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Kompleksowa analiza wylesiania w krajach tropikalnych - bezpośrednie czynniki wylesiania, emisje dwutlenku węgla i równowaga wartości usług ekosystemów

A comprehensive study on deforestation in the tropics - direct deforestation drivers, carbon emissions and ecosystem service value balance

Master's Thesis
on the course of - Forestry

Thesis written under the supervision of
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Research Domain II - Climate Climate Impacts & Vulnerabilities

Potsdam, 2018

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1 Introduction

1.1 Tropical forest

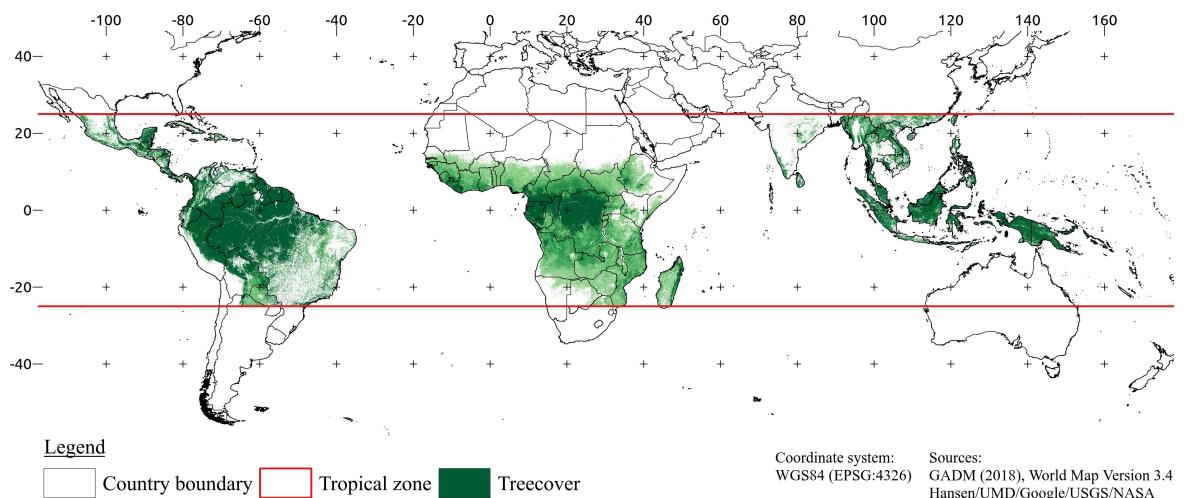


Figure 1.1. Geographic tropical zone framed red and the tropical forest

1.1.1 Current state

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1.1.2 Contribution to climate

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1.1.3 Forest definitions

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1.2 Deforestation

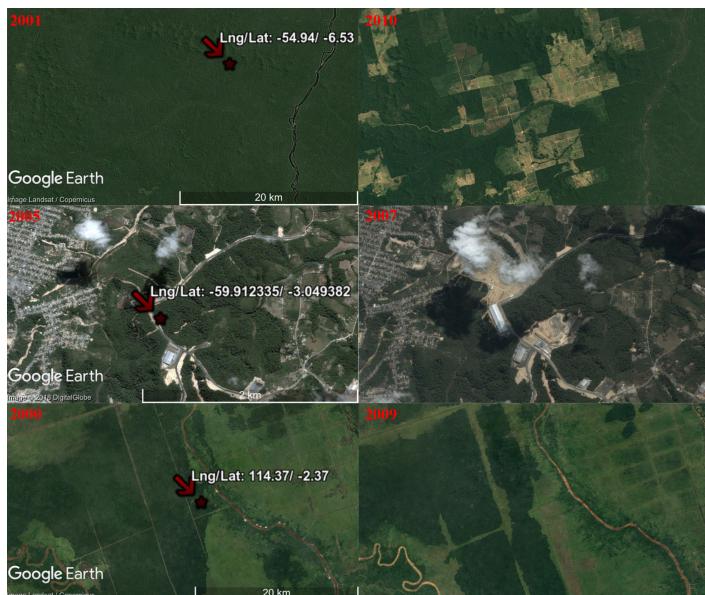


Figure 1.2. Upper Brazil agriculture, middle Brazil urbanization, lower Indonesia large scale palm oil plantations

1.2.1 Land use and land cover change

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1.2.2 Drivers of deforestation

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1.2.3 Emissions trough deforestation

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1.2.4 Removal of AGB

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1.2.5 Soil organic carbon change and soil dynamics

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1.3 Ecosystem services

1.3.1 Ecosystem service values

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1.3.2 Research objective and questions

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2 Data and methods

2.1 Data

2.1.1 Spatial data

2.1.1.1 Global Forest Change

Global Forest Change (GFC) 2000-2012 Version 1.0 is the first high-resolution dataset that provides a comprehensive view of the annual global forest cover change between 2000 and 2012 [Hansen et al. 2013; Li et al. 2017]. The initial GFC dataset released by Hansen et al. is extended by recent releases which encompass the annual forest cover changes between 2000-2013, 2000-2014, 2000-2015 and 2000-2016, respectively. All versions of this dataset have in common, that they are derived from growing season imagery captured by the remote sensing satellite Landsat 7 Enhanced Thematic Mapper Plus (ETM+) enhanced by band metrics of other sensors like Quickbird imagery, existing percent tree cover layers from Landsat data, and global Moderate Resolution Imaging Spectroradiometer (MODIS) percent tree cover [Hansen et al. 2013]. On the satellite imagery, a time-series spectral metrics analysis is applied to gather the global forest extent at 2000 as well as the annual forest loss and the accumulated gain for the period 2001 till 2012. Hence, GFC comprises three independent data layers tree cover, annually forest loss and forest gain divided into 10x10 degree tiles by the geodetic coordinate system World Geodetic System 1984 (WGS84) (EPSG:4326) with a spatial resolution of 1 arc-second per pixel. Furthermore, across the provided Geo-Tiff (GTiff) layers the pixel data is coded in unsigned 8-bit integers. Hansen et al. defined trees as all vegetation taller than 5 meters for their study. For each pixel covered by trees, a canopy density ranging from 0 to 100% is computed. Forest loss is defined as a stand displacement disturbance leading from a forest state to a non-forest state (e.g. canopy density >50% to 0%). Tree cover gain is defined as the inverse of loss where the canopy density must exceed 50% to get recognized.

Accuracy

The Hansen et al. GFC dataset is without any constraint publicly available for download. On the version 1.0 dataset homepage you may download "/*.txt" files containing the download Uniform Resource Locator (URL) of the tiles for each sub dataset. The spatial location of an image tile can be determined with a tile identifier "{NAME}_{LAT}[NS]_{LNG}[WE]" were latitude (LAT) and longitude refer to the top left decimal corner coordinates in WGS84 and N or S as well W or E to the orientation on the hemisphere. For this project we needed the subdatasets: Treecover2000, lossyear and gain. The download process is fully automatized with an Python script by using the Standard Library (stdlib) modules urllib, re and threading. First this script downloads the required "/*.txt" files and creates an list where each URL is a list element. Next it iterates over the list and extracts the corner coordinates from the file identifier with an Regular Expression (REGEX). This coordinate string is converted to an numeric identifier where latitude coordinates on the northern hemisphere are between [90, 0] and on the southern hemisphere between (0, -90]. Now a dataset tile is only downloaded if it is within the study extent between [30,-20] latitude. The acquired image tiles are shown in the top panel (green squares) in Figure 2.1. Because we have to download in total 678 images tile the entire download process is parallelized by means of multithreading.

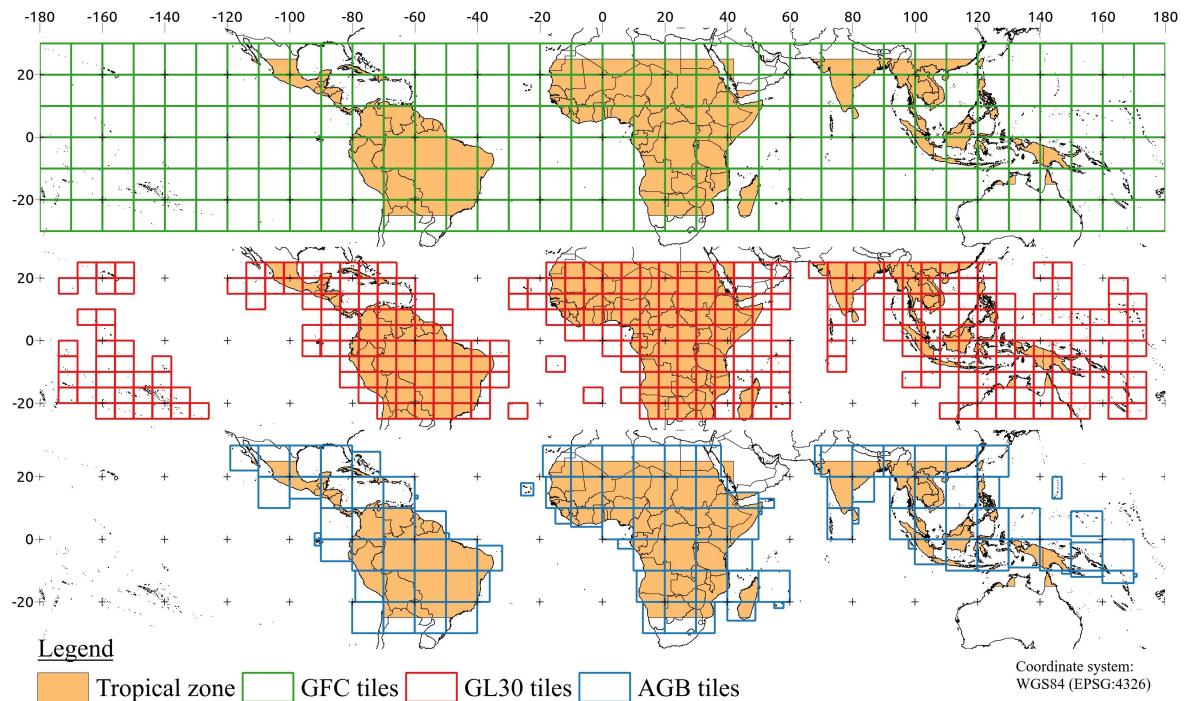


Figure 2.1. Map of downloaded dataset tiles: This map shows the acquired image tiles for this study. From top to bottom in green Global Forest Change (GFC) dataset tiles (Treecover2000, lossyear and gain), the land cover dataset GlobeLand30 (GL30) image tiles in red, and in blue the Aboveground Biomass (AGB) dataset tiles. The orange filled shapes highlight countries within the tropical zone.

2.1.1.2 GlobeLand30

GlobeLand30 (GL30) is the first 30 meter per pixel spatial resolution global land cover dataset that provides a comprehensive view on the distribution of 10 different land cover classes (Table 2.1) over the earth [Chen et al. 2017]. Currently this dataset is for two different time frames available 2000 and 2010 [Chen et al. 2015]. The dataset is coded in unsigned 8 bit integers and as coordinates system it uses WGS84 in Universal Transverse Mercator (UTM) projection and is shipped as GTiff in a tiled manner where each tile covers 6x5 degrees [Chen et al. 2014]. For detection of the 10 land cover classes Chen et al. used a so called Pixel-Object-Knowledge (POK) oriented approach [Chen et al. 2015]. The assigned pixel values and the corresponding land cover class is listed in Table 2.1. They grouped mapping process in different stages where each land cover type is detected separately and deleted from the source satellite image the order is: water bodies, wetland, snow and ice, cultivated land and forest, shrub land, grass land and bare land synchronous. For the detection of a land cover type they used at pixel level one of the following classifiers: Decision Tree (DT), Support Vector Machine (SVM) or Maximum Likelihood Classifier (MLC). After pixel detection they grouped the classified pixel to an object and validated this object by expert knowledge. For their approach they used satellite imagery from Landsat and HJ1 and auxiliary data like MODIS NDVI.

Chen et al. estimates an overall accuracy of 80.33% for the product from 2010 and 78.6% for the product from 2000 (2000 only validated at Shaanxi province in China) [Chen et al. 2015]. Various scientists besides Chen et al. validated the mapping accuracy of GL30 at different regions and scales. Arsanjani et al. estimates an accuracy of 77.9% for Iran and an accuracy >80% for Germany [Arsanjani et al. 2016a,b]. Yang, Cao and Jacobson estimate an accuracy of 82.4%, 80.1% and 83.1% for China, Nepal and East Africa, respectively [reference](#). Unfortunately, there are no estimates for countries regions falling completely in the tropical zone.

Chen funded the GL30 land cover mapping to the UN but it is not barrier less public available. Restriction is registration on the dataset homepage but the author was not able to register at the platform. Fortunately the supervisor of this work had already an account for this page otherwise I would be fucked. To download tiles of this dataset a order application must be filled with the required image tiles identifiers and the the year must be selected. An tile identifier "[NS] {LAT}_ {LNG}" consist of the hemisphere orientation followed by the top left corner latitude and logitude decimal coordinate (WGS84). The homepage provides an interface for selecting the required image tiles but it is broken and buggy, especially the selection of multiple tiles did not work. Fortunately they provide a vector file which contains the dataset tile polygons with assigned identifies. This file was used to select all required tiles within the tropical zone between approxiamtely 23°N and 23°S (WGS84), the selection

Table 2.1. Classification schema of the GlobeLand30 product: The code column is the assigned pixel value, type the corresponding land cover type and definition explains in broad terms which types of surfaces fall into the land cover type [Chen et al. 2017].

Code	Type	Definition
10	Cultivated land	used for agriculture, horticulture and gardens, including paddy fields, irrigated and dry farmland, vegetable and fruit gardens, etc.
20	Forest	covered by trees, vegetation covers over 30%, including deciduous and coniferous forest, and sparse woodland with cover 10-30%, etc.
30	Grassland	covered by natural grass with cover over 10%, etc.
40	Shrubland	covered by shrubs with cover over 30%, including deciduous and evergreen shrubs, and desert steppe with cover over 10%, etc.
50	Wetland	covered by wetland plants and water bodies, including inland marsh, lake marsh, river floodplain wetland, forest/shrub wetland, peat bogs, mangrove and salt marsh, etc.
60	Water bodies	in land area, including river, lake, reservoir, fish pond, etc.
70	Tundra	covered by lichen, moss, hardy perennial herb and shrubs in the polar regions, including shrub-, herbaceous-, wet- and barren-tundra, etc.
80	Artificial surfaces	modified by anthropogenic influence, including all kinds of habitation, industrial and mining area, transportation facilities, and interior urban green zones and water bodies, etc.
90	Bareland	with vegetation cover lower 10%, including desert, sandy fields, Gobi, bare rocks, saline and alkaline land, etc.
100	Snow and ice	covered by permanent snow, glacier and icecap

is shown in red in the middle panel at Figure 2.1. The corresponding identifiers were converted to a single line string and copied to application form. After submitting the form your order will be checked and approved. After one week we received 2 weeks limited access to an password protected ftp server where we downloaded the data. Due to restrictions this process of selecting data and download it could not be automatized with one pipeline only the selection and string conversion was automatized with a throw away script.[missing total number of tiles](#)

2.1.1.3 Intact Forest Landscapes

Intact Forest Landscapes (IFL) 2000 is a dataset comprising a mosaic of forest and naturally treeless ecosystems without signs of human activity and large enough to maintain all native biological diversity for the time period 2000 [Potapov et al. 2017]. Due to the fact that IFL comprises different intact natural landscape patterns like primary forests, non-forest ecosystems, temporary treeless areas after a natural disturbance, and water bodies the term is

not congruent to the term primary forest defined by the Food and Agriculture Organization of the United Nations (FAO) [FAO 2012]. But as mentioned IFLs includes large patches of primary forests with a minimum extent of 500 Km² therefore primary forests can be extracted from the layer. Still there are smaller fragments of primary forest outside of the IFLs. In regards of the extent a IFL has a minimum size of 500 Km², a minimum width of 10 Km, and a minimum corridor/appendage width of 2 Km. Further a IFL should not contain any of the following: ecosystem alternation, fragmentation by infrastructure and disturbance, and areas altered or managed trough agriculture, logging, and mining. For mapping and detecting IFLs Potapov et al. used Landsat imagery and several auxiliary data sources like GFC, and national transportation maps. The dataset is may be downloaded as a Shapefile (SHP) with the coordinate reference system WGS84. Each polygon in the SHP represents an IFL patch at an certain location on our planet.

Data acquisition is pretty straight forward the IFL dataset is barrier-less public available for download. As mentioned it is an SHP so you must only download a single compressed archive. This download is realized with an Python script by using the stdlib module urllib.

2.1.1.4 Aboveground Woody Biomass

The Aboveground live woddy Biomass density (AGB) raster dataset is prepared by Global Forest Watch (GFW) with an adapted approach of Baccini et al. [Baccini et al. 2012, 2015, 2017]. For the year 2000, this dataset comprises the aboveground biomass density in Mg C ha⁻¹ (mega gram carbon per hectare) per pixel, and a confidence estimate per pixel at a spatial resolution of approximately 1 arc-second. The dataset covering the global tropical zone as an mosaic of GTiff raster images where each tile has the Coordinate Reference System (CRS) WGS84 and is coded in float. For deriving biomass density GFW used canopy metrics from Geoscience Laser Altimeter System (GLAS) Light Detection and Ranging (LIDAR) footprint and several allometric equations. The resulting GLAS AGB estimates are used to train a Random Forest (RF) model based on Landsat 7 ETM+.

The AGB raster image tiles are public available for download on the homepage of GFW. As mentioned before this dataset covers only the tropical zone therefore no filtering is needed before download. To receive the URL of each image tile the GFW homepage provides an Geographic JavaScript Object Notation (GeoJSON) Application Programming Interface (API). The response of this API if requested is an GeoJSON feature collection containing the URL of the actual biomass layer, the URL of the uncertainty layer, and the rectangular bounds of each image tile. The data acquisition is automatized by a Python script by using the stdlib modules urllib, threading, and the open source library Geopandas. At first the GeoJSON is downloaded via an API call and eventually stored on disk. Next we

iterate over each feature of the GeoJSON feature collection and extract the URLs (biomass and confidence) of each tile. These URLs are piped to our multi-threaded downloader and eventually store on disk. Despite mentioning the confidence layers in the dataset description, the server answers with a 404 if the confidence URL is requested. Therefore the confidence layers are not available. In total we downloaded 105 different image tiles, their extent is shown in blue at the bottom panel of Figure 2.1.

2.1.1.5 Global Soil Organic Carbon

Is a joint project between Global Soil Partnership (GSP) and Intergovernmental Technical Panel on Soils (ITPS) to produce a global Soil Organic Carbon (SOC) map by means of a country driven approach [FAO and ITPS 2018]. Dataset: As now two versions exist 1.0 and 1.2 it is a long live dataset which will improve over time. It is shipped in WGS84 with 30 arc seconds spatial resolution, soil depth is 0-30cm horizon, stock is given in Mg C/ha, float type, gtiff covering the entire globe. Approach: baseline data 1990, country approach each country prepares own soc map by meeting the criteria (share auxiliary info about national sampling, applied methods for estimation) shipped should be SOCMap, Uncertainty assessment, the contributors can join a training/ or use the cookbook as guidance, ISRIC provides national environmental covariates DEMs, spectral remote sensing images and so on, 67 countries contributed till now (63%) of land mass, interpolation by various methods geo matching, class matching, multiple linear regression, random forest, support vector machine and so on, final map 680 Pg, tropics 208 Pg (31% of world), forests store 216 Pg (33% of world).

Issue border differences between countries caused by different methodologies and gap filling (if country does not use provided mask there is no overlap)

Is publicly available as geotiff, download at fao hp, download one huge gtiff, acquisition performed by python.

2.1.1.6 Auxiliary

As source for country boundaries we used the Global Administrative Areas Map (GADM) [Hijmans et al. 2018].

Table 2.2. Relative soil organic carbon change for certain land-use change types: [Don et al. 2010]

LUC type		Relative SOC change	
From	To	[%]	SEM
Primary forest	Grassland	-12.1	±2.3
Primary forest	Cropland	-25.2	±3.3
Primary forest	Secondary forest	-8.6	±2.0
Secondary forest	Grassland	-6.4	±2.5
Secondary forest	Cropland	-21.3	±4.1

2.1.2 Empirical data

2.1.2.1 Soil Organic Carbon

2.1.2.2 Ecosystem Service Values

2.2 Methods

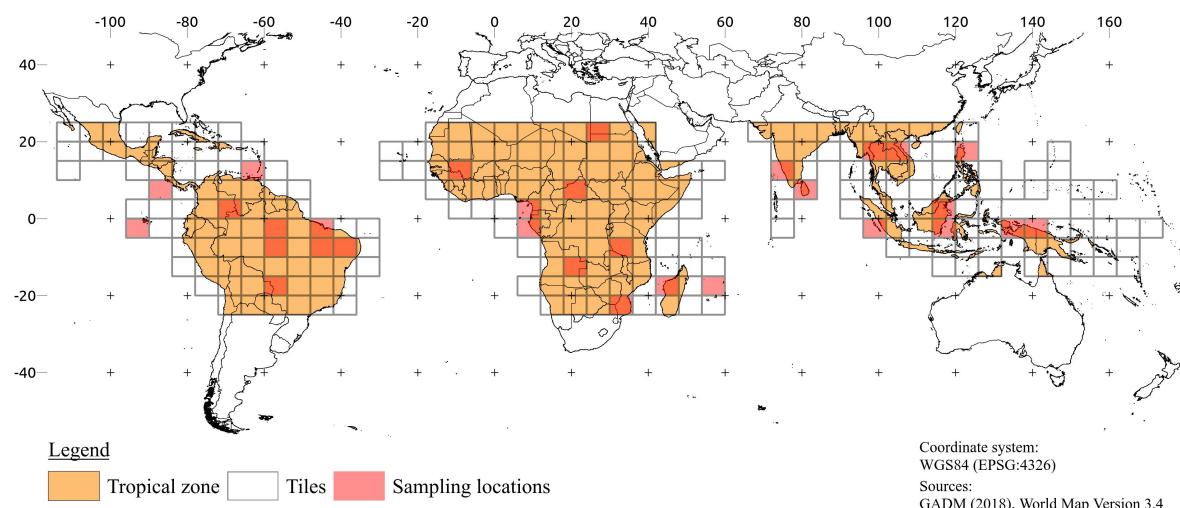


Figure 2.2. Map of aligned data tiles and sampling locations: The map shows the location of the aligned multi-image stack tiles as black-framed square sized polygons, the sampling locations for accuracy assessment in red, and countries within the tropical zone in orange.

2.2.1 Pre-processing

Problem description, all data in different crs, also all data has different extent, also some data is vector data must be converted to raster data. from each raster data where only tilled data set created a tile mask in target crs projection where stored name of the file and its extent. select a template datasets in our case gl30 2010. intersection compute with mask intersections are

selections, now pipeline if more tiles for one needed merge them, after reproject them next clip then, for vector data to raster, software python geopandas and rasterio

2.2.2 Deforestation

2.2.2.1 Forest definition

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2.2.2.2 Land use change driver

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2.2.2.3 Accuracy assessment

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2.2.3 Emissions

2.2.3.1 Above ground biomass

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2.2.3.2 Soil organic carbon change

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2.2.4 Ecosystem service values

2.2.4.1 Ecosystem service value loss

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2.2.4.2 Ecosystem service value gain

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2.2.5 Binning analysis

The previous sections were focused on the generation of large scale spatial data. Now, a feasible method must be developed for analyzing, aggregating, interpreting and visualizing the output data. To develop a good approach we must formalize the problem domain. At first we are confronted with large N (many samples) which results in many variables (dimensionality) and complexity of relationships among this variables [Carr 1990]. From a visual/analytical perspective georeferenced raster maps can be interpreted as a multivariate scatter plot of large datasets where longitude and latitude represent the x and y coordinate of an data point and the pixel values (in this case nominal scaled) representing the third dimension as an group coloring. Therefore we have a large multidimensional dataset combined with a scatter

plot visualization which leads commonly to over plotting issues and hidden point densities [Carr et al. 1987]. Due to the spatial nature of your data we are also confronted with not equal distributed data some regions show high data densities and other regions have sparse to no data. Also a severe problem domain is the frame size of our representation. Goal is to present data on a continental level which intensifies visual problems. Each pixel has a resolution of approximately 30x30m, the continental representation of americas spanning approximately 1200000x120000km². Therefore small scale isolated changes are hidden and only large scale changes are visually detectable. Which results in hidden details and not perceivable patterns of change.

Goal should be to develop a process who solve this issues and generates satisfying output for our multivariate data. In case of raster data a re-sampling to coarser resolution could solve over plotting and resolution issues as well normalize the unequal distributed data. But the nature of re-sampling (for nominal data a nearest neighbor or majority wins [Reference](#)) would negate important spatial patterns as well frequency distributions. Another well known approach is to use binning of the spatial explicit data with a certain kind of regular polygon that is tessellating the plane [Carr et al. 1992]. Polygon tessellations provide numerous opportunities for presenting multivariate statistical summaries. The scaling of the polygon could be used to represent pixel densities within the polygon area, a polygon filling color gradient is applicable to show nominal or ordinal scaled data. Also it is imaginable to use the polygon interior for a pie chart. To use regular tessellation it is important to mention there are only three types of regular polygons tessellate the plane: squares, equilateral triangles and hexagons [Carr et al. 1992]. Square tessellation is the most common approach used for binning in spatial visualization. A raster image is a square tessellation. In a square mosaic each polygon shares 4 edge neighbors and 4 vertex neighbors [more explanation error distance disadvantages etc Hexagons properties, advantages disadvantages of both tessellations](#). Final goal is to show your analysis results of spatial explicit raster data in hexagonal binned form. For bivariate maps we choose a visual representation with scaled hexagons and colorization. For multivariate details we choose a pie chart alike visualization. We split the hexagons horizontal in regards of the presented ratio. The ratios should be ordered descending so that the greatest ratio is south oriented. It is following a general description how we created the hexagon grids and how we tackled the polygon split problem.

To be flexible at hexagon construction we accept 4 different parameters as construction arguments: D long diagonal (Diameter of the circumscribing circle), d short diagonal (diameter of the inscribed circle), A area the hexagon should span and/or e the edge length. One selected parameter of these is used to compute R the radius of the circumscribing circle with respect to input parameter as shown in equation 2.1. R is used to calculate the midpoint $\langle c_x, c_y \rangle$ of the hexagon located in the first quadrant of the cartesian coordinate system Equation 2.2 and 2.3. Equation 2.4 shows the computation of the hexagon anti-clockwise

vertex matrix. Whereas the two leftmost vertices (first and last row of the matrix \mathbf{H}) are located at koordinatenursprung, will sagen auf deutsch korridanten at x=0 und y=value of matrix. In summary equation 2.1 to 2.4 show the creation of an hexagon at the leftmost corner of first quadrant (Figure 2.3). The orientation is important for the subsequent mosaic creation.

$$R = \frac{\sqrt{2A}}{\sqrt[4]{27}} = \frac{D}{2} = \frac{d}{\sqrt{3}} = e \quad (2.1)$$

$$c_x = \frac{R\sqrt{3}}{2} \quad (2.2)$$

$$c_y = R \quad (2.3)$$

$$\mathbf{H} = \begin{bmatrix} 0 & c_x & 2c_x & 2c_x & c_x & 0 \\ R\sin\left(\frac{7\pi}{6}\right) + c_y & 0 & R\sin\left(\frac{11\pi}{6}\right) + c_y & R\sin\left(\frac{\pi}{6}\right) + c_y & 2R & R\sin\left(\frac{5\pi}{6}\right) + c_y \\ 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix} \quad (2.4)$$

A polygon tessellation needs several polygons to create a grid in case of the creation of one hexagon with the presented algorithm needs approximately **benchmark** but the creation of **several N hexagons** needs approximately **benchmark**. Therefore it is much simpler to create only one hexagon with the presented algorithm and to create the grid polygons by copying the coordinates of the source polygon and translating them to their target position with a affine transformation matrix shown in equation 2.5. To create the grid we get the rectangular bounds of the area to tessellate as a matrix $\mathbf{B} \in R^{2 \times 2}$ (equation 2.6), where the first column of the matrix contains the lower left corner and the second column the upper right corner of the image. Each subsequent translation in regards of x_{off} is $x_1 + d$ for even rows and bla bla for odd rows. Y_{off} is computed by bla bla see figure 2.3.

$$\mathbf{T} = \begin{bmatrix} 1 & 0 & x_{off} \\ 0 & 1 & y_{off} \\ 0 & 0 & 1 \end{bmatrix} \circ \mathbf{H} \quad (2.5)$$

$$\mathbf{B} = \begin{bmatrix} x_1 & x_2 \\ y_1 & y_2 \end{bmatrix} \quad (2.6)$$

Binning of raster data is easy we just have a point in polygon problem each points/pixels falling in hexagon are counted and aggregated through a function. In case of drivers of deforestation we count all driver classes per hexagon and compute ratios next we compute the sha **describe for each map how you build it** As mentioned before for the visualization of the drivers of deforestation map we want to segment the hexagons with horizontal lines and each segment should represent the share of the direct deforestation driver within the tessellated area. To compute the split line for a certain hexagon we need the hexagon R computeable from the area of the hexagon equation 2.7 and the rectangular bounds of the hexagon. We compute the relative share of an deforestation driver per hexagon this relative

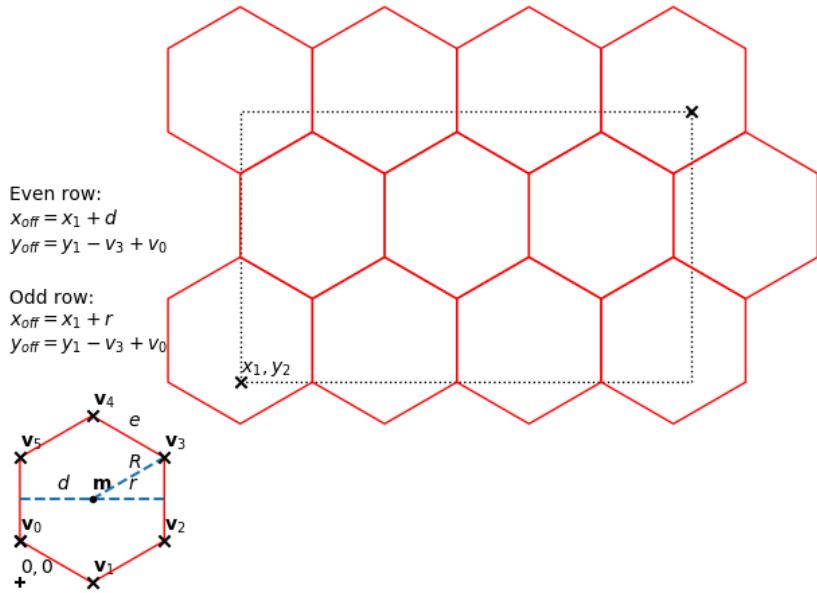


Figure 2.3. Hexagon tessellation: Located at the left bottom corner in red a hexagon defined by its geometric properties the 6 vertex vectors $\{\vec{v}_0, \dots, \vec{v}_5\}$ (black crosses), with center vector \vec{m} , edge length e , R radius of the circumscribing circle, r radius of the inscribed circle and d the length of the short diagonal. Top right black dotted box are the bounds of an area which is tessellated by a hexagon grid in red. Each grid cell is translated from the origin hexagon at its position by computing the x_{off} and y_{off} offset with the presented equations at the left-hand side of the grid.

share can be used to compute the y-axis coordinate of an split line equation 2.8. A regular hexagon can not only be presented in it vertex form as shown above. We can also use functions to define the hexagon shape. A hexagon consist of 2 picewise functions where each function consist of 3 linear functions restricted to an intervall. If we invert these functions we can use these functions to compute the x-coordinate of the split line with the previous computed y-coordinate Equations 2.9 and 2.10. As a results we receive the solution matrix L which represents the horizontal line segment splitting the hexagon at the point where we want (driver ratio share) equation 2.11. The solution matrix can be plugged in to a polygon split function which separates the hexagon polygon in a upper and lower part to do so we iterate over the hexagon vertices and decide if they are above or under the split line and append to a lower upper polygon. These list are our results [explain better split function](#).

$$R = \frac{\sqrt{2A}}{\sqrt[4]{27}} \quad (2.7)$$

$$y = \frac{P(y_2 - y_1)}{100} + y_1 \quad (2.8)$$

$$f^{-1}(y) = \begin{cases} -\frac{y-y_1}{\tan(\frac{\pi}{6})} + \frac{x_1+x_2}{2} & \text{if } y_1 \leq y < y_1 + R \sin(\frac{5\pi}{6}) \\ x_1 & \text{if } y_1 + R \sin(\frac{5\pi}{6}) \leq y < R(\sin(\frac{5\pi}{6}) + 1) \\ \frac{y-y_2}{\tan(\frac{\pi}{6})} + \frac{x_1+x_2}{2} & \text{if } R(\sin(\frac{5\pi}{6}) + 1) \leq y \leq y_2 \end{cases} \quad (2.9)$$

$$g^{-1}(y) = \begin{cases} \frac{y-y_1}{\tan(\frac{\pi}{6})} + \frac{x_1+x_2}{2} & \text{if } y_1 \leq y < y_1 + R \sin(\frac{5\pi}{6}) \\ x_2 & \text{if } y_1 + R \sin(\frac{5\pi}{6}) \leq y < R(\sin(\frac{5\pi}{6}) + 1) \\ -\frac{y-y_2}{\tan(\frac{\pi}{6})} + \frac{x_1+x_2}{2} & \text{if } R(\sin(\frac{5\pi}{6}) + 1) \leq y \leq y_2 \end{cases} \quad (2.10)$$

$$\mathbf{L} = \begin{bmatrix} f^{-1}(y) & g^{-1}(y) \\ y & y \end{bmatrix} \quad (2.11)$$

3 Results

3.1 Forest definition and accuracy assessment

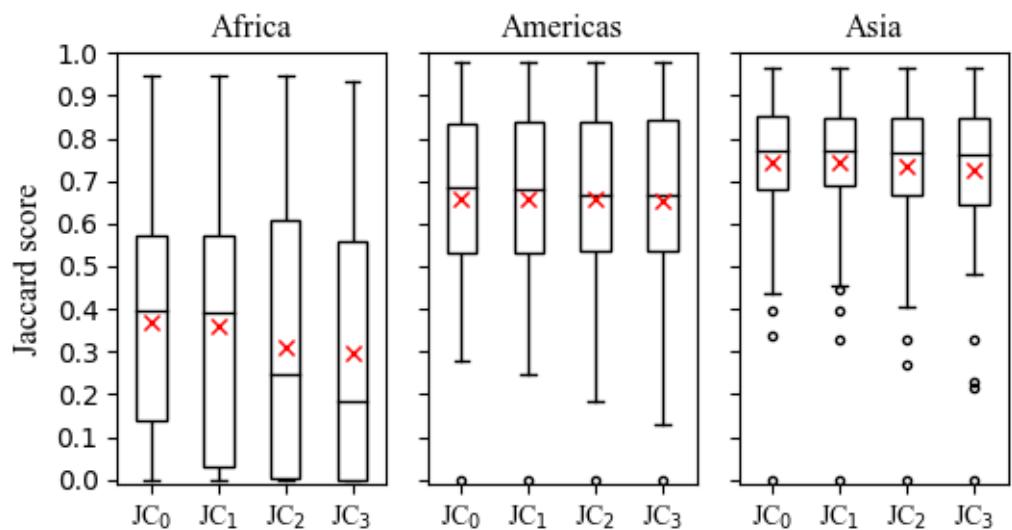


Figure 3.1. Similarity distribution of GFC tree cover vs. GL30 tree cover at 2000: Americas from JC₀ till JC₃: $\bar{x} \approx .71, .71, .70, .69; \tilde{x} \approx .77, .77, .76, .75; Q_1 \approx .64, .65, .64, .63; Q_3 \approx .84, .84, .84, .83$; Asia from JC₀ till JC₃: $\bar{x} \approx .71, .71, .70, .69; \tilde{x} \approx .77, .77, .76, .75; Q_1 \approx .65, .66, .64, .63; Q_3 \approx .84, .84, .84, .83$; Africa from JC₀ till JC₃: $\bar{x} \approx .39, .39, .34, .32; \tilde{x} \approx .40, .40, .31, .29; Q_1 \approx .14, .10, .00, .00; Q_3 \approx .60, .61, .63, .56$

Table 3.1. Two-sided Wilcoxon signed-rank test:

$H_0: \tilde{x}_1 = \tilde{x}_2$												
Cls	Americas				Asia				Africa			
	JC ₀	JC ₁	JC ₂	JC ₃	JC ₀	JC ₁	JC ₂	JC ₃	JC ₀	JC ₁	JC ₂	JC ₃
JC ₀	1.					1.				1.		
JC ₁	.00	1.				.72	1.			.22	1.	
JC ₂	.06	.36	1.			.00	.00	1.		.03	.03	1.
JC ₃	.16	.50	.60	1.		.00	.00	.00	1.	.00	.00	1.

Table 3.2. One-sided Wilcoxon signed-rank test:

$H_0: \tilde{x}_1 \leq \tilde{x}_2$													
	Americas				Asia				Africa				
	Cl	JC ₀	JC ₁	JC ₂	JC ₃	JC ₀	JC ₁	JC ₂	JC ₃	JC ₀	JC ₁	JC ₂	JC ₃
\tilde{x}_2^{Ω}	JC ₀	1.	.00	.03	.08	1.	.64	1.	1.	1.	.11	.98	1.
\wedge^1	JC ₁	1.	1.	.18	.25	.36	1.	1.	1.	.89	1.	.99	1.
\tilde{x}_1^{\cdot}	JC ₂	.97	.82	1.	.30	.00	.00	1.	1.	.02	.01	1.	1.
$H_0: \tilde{x}_1^{\cdot} \leq \tilde{x}_2^{\Omega}$	JC ₃	.92	.75	.70	1.	.00	.00	.00	1.	.00	.00	.00	1.

Table 3.3. Confusion matrix for accuracy assessment

		Reference												
		Cl	10	20	25	30	40	50	60	80	90	Tot	UAc	Om
Prediction	10	732	38	62	15	16	2	3	5	0	873	.84	.16	
	20	42	751	57	189	31	12	0	17	4	1103	.68	.32	
	25	29	202	1155	173	22	10	5	11	4	1611	.72	.28	
	30	36	187	32	1466	73	21	0	17	0	1832	.80	.20	
	40	14	21	4	41	352	1	1	2	1	437	.81	.19	
	50	0	5	3	10	4	50	0	1	0	73	.68	.32	
	60	2	1	0	3	0	2	18	2	0	28	.64	.36	
	80	3	4	0	1	1	1	0	50	0	60	.83	.17	
	90	0	0	0	1	0	0	0	3	5	9	.56	.44	
	Tot	858	1209	1313	1899	499	99	27	108	14	6026			OvAc
		PAC	.85	.62	.88	.77	.71	.51	.67	.46	.36			
		Com	.15	.38	.12	.23	.29	.49	.33	.54	.64			.75

3.2 Deforestation drivers

3.2.1 Global

3.2.2 Americas

3.2.3 Asia

3.2.4 Africa

Table 3.4. Absolute in km²

Type	Class	Americas	Asia	Africa
Agriculture	Cropland	rel. abs.	24.37 95908	18.37 38719
	Grassland	rel. abs.	46.19 181781	8.41 17726
Forestry/Plantations	Regrowth	rel. abs.	14.40 56671	70.27 148111
	Shrubland	rel. abs.	12.69 49941	1.11 2340
Urban/Mining	Artificial	rel. abs.	0.41 1614	0.46 970
	Bareland	rel. abs.	0.10 394	0.03 63
Natural	Wetland	rel. abs.	1.50 5903	0.97 2045
	Water	rel. abs.	0.32 1259	0.38 801
Forest loss		rel. abs.	3.87 393550	4.68 210774
Forest cover		abs.	10223187	177400
		abs.	4457940	10496591

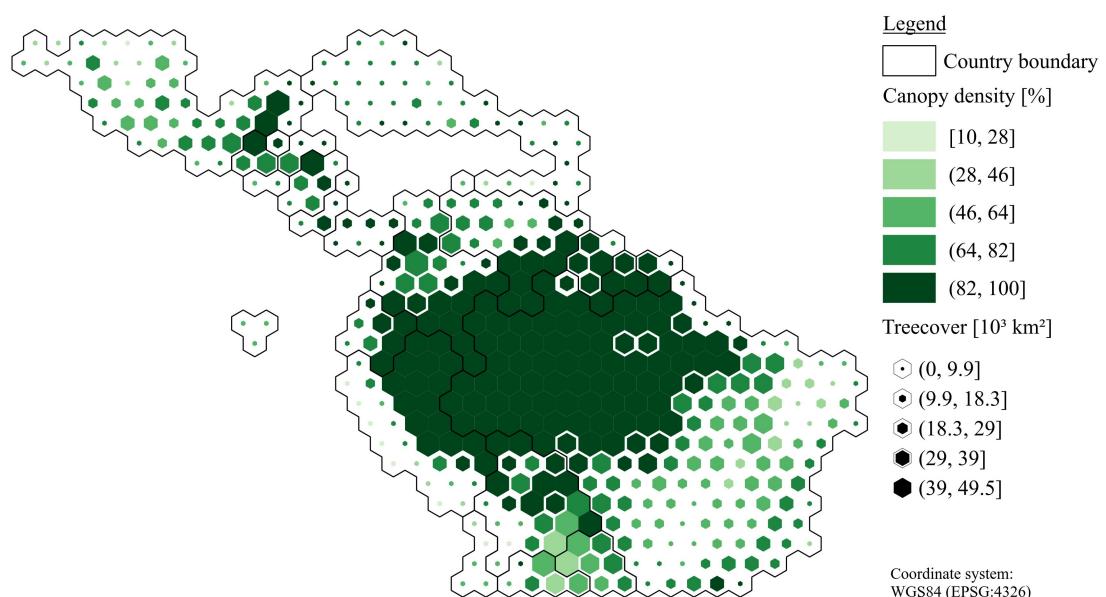


Figure 3.2.

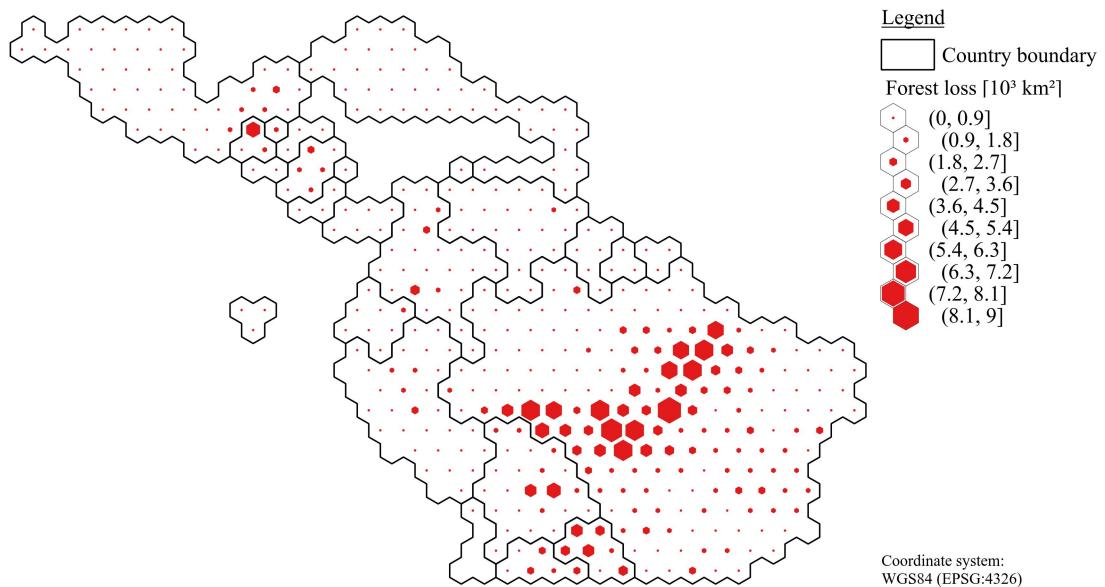


Figure 3.3.

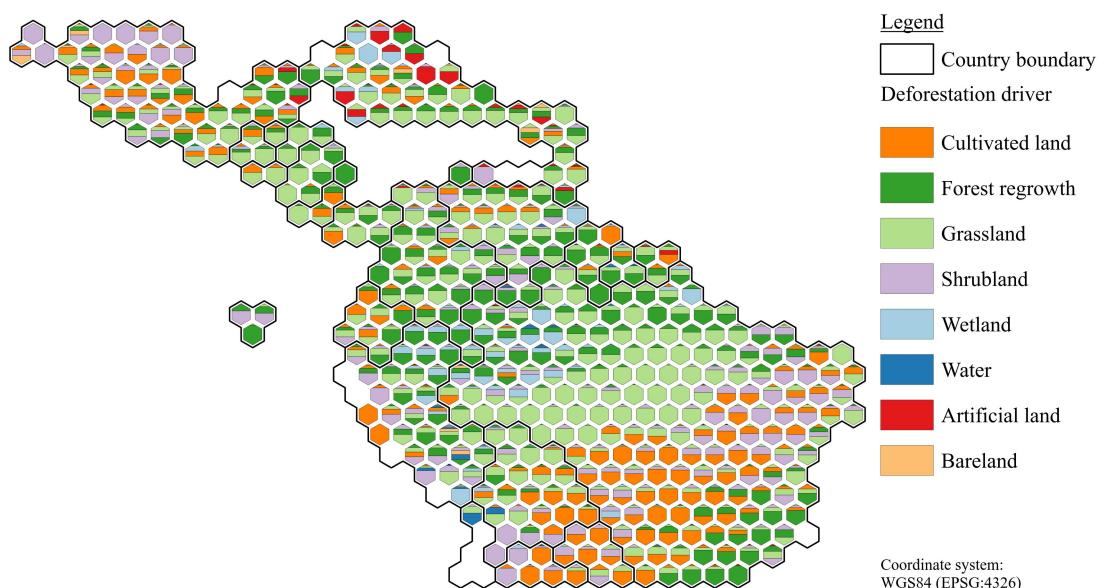


Figure 3.4.

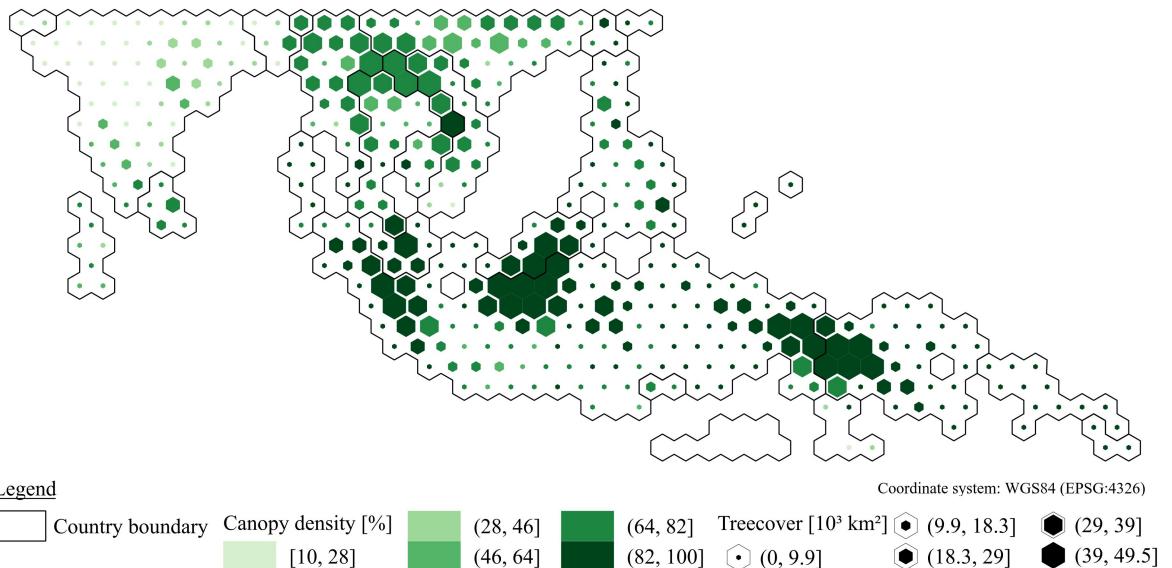


Figure 3.5.

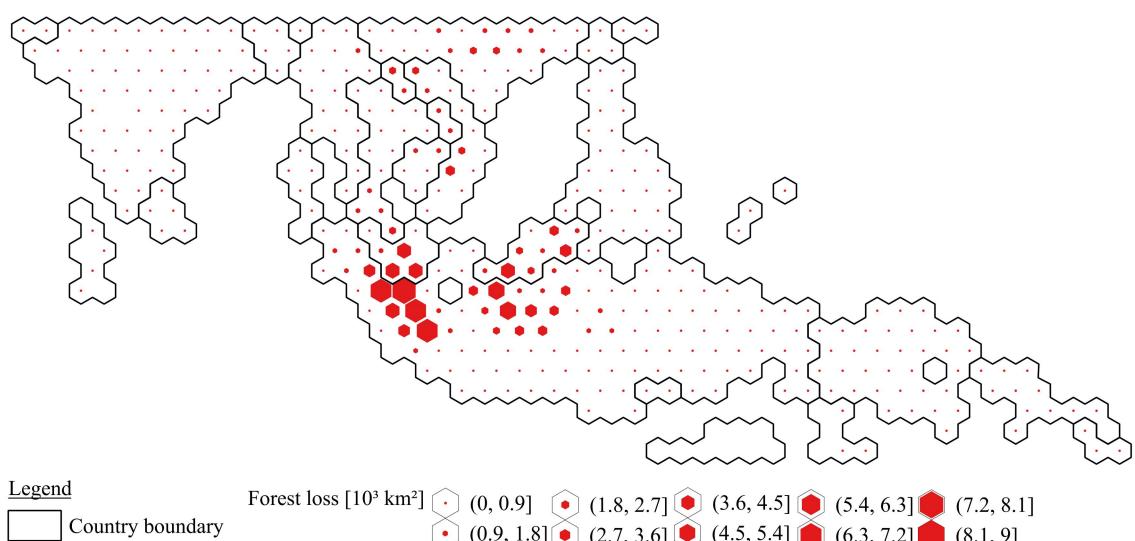


Figure 3.6.

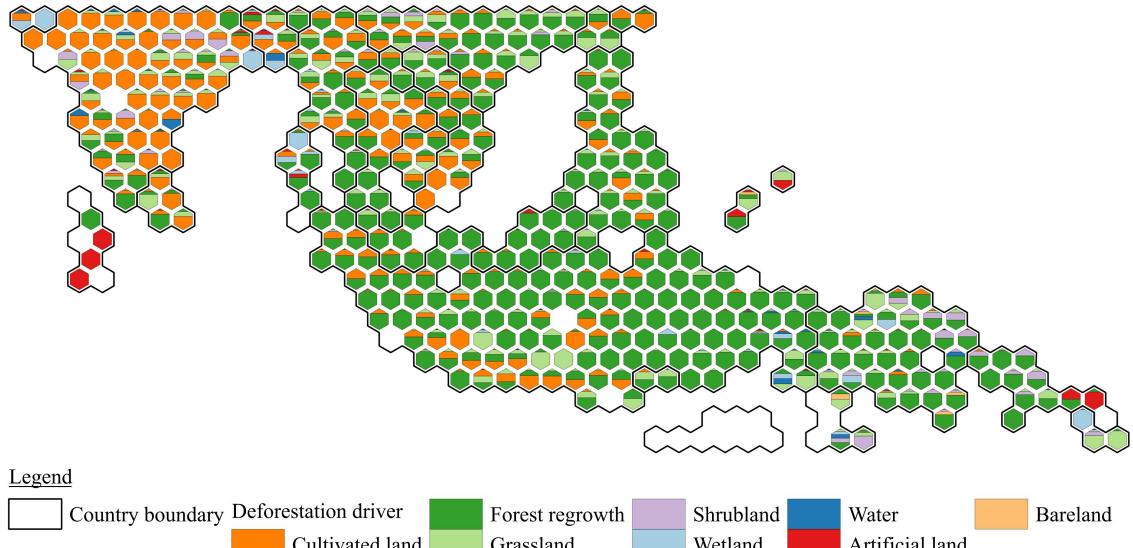


Figure 3.7.

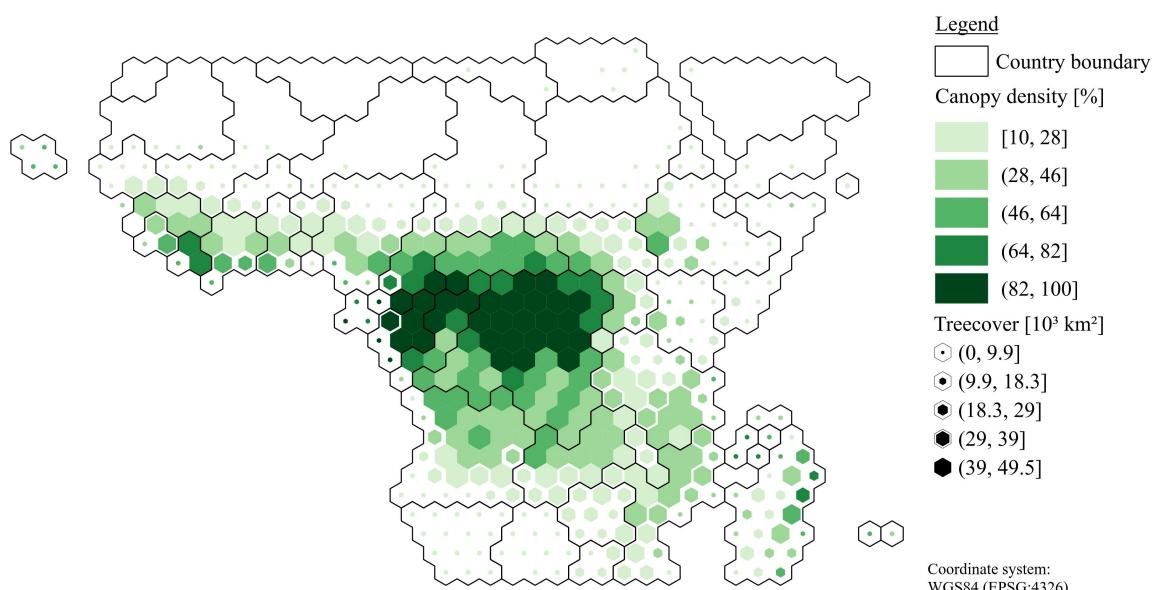


Figure 3.8.

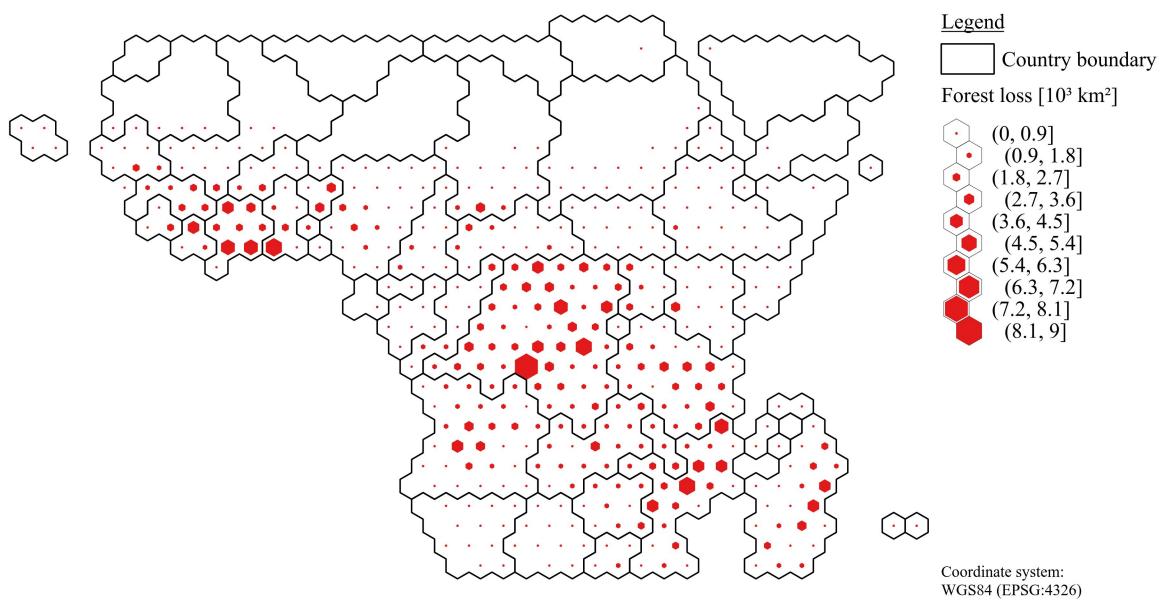


Figure 3.9.

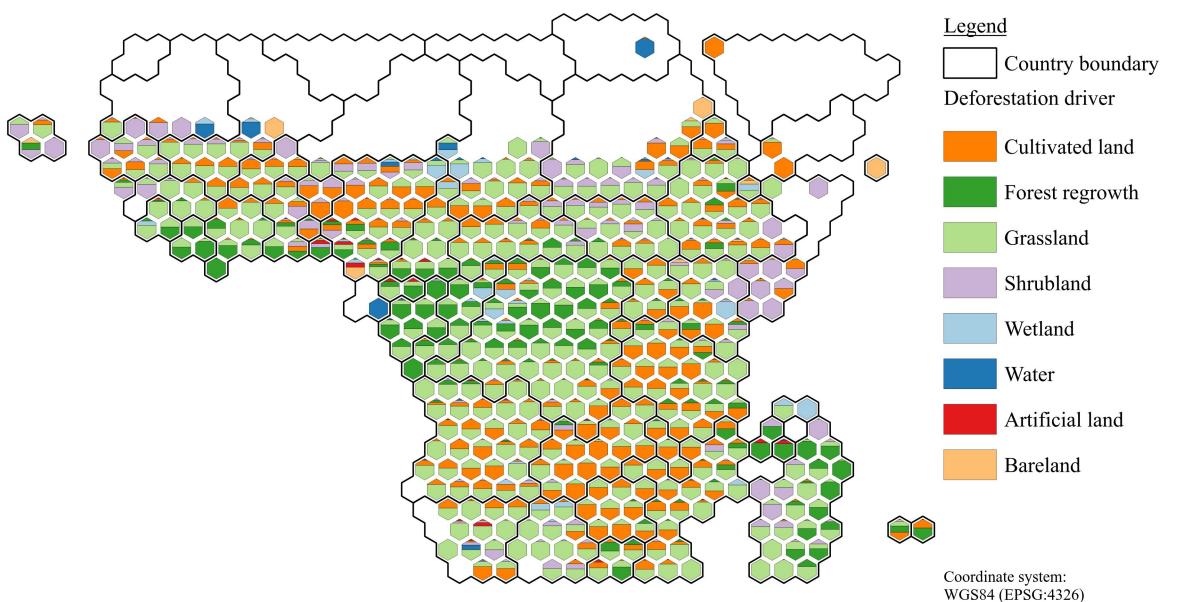


Figure 3.10.

3.3 Defore

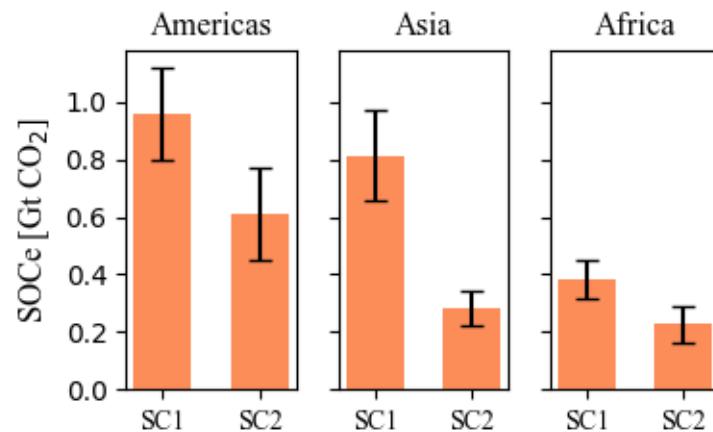


Figure 3.12.

Table 3.5. Soil organic carbon emissions

Region	SC1			SC2			SC3		
	min	mean	max	min	mean	max	min	mean	max
Americas	0.80	0.96	1.12	0.45	0.61	0.77	0.43	0.59	0.76
Asia	0.66	0.81	0.97	0.22	0.28	0.34	0.22	0.28	0.33
Africa	0.32	0.39	0.45	0.17	0.23	0.29	0.16	0.23	0.29

3.3.1 Global

3.3.2 Americas

3.3.3 Asia

3.3.4 Africa

3.4 Ecosystem service value balance

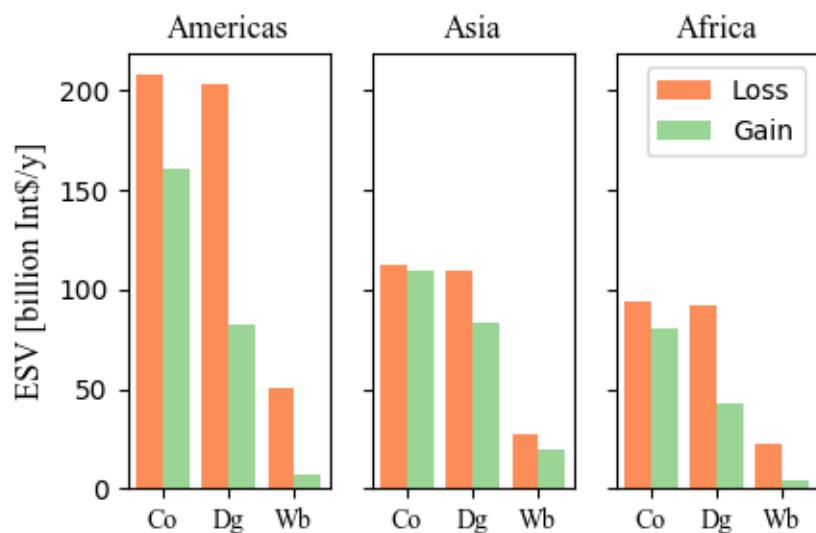


Figure 3.13.

3.4.1 Global

3.4.2 Americas

3.4.3 Asia

3.4.4 Africa

4 Discussion

Acknowledgements

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List of Abbreviations

AGB	Aboveground live woddy Biomass density
API	Application Programming Interface
CRS	Coordinate Reference System
DT	Decision Tree
ETM+	Enhanced Thematic Mapper Plus
FAO	Food and Agriculture Organization of the United Nations
GADM	Global Administrative Areas Map
GFC	Global Forest Change
GFW	Global Forest Watch
GIS	Geographic Information System
GL30	GlobeLand30
GLAS	Geoscience Laser Altimeter System
GTiff	Geo-Tiff
GeoJSON	Geographic JavaScript Object Notation
IFL	Intact Forest Landscapes
IPCC	Intergovernmental Panel on Climate Change
LIDAR	Light Detection and Ranging
LULC	Land Use/Land Cover
MLC	Maximum Likelihood Classifier
MODIS	Moderate Resolution Imaging Spectroradiometer
POK	Pixel-Object-Knowledge
REGEX	Regular Expression
RF	Random Forest
SHP	Shapefile
SVM	Support Vector Machine
URL	Uniform Resource Locator
UTM	Universal Transverse Mercator
WGS84	World Geodetic System 1984
stdlib	Standard Library
GSP	Global Soil Partnership
ITPS	Intergovernmental Technical Panel on Soils
SOC	Soil Organic Carbon
LUC	Land-use Change
ISRIC	International Soil Reference and Information Center

Appendix

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