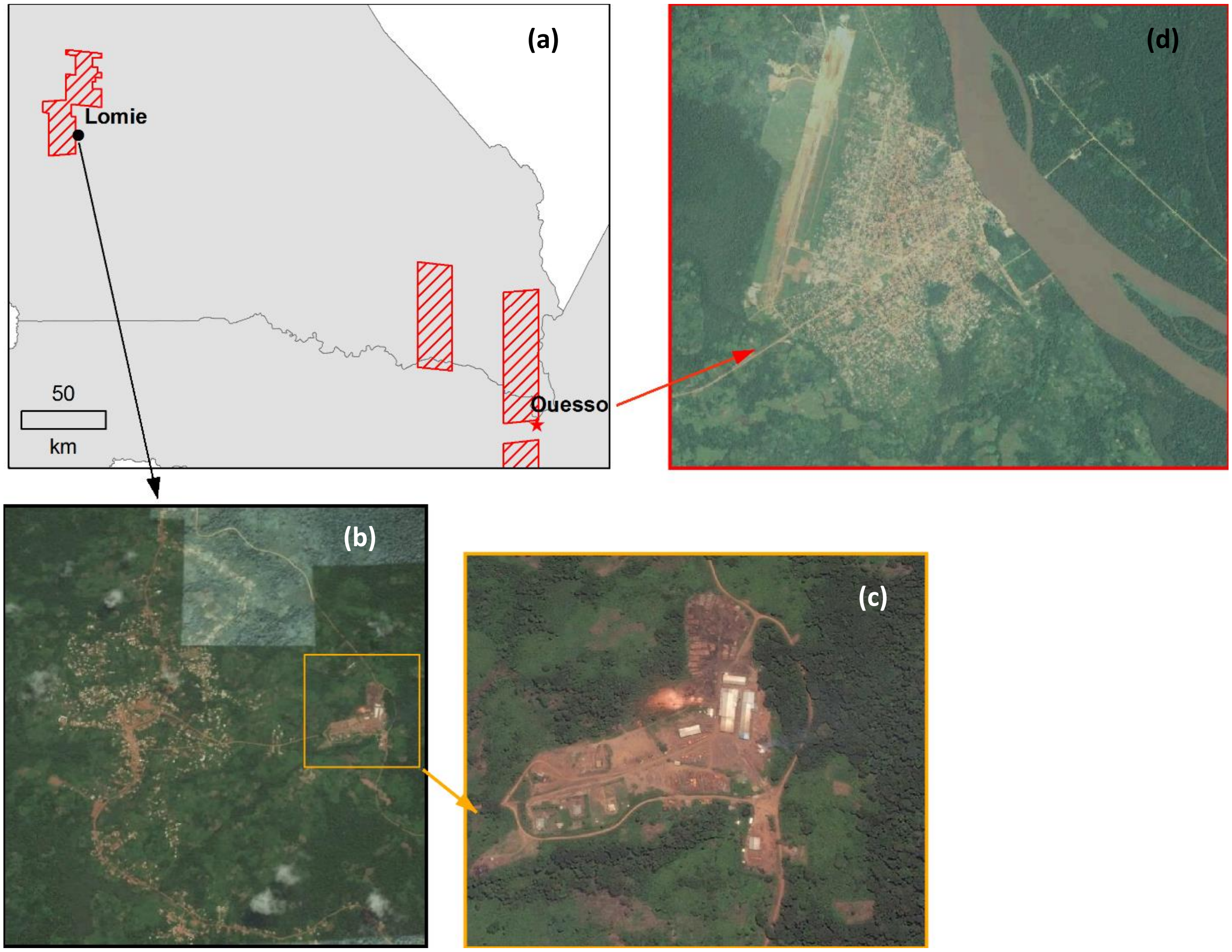

Figure E.32. (a) Larger population centers nearby case sites, the town of Lomié (outside Site 1) and the city of Ouesso. (b) Lomié extent (c) commercial sawmill within Lomié, (d) Ouesso extent including large infrastructure (e.g. airport runaway).Source: Digital Globe and Google Earth circa 2003. (Google Earth and Digital Globe 2016).

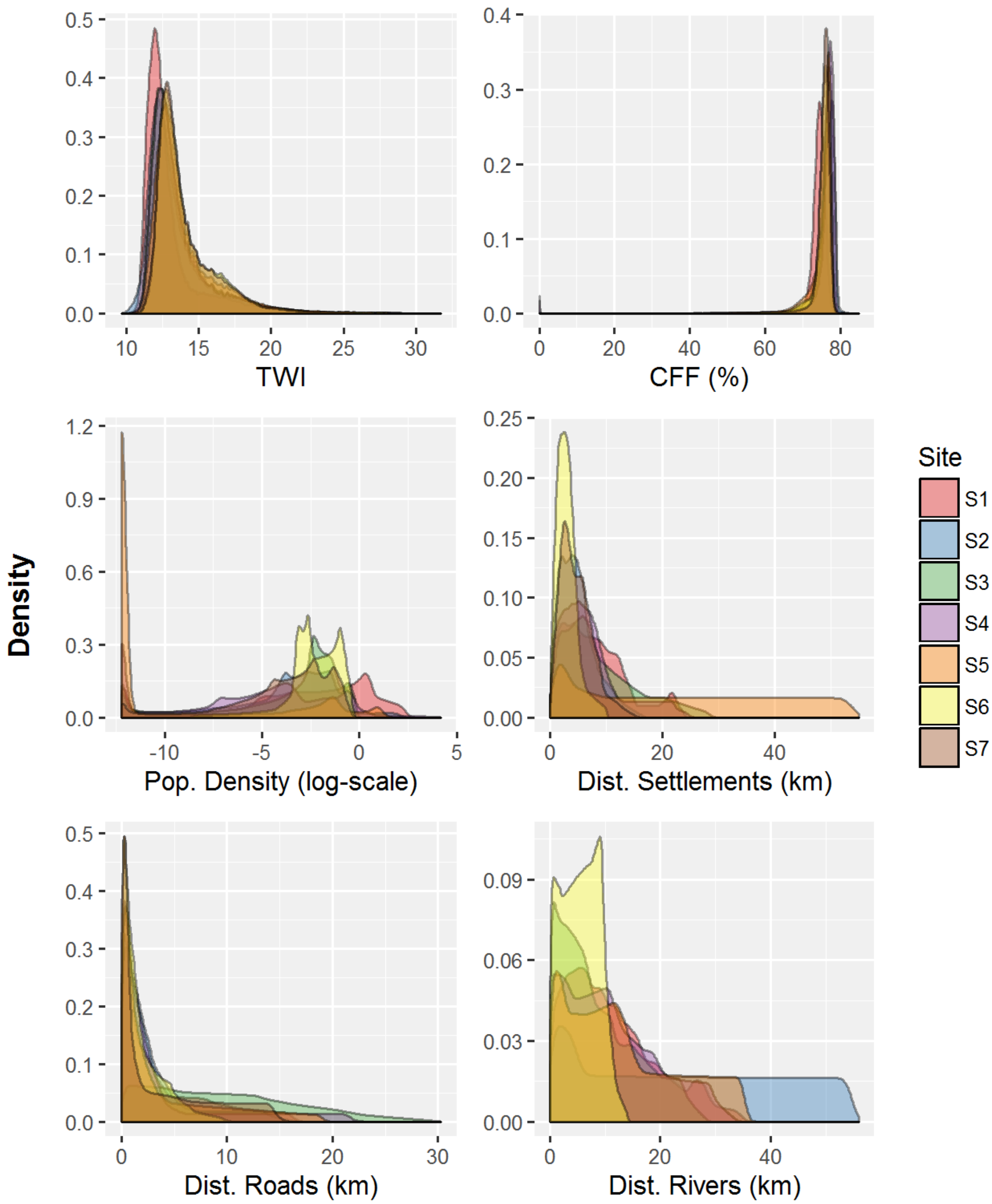

Figure E.33. Histogram distribution per case study site for all raster variables employed on the spatial statistical model.

APPENDIX F.

Clustering analysis supplementary data

Table F.1. Summary statistics for the agricultural characteristic for the four clusters of agricultural conditions identified in the Mem 03.

	Variable	Cluster	Min	Max	Mean	Median	SD	IQR	
								Q1	Q3
Internal plot	Plot size (ha)	1	0.149	0.35	0.26	0.27	0.10	0.21	0.31
		2	0.612	128.78	16.21	4.90	34.69	1.93	9.37
		3	0.012	85.48	1.73	0.51	5.31	0.24	1.44
		4	0.017	85.67	2.26	0.63	6.04	0.30	1.77
	Sub-plot size (ha)	1	0.149	0.35	0.26	0.27	0.10	0.21	0.31
		2	0.612	10.73	3.74	2.90	2.99	1.84	4.74
		3	0.000	32.59	0.64	0.18	1.80	0.01	0.7
		4	0.000	7.33	0.58	0.22	0.92	0.01	0.7
	Sub-plot number (n)	1	1.000	1.00	1.00	1.00	0.00	1.00	1.00
		2	1.000	12.00	3.00	1.00	3.65	1.00	3.00
		3	1.000	11.00	1.25	1.00	0.84	1.00	1.00
		4	1.000	27.00	1.64	1.00	1.83	1.00	2.00
Plot neighborhood	Nearest neighbor (500 m radius) (n)	1	0.000	4.00	1.67	1.00	2.08	0.50	2.50
		2	0.000	5.00	2.00	1.00	2.00	0.00	4.00
		3	0.000	11.00	2.27	2.00	2.01	1.00	3.00
		4	0.000	18.00	5.68	5.00	3.36	3.00	8.00
	Nearest neighbor (> 500 & < 1000 m radius) (n)	1	0.000	6.00	3.33	4.00	3.06	2.00	5.00
		2	0.000	12.00	5.77	6.00	3.14	4.00	6.00
		3	0.000	11.00	1.93	1.00	2.02	0.00	3.00
		4	1.000	29.00	9.84	9.00	4.98	6.00	13.00
	Distance to nearest neighbor (km)	1	0.042	1.06	0.42	0.16	0.56	0.10	0.61
		2	0.070	1.07	0.35	0.23	0.30	0.11	0.53
		3	0.041	17.36	0.63	0.22	1.60	0.12	0.43
		4	0.035	0.80	0.19	0.16	0.12	0.11	0.24
	Distance to 10th nearest neighbor (km)	1	1.070	1.52	1.27	1.21	0.23	1.14	1.37
		2	0.767	1.58	1.13	1.17	0.31	0.82	1.45
		3	0.406	34.54	3.75	2.66	4.27	1.61	3.93
		4	0.250	1.88	0.77	0.72	0.26	0.58	0.96
	Distance to 20th nearest neighbor (km)	1	1.794	2.72	2.26	2.26	0.46	2.03	2.49
		2	1.624	7.73	3.17	2.47	1.99	2.07	2.54
		3	1.460	38.25	6.89	5.36	5.73	3.34	7.58
		4	0.520	4.09	1.44	1.23	0.65	0.97	1.77
Accessibility	Distance to nearest transportation (km)	1	0.000	0.03	0.01	0.00	0.02	0.00	0.02
		2	0.000	6.93	1.30	0.28	2.24	0.06	1.37
		3	0.000	14.29	1.17	0.18	2.49	0.03	1.02
		4	0.000	3.53	0.37	0.18	0.54	0.03	0.52
Social	Distance to settlements (km)	1	0.000	30.00	10.06	0.18	17.27	0.09	15.09
		2	0.060	2135.91	164.91	0.69	592.21	0.19	0.80
		3	0.000	8530.35	151.09	1.14	844.95	0.25	3.82
		4	0.000	1431.22	107.62	0.54	271.80	0.24	1.36
	Population density (n/km^2)	1	1.110	32.23	11.55	1.30	17.91	1.21	16.77
		2	0.000	3.16	1.03	0.46	1.13	0.28	2.02
		3	0.000	21.40	0.68	0.34	1.74	0.09	0.64
		4	0.000	22.83	4.42	3.08	3.76	1.54	6.41

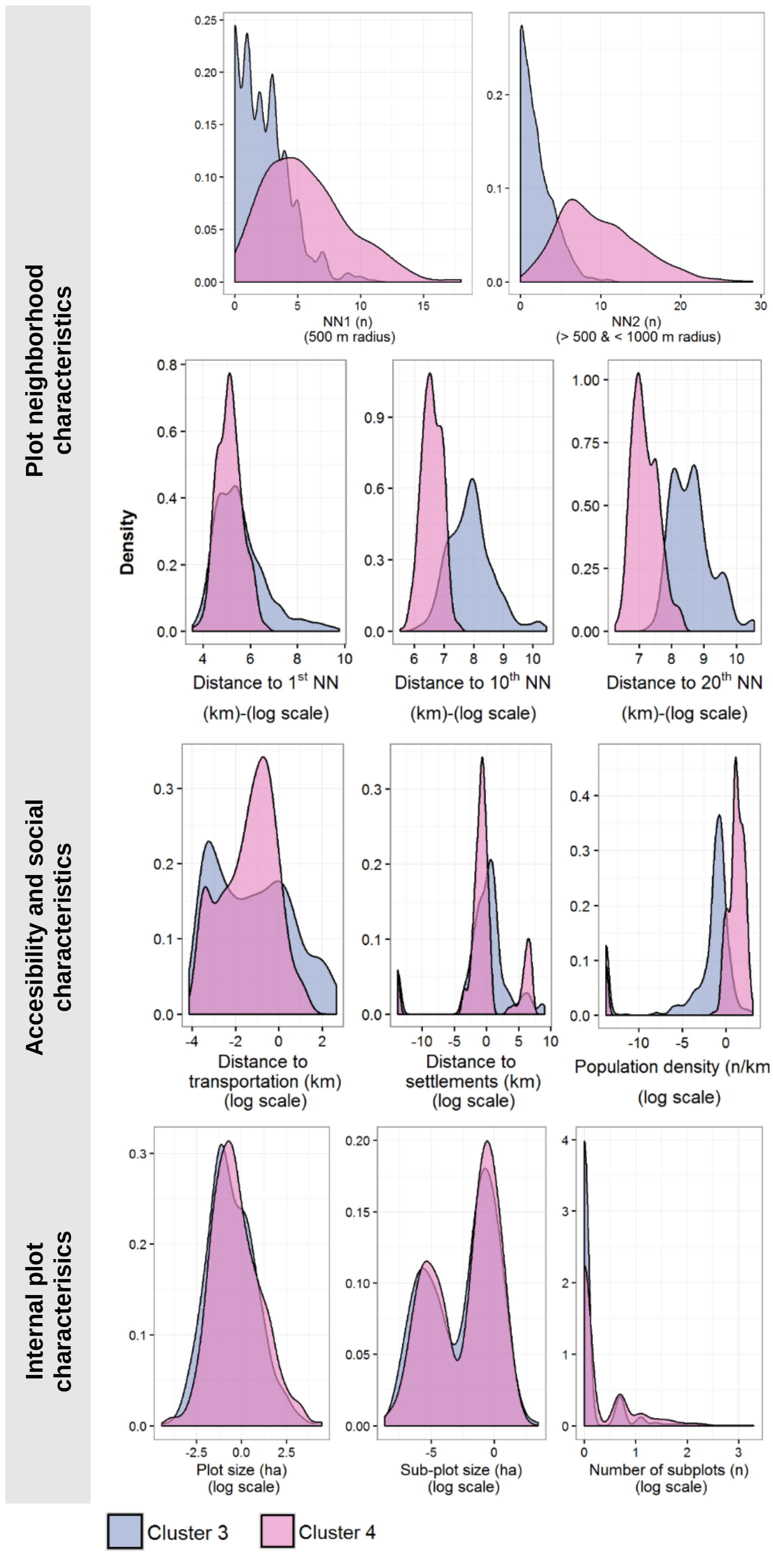

Figure F.1. Histogram distribution for the agricultural variables evaluated in the clustering analysis. Results correspond to clusters obtained in the Mem 03output. Histograms overlaid result of only the two dominant clusters.

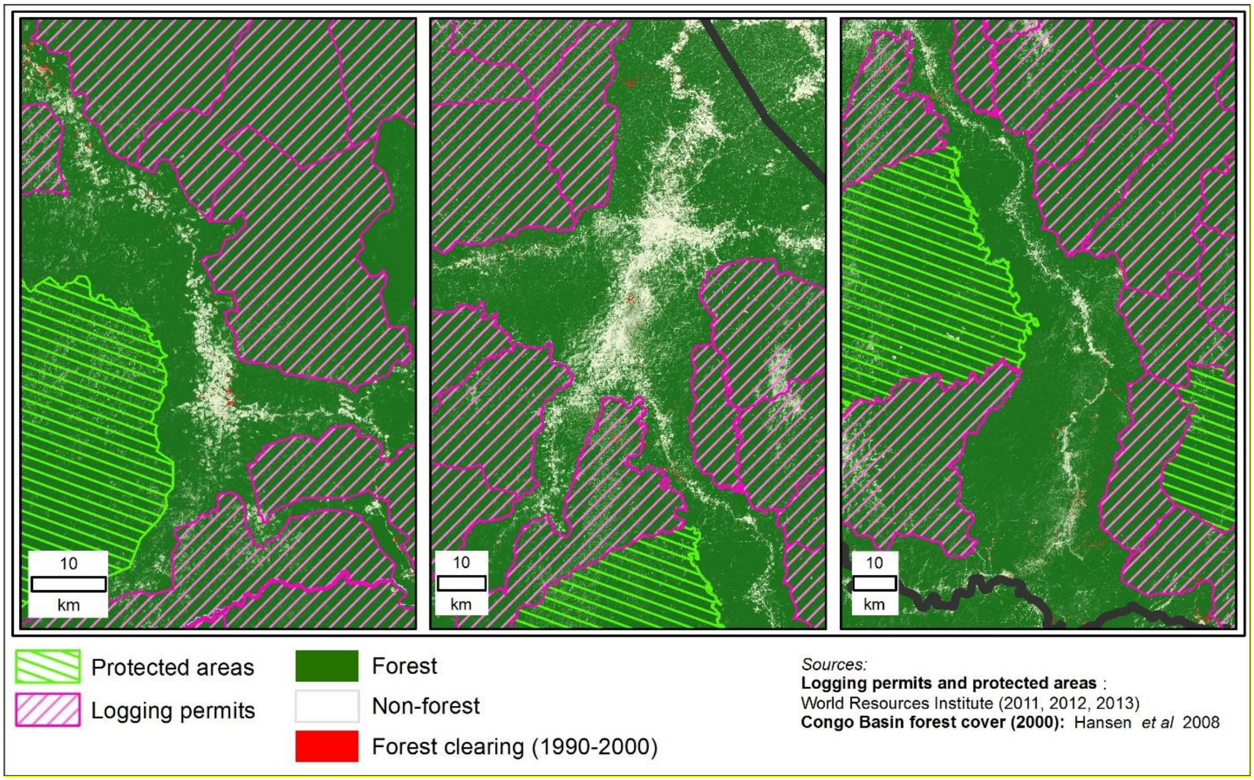

Figure F.2. Distribution of forest and non-forest areas in Cameroon in relation with the permanent forest estate (PFE) which include land under forest management units (logging permits) and protected areas. Forest and non-forest land excluded from the PFE were considered part of the nPFE.

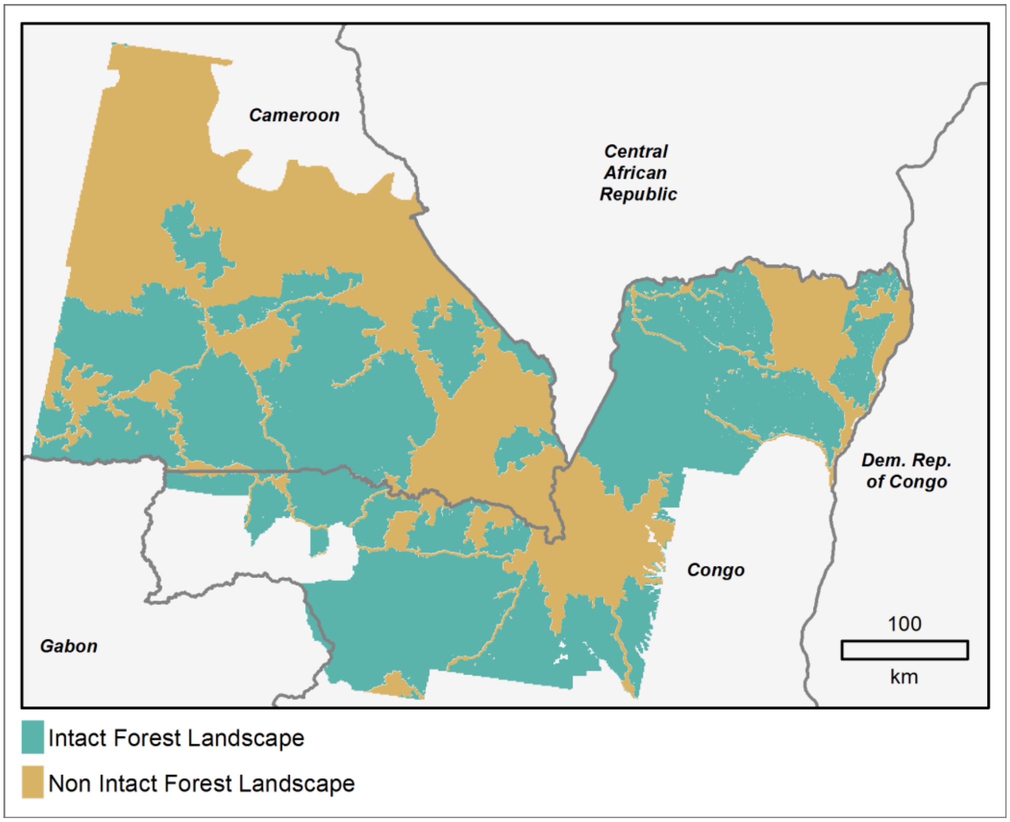

Figure F.3. Distribution of the intact forest landscapes as defined by Poptapov *et al* (2008) within the broad study area