Remote Sensing of Pasture Degradation Processes in Southern Pará

Woody Encroachment Trajectories from Landsat TM and ETM+ Data (1984-2012)

Master's Thesis

Humboldt-Universität zu Berlin
Geography Department

[redacted]

Supervisors:

Prof. Dr. Patrick Hostert
Humboldt-Universität zu Berlin
Geography Department

Dr. Dirk Pflugmacher
Humboldt-Universität zu Berlin
Geography Department

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a,∗

[a]Geography Department, Humboldt University Berlin, Rudower Chaussee 16, 12489 Berlin

Abstract

Encroachment of woody vegetation is contributing to decreased productivity on managed grasslands in the Brazilian Amazon. Secondary succession on pastures has previously been shown to vary over time, whereas the duration of land-use and intensity of the prevalent management schemes steer the rates of regrowth. It is hypothesized, that the relationship between pasture age and the prevalence of woody vegetation is non-stationary, due to changing political and economic frameworks which direct towards more or less intensive management schemes. Remote sensing offers large potential to monitor trajectories of pasture vegetation structure to better understand vegetation-age relationships in a regional context. In the present study, annual time-series of Landsat-based dry-season metrics were generated to explore spectral-temporal behavior of grass-dominated and wood-encroached pastures. Two metrics were selected and subsequently employed to investigate the regional relationship between pasture age and woody vegetation cover. Trajectories of pastures established in varying years were compared to assess whether the age-vegetation relationship is temporally variant. Coincidences with changes in policies, widely supporting the observed trajectory changes, were discussed. The main findings of this study suggest a decline in woody vegetation cover until pasture ages of eight years, which is followed by stable and low fractions. Trajectories of vegetation cover changed with varying year of pasture establishment, suggesting the timing of forest conversion to be a determinant of the properties of pasture trajectories. Two main periods of management regimes are suggested using this approach, whereas a period of a gradual transition from extensive towards increasingly intensive land-uses between 1988 and 1995 was followed by a period of continuously intensive management schemes with increased sensitivity to effects of global market dynamics.

Keywords: Amazon, pasture, woody encroachment, time series, Landsat, variability metrics

1. Introduction

Conversion of tropical primary forests into managed grasslands is the major land-use change process in the Brazilian Amazon region (Bowman et al., 2012; Steinfeld, 2006; Wassenaar et al., 2007). These cattle pastures generally operate on low productivity, with stocking densities frequently below 1 animal per hectare (Valentim and Andrade, 2009). However, in 2005 the head of cattle in the federal state of Pará exceeded 18 million (Instituto Brasileiro de Geografia e Estatística, 2006). The rapid growth of the herd coupled with notoriously inefficient management regimes imply that the area required to provide sufficient forage is vast. Encroachment of woody vegetation contributes to agronomical productivity declines on pastures on a global scale (Asner et al., 2004a). Accessibility of forage grass patches is diminished, and indigestive woody vegetation competes with forage species for light and plant-available nutrients (Feldpausch et al., 2004; Krummel et al., 2008). Highly promoted by the climatic conditions which speed up vegetation growth, this type of pasture degradation is especially abundant within the Amazon biome (Dias-Filho, 2011; Landers, 2007).

Besides the effects of regional biophysical conditions on productivity of managed grasslands, previous research in the Amazon context focused on the relationships between management and woody encroachment. Uhl et al. (1988) found the duration and intensity of pastoral land-use to be negatively associated to the speed and amount of secondary succession. Land-use intensities in terms of stocking rates, herbicide input, frequency and amount of fertilization as well as fires and clearing thereby further determine the amount of successful regrowth of shrubs and trees on Amazon pastures (Fearnside, 2001; Landers, 2007; Nepstad et al., 1996). Historically changing frameworks in politics, global to local market dynamics, as well as technical advances constantly create and diminish incentives for land-use intensification, thus potentially leading to temporal variations in regional management schemes (Bowman et al., 2012). Extensive management practices, such as frequent pasture burning and labor-intensive manual removal of invasive plants dominate the Amazonian production systems, mostly because of restricted access to financial resources (Mertens et al., 2002). As a consequence, modern

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∗Corresponding author

practices of pasture maintenance, for instance by means of liming and plowing to restore high levels of productivity remain an exception (Fearnside, 1997). The necessary financial input for this type of pasture recuperation exceeds the costs of acquiring new land (Fearnside, 2001), which discourages maintenance and intensification of existing pasture areas unless incentives are given to change the established practices.

Governmental policies in Brazil have, throughout the last four decades, promoted highly ambivalent concepts concerning the resource land. The valorization of land through deforestation was subsidized via tax incentives until the middle 1980s (Mertens et al., 2002), thereby promoting extensive management practices and land abandonment. Environmental law started to emphasize forest conservation with the establishment of deforestation monitoring programs and fining mechanisms in the late 1980s. Economic driving forces, such as the increasing liberalization of global markets in the 1990s triggered large-scale increases in agricultural production (Barona et al., 2010). The declining prices for Brazilian beef increased the attractiveness as an international commodity in the early 2000s, and the successive opening of the Amazon region for export markets lead to an exponential growth of the cattle herd few years later (Nepstad et al., 2006). These developments raise the question, if differing political and economic contexts at the time of pasture establishment can lead to altered pathways of vegetation on pastures. If so, the relationship between the age of a pasture and the fractions of woody vegetation can be considered non-stationary and dependent of the year at which pastoral land use was established.

Numerous studies investigated the effect of market dynamics and policy changes on deforestation processes in the Amazon (Barona et al., 2010; Soares-Filho et al., 2006; Verburg et al., 2014), but their influence on regional pathways of post-deforestation land-use remains widely unknown. Understanding trends and driving forces of woody encroachment on pastoral land is crucial to guide policy-makers in developing essential land-management strategies to reduce carbon emissions from land-use and deforestation (Cardille and Foley, 2003). Compact information on the effects of policy and economy on pastoral management on a regional scale can help to direct policy interventions to meet the specific requirements of a region and its bio-physical and socio-economic conditions.

Remote sensing matches the spatially extensive character of pasture systems and is therefore frequently used to investigate pasture characteristics in the Amazon region. The recent opening of the USGS Landsat image archives facilitates the generation of dense time-series of medium spatial resolution and thereby fuels the incorporation of temporal information in remote sensing studies (Wulder et al., 2012). In this context, spectral variability metrics capturing temporal variation of the surface reflectance of a given ground feature find increasing application (Griffiths et al., 2013a; Müller et al., 2014; Potapov et al., 2012). Seasonal variations of pasture vegetative cover contain valuable information regarding pasture condition (Aguiar, 2013). Brinkmann et al. (2011) successfully captured the annual peak in vegetation cover with a metric describing the annual maximum of the Normalized Difference Vegetation Index (NDVI) to assess trends in rangeland productivity in a semi-arid region. In the Amazonian context, productive grass-dominated pastures and those with degraded productivity show largest differences during the dry season (Numata et al., 2007b). The computation of spectral variability metrics within a dry season temporal window therefore allows for emphasizing the relevant phenological period to distinguish these land-cover types.

A range of approaches have been applied to characterize vegetation cover on managed grasslands. Spectral mixture analyses (Davidson et al., 2008; Numata et al., 2007a) is widely applied in the Amazon region to derive fraction images of ground cover types, such as soil and vegetation. The essential drawback of this method is the necessity of a spectral library or, alternatively, an appropriate selection procedure to derive the required end-members based on satellite imagery. Analyses with vegetation indices are numerous (Aguiar, 2013; Cook and Pau, 2013), yet these indices are mostly based on few spectral bands and therefore potentially exclude relevant information. Image transformations counteract this loss of information by extracting desired spectral characteristics from all spectral bands into single components. Global transformation coefficients furthermore allow for outputs which are comparable between scenes and over time. The components resulting from the tasseled cap transformation strongly relate to physical scene characteristics (Crist and Cicone, 1984). Its third component, termed tasseled cap wetness (TCW) contrasts the mid-infrared reflectance (reduced by high water content) with the near-infrared band reflectance (increased by vegetation abundance). Due to its strong relationship to vegetation cover and lower sensitivity to soil types compared to other vegetation indices (Todd and Hoffer, 1998), the TCW is suitable for grazing-related research (Todd et al., 1998).

This study aimed at investigating regional trajectories of woody encroachment on pastures with annual time series of TCW dry-season metrics, which were derived from the Landsat TM and ETM+ archive from 1984 to 2012. The main objectives were to (1) investigate the spectral-temporal characteristics of pastures with high and low fractions of woody vegetation using Landsat-based dry-season metrics. Subsequently, (2) regional pathways of woody vegetation with increasing pasture age were determined. Lastly, (3) pasture trajectories starting at different establishment years were compared to capture temporal shifts in the regional relationship between woody vegetation on pastures and their respective age. Temporal coincidences of temporal shifts with relevant changes in policy frameworks and economic developments, which potentially triggered the observed changes, were discussed.

2. Data & Methods

2.1. Study Area

The region surrounding the town of Novo Progresso in southern Pará was selected as study area due to its relatively young colonization history and continuous deforestation processes (Nepstad, 2002), which generated a range of land use ages under similar edaphic and climatic conditions. Most importantly, 87% of the cleared forest areas are used as managed grasslands (Instituto Brasileiro de Geografia e Estatística, 2006), making the wider Novo Progresso region highly suitable for pasture-related research. Furthermore, increased speed of vegetation succession in southern Pará (Moran et al., 2000) suggest beneficial conditions for woody encroachment to occur.

The region's climate is characterized by a strong seasonality in precipitation. The average annual precipitation sums up to 2225mm, of which 97% fall between September and May (Tropical Rainfall Measuring Mission Project, 2013). The dry season lasts from June to August, with annual variations of a few days to weeks. The region is characterized by a rolling topography with rock outcrops, impeding the application of large-scale mechanized agriculture (Nepstad et al., 2006). The soils in the area are dominated by Acrisols with medium to low nutrient availability due to extensive leaching. These poor edaphic conditions limit the productivity of the regional pastoralism.

The socio-economic development of the region was triggered by governmental policies, which promoted land reclamation. The National Integration Plan, which was launched in the 1960s provided incentives for land-seeking people to settle in the remote areas of the Amazon (Mertens et al., 2002). The plan's maxim "uma terra sem homens para homens sem terra", literally translating to "a land without people for people without land", reflects the perception of land being available as ubiquitous resource. The dominating activities during the initial land-valorization period were extensive pastoralism with a tendency to abandon degraded lands, followed by gold mining and timber extraction (Fearnside, 2001). In 1988, the Brazilian government enforced a new constitution, which emphasized environmental protection. Further forest conservation efforts include the alteration of the national forest code in 1996, obliging land owners in the Amazon to maintain 80% of their properties as legal reserve (Bowman et al., 2012). However, Amazon-wide deforestation rates were sharply rising until they peaked in 2004. By the year 2012, a total of 517.460 ha were deforested (Instituto Nacional de Pesquisas Espaciais, 2013), roughly corresponding to a fifth of the total study area (see fig. 1). It should be stressed that the dynamic land change history of the region potentially serves as an archetype for yet unexploited parts of the Brazilian Amazon, rendering this case relevant well beyond its explicit geographical extent.

2.2. Landsat Data & Preprocessing

2.2.1. Data Selection

The Landsat TM and ETM+ archive constitutes the data fundament of this study. A total of 368 terrain-corrected (L1T) images were available between 1984 and 2012 for Landsat scene path 227, row 65 (WRS-2) in the USGS archive (see fig. 2). The temporal distribution of images within each year was highly irregular. Generally, few wet season images were available, whereas those were also of limited usefulness due to high cloud cover. Imbalances in inter-annual image availability are driven by launches of new satellites (Landsat 7 in 1999), definition of image acquisitions (e.g. reduced data transmissions due to sensor failures (SLC-off)), the decommissioning of the Landsat 5 satellite in 2011 and the still incomplete consolidation of third-party archives (Wulder et al., 2012).

Precipitation estimates (Tropical Rainfall Measuring Mission Project, 2013) were used to define the limits of the dry season (see Appendix B.1). Furthermore, the irregular distribution of observations was critical for the exact definition of the dry-season temporal window. To integrate a maximum number of images, the start and end of the dry season was expanded by one week in each direction. A total of 193 images are available within the dry season window between day of year (DOY) 145 and 250.

2.2.2. Image Processing

Processing and analyses were performed using the software CRAN R (R Core Team, 2013), and its raster package (Hijmans, 2013) for image-processing. In case other software packages were used, those are explicitly mentioned in the respective paragraph.

To account for atmospheric conditions at the time of image acquisition and to achieve comparability between images, all images were converted to surface reflectance using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) algorithm for sensor calibration and atmospheric correction (Masek et al., 2006). To extract observations free from clouds and cloud shadows, the object-based cloud and cloud shadow detection algorithm Fmask was applied (Zhu and Woodcock, 2012). To minimize the error of omission in the cloud detection, a conservative setting of cloud probability was used. Resulting cloud masks served as a basis for a pixel-based selection of cloud-free observations. The average cloud cover over the dry-season scenes detected by Fmask is 25.9% (41.22% when wet-season scenes are included), whereas the nearly cloud-free scenes accumulate between middle of May and middle of September.

In this study, TCW was chosen as an indicator for vegetation cover on pasture areas. The coefficients of Crist and Cicone (1984) were used to transform the 6 spectral bands of the Landsat images into the desired TC components. To minimize the size of data, surface reflectance values were multiplied by factor 10^3 to receive raster data in integer format, which propagates into the TCW values.

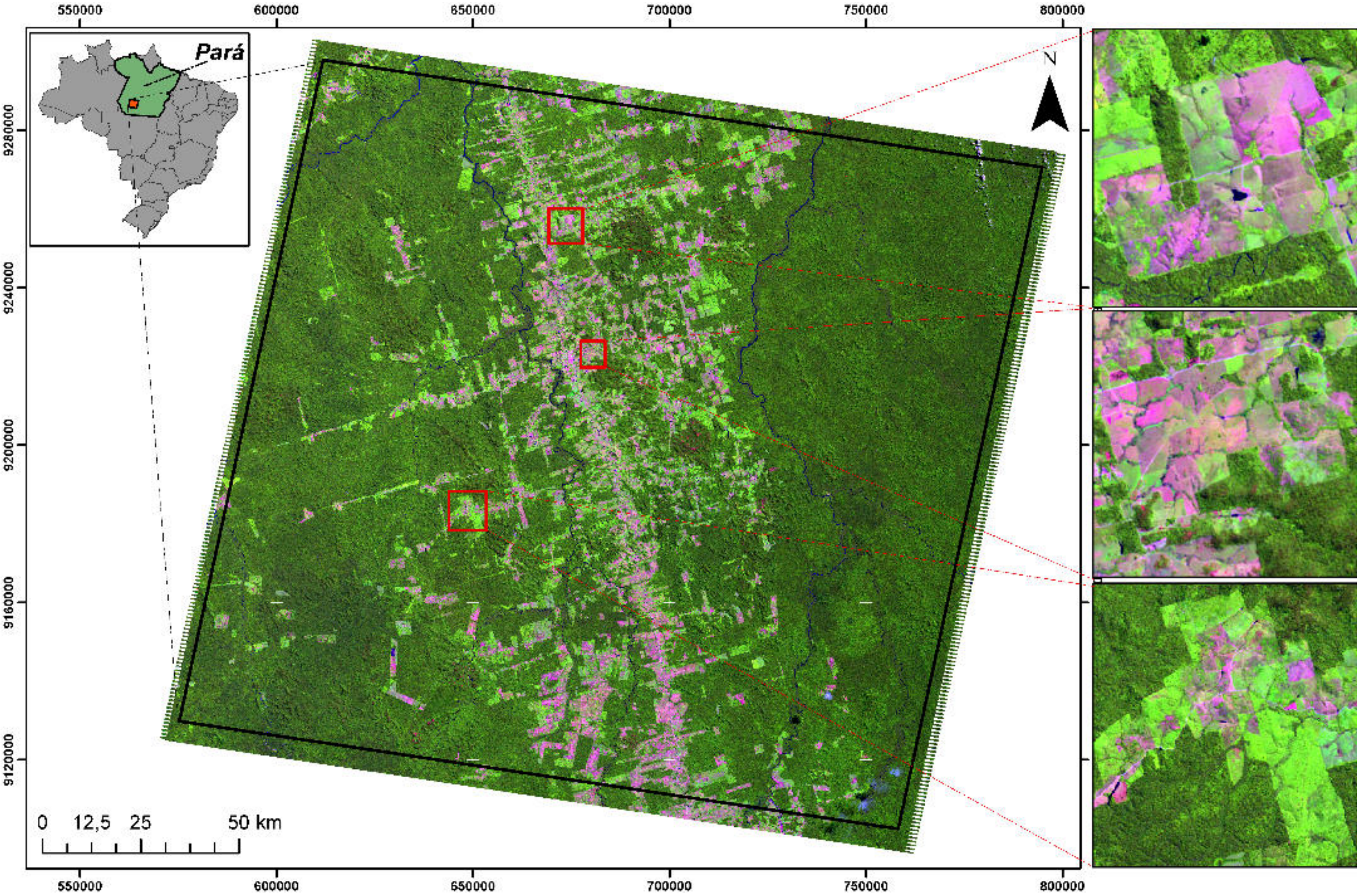

Figure 1: Location of the study area in Brazil (top left) and false-color Landsat TM image (R=band 5, G=band 4, B=band3, image acquisition at May 31st, in 2011). Image chips to the right suggest heterogeneity of managed lands. Magenta areas correspond to land with low vegetation cover, bright green indicates high levels of trees and shrubs, dark green areas are primary forests. Image projected in UTM, zone 21S.

The TCW therefore has a value range from forests with values scattered around -550 (see Appendix A.2) towards lower values on non-vegetated surfaces.

2.3. Methods

2.3.1. Computation of dry-season metrics

An annual time-series of dry-season metrics served as the basis for the following analyses. The resulting raster data describe the temporal variation of TCW throughout a dry season (e.g. standard deviation), key events within the dry-season (e.g. minimum value), as well as information on the number and temporal distribution of included observations. A number of metrics were excluded due to collinearity and outlier-sensitivity.

A pixel-based processing chain was developed, where all cloud/shadow-free observations were used for the computation of the mean ($\mathrm{TCW}_{\bar{x}}$), the median ($\mathrm{TCW}_{\mathrm{median}}$), the minimum ($\mathrm{TCW}_{\mathrm{min}}$), the maximum ($\mathrm{TCW}_{\mathrm{max}}$), and the standard deviation (TCW_{σ}) metric raster datasets for each respective dry-season. Furthermore, the slope between the first and the last observation during each dry season, termed as TCW_{β} was calculated, where

$$TCW_{\beta} = \frac{(TCW_{\text{first obs}} - TCW_{\text{last obs}})}{(DOY_{\text{last obs}} - DOY_{\text{first obs}})}$$

Additional metadata was calculated, which captures the temporal distribution of included observations on a pixel basis. Therefore, the minimum ($\mathrm{DOY}_{\mathrm{min}}$), the maximum ($\mathrm{DOY}_{\mathrm{max}}$) and mean day of year ($\mathrm{DOY}_{\bar{x}}$) as well as the total number of dry-season observations ($\mathrm{N}_{\mathrm{obs}}$) were derived. As a result, 10 raster datasets are generated annually for the study period of 1984 - 2012 (figure 3 presents the metrics datasets except $\mathrm{TCW}_{\bar{x}}$ for the year 2010).

The high temporal dimensionality (29 years) coupled with a high number of metrics (6) suggested to reduce the amount of data. To check for high similarities in the information content between metrics datasets, Spearman correlation coefficients were calculated between all metrics in 2010, using n=29.000 points with previous disturbances in 1985 to 2011. Correlation coefficients have shown $\mathrm{TCW}_{\bar{x}}$ and $\mathrm{TCW}_{\mathrm{med}}$ to be highly collinear ($\rho = .98$), first of which was excluded due to higher outlier sensitivity. The visual interpretation of the metrics datasets to assess gaps

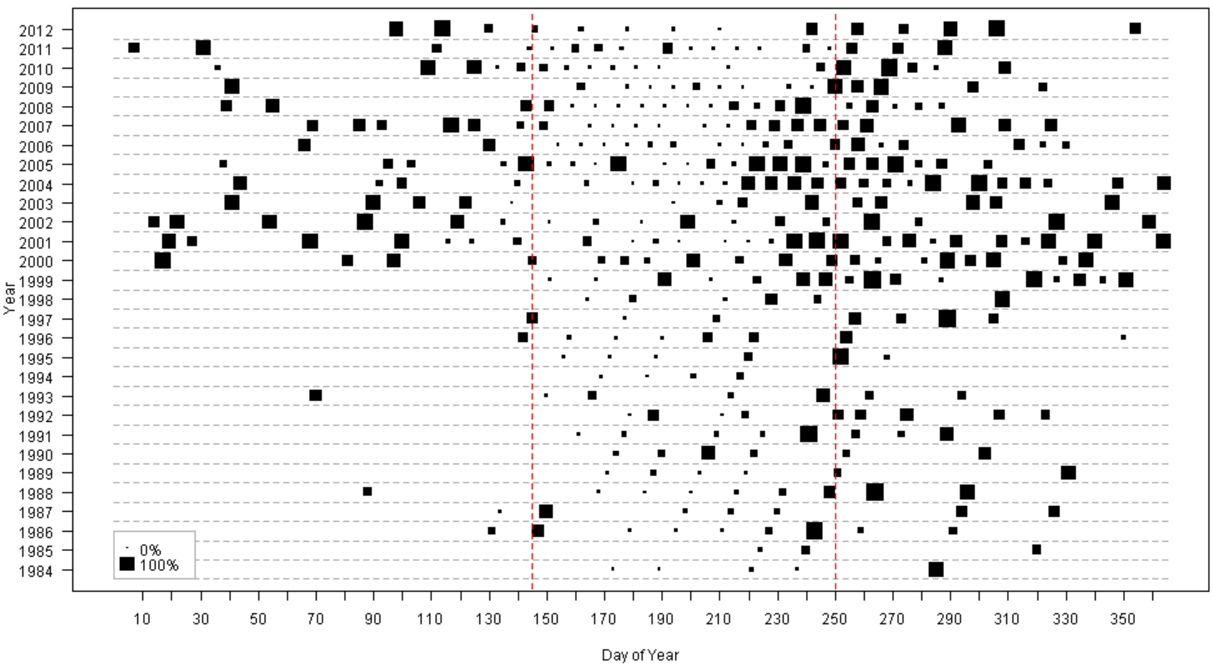

Figure 2: Distribution of Landsat TM/ETM+ observations for each year. Size of dots represents cloud cover detected by Fmask. Red lines mark beginning and end of the dry season.

and irregular patterns due to cloud remnants and SLC-off data suggested the exclusion the variable TCW_{max}. Metrics which include few observations and thereby potentially error-prone maximum values were characterized by high outlier sensitivity (TCW_{max} and TCW_{β} were excluded). TCW_{min} was chosen over TCW_{med}, since it captures the point of lowest vegetation cover, which is vital for the differentiation between grass-dominated pastures and pastures with woody encroachment. TCW_{σ} and TCW_{β} also showed collinearity ($\rho = .92$), first of which was preferred due to its reduced sensitivity towards outliers via the inclusion of a higher number of observations. The selected dry-season metrics were: 1) TCW_{min}, representing a pixel's minimum vegetation cover during each year; and 2) TCW_{σ}, being an indicator of the seasonal variation of vegetation reflectance due to phenology.

2.3.2. Analyses

To investigate processes and pathways of woody encroachment on pastures, (1) the spectral-temporal behavior of pastures was investigated using two sets of reference data. (2) Stratified samples were drawn to distinguish pastures of varying age. Subsequently, (3) an "artificial time-series" was created to investigate the response of pastures towards increasing age. To gain information on temporal variation of this relationship (4) "real time-series" for pastures of varying establishment years were created and compared. Lastly, (5) observed changes in these time series were embedded into the political and economic context of the time.

The spectral characteristics of wood-encroached and grass-dominated pastures were assessed using ground data collected during a field visit in October 2013 (see Appendix A.1). For each pasture type, $n = 5$ ground plots were selected. The pastures with woody encroachment were characterized by a summed shrub and tree cover ranging from 40% to 90%, whereas the opposing pasture type showed shrub and tree sums between 0% and 30%. Their respective phenological profiles were derived from all cloud-free TM and ETM+ observations of 2011. The temporal disagreement was tolerated as a trade-off to the high data availability during this year. Additionally, an existing land-use / land-cover classification called TerraClass2010 (Almeida et al., 2009) was employed to sample both pasture types. To retain spectral characteristics of a larger sample, the median and the standard deviation was derived from $n = 2000$ randomly placed TerraClass pixels of productive (corresponds to class "pasto limpo") and wood-encroached (corresponds to class "pasto sujo") pastures, respectively. Besides the evaluation of detailed phenological profiles, the two dry-season metrics were derived for both pasture conditions to better understand the behavior of wood-encroached pastures and grass-dominated pastures.

To investigate pastures in dependency of their age, a dataset containing annual forest disturbance from 1985 un-

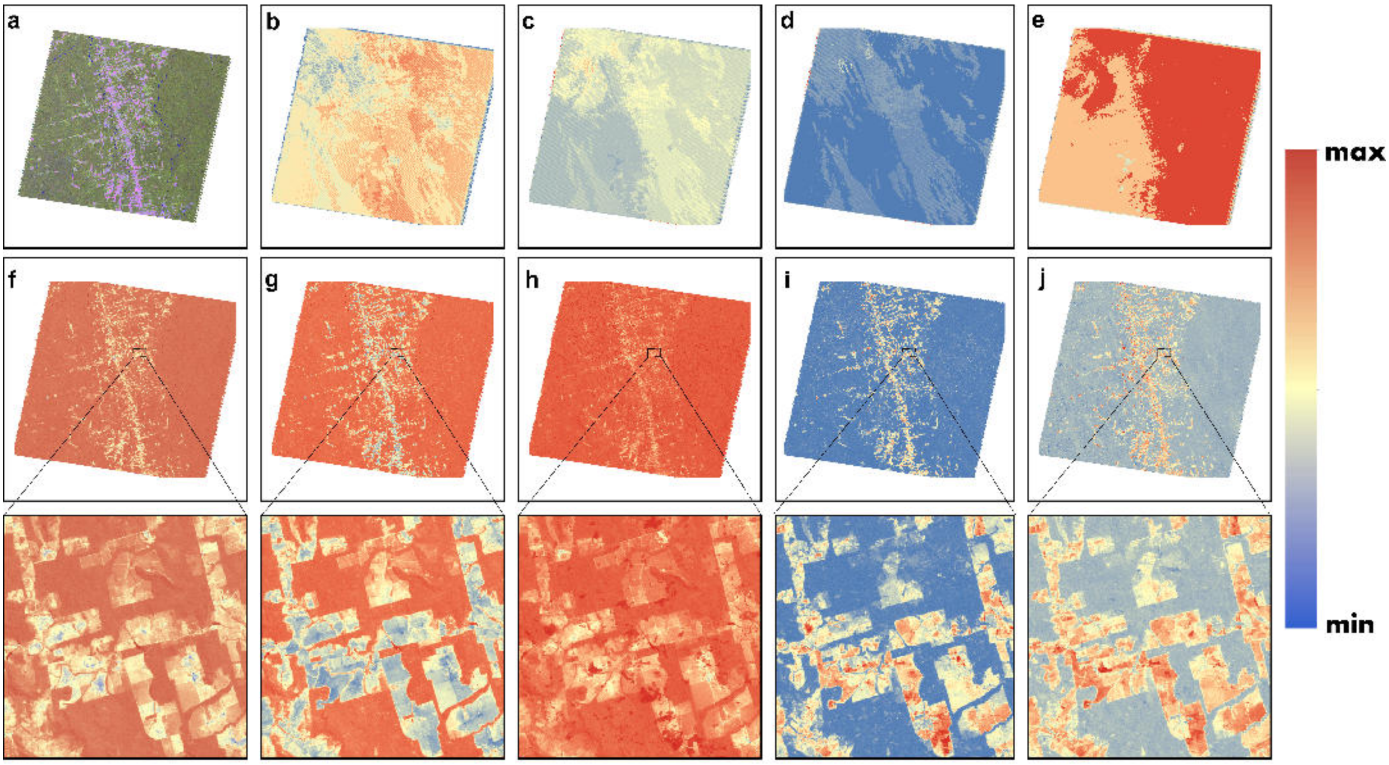

Figure 3: (a) Landsat image; (b) N_{obs} (min=1, max=10); (c) $DOY_{\tilde{x}}$ (min=145, max=250); (d) DOY_{min} (min=145, max=250); (e) DOY_{max} (min=145, max=250); (f) TCW_{median} (min=-4000, max=0); (g) TCW_{σ} (min=0, max=1000); (h) TCW_{min} (min=-4000, max=0); (i) TCW_{max} (min=-4000, max=0) and (j) TCW_{β} (min=-1000, max=3000). Last row represents zoom on forest and pasture areas west of Novo Progresso Town.

til 2011 ((Müller, unpublished), see Appendix A.2) was stratified by the year of disturbance and sample points were randomly placed within each strata ($n = 10000$ per year, $N = 270,000$). The major proportion of land-use on disturbed areas in the study region is attributable to pastoral land uses (87%) (Instituto Brasileiro de Geografia e Estatística, 2006). Remaining areas are settlements (7%) and agro-silvo-pastoral land uses (2%), first of which existed before 1985 and hence did not occur in the disturbance year dataset and in the sample, respectively. The remaining area (4%) consists of water and rock outcrops. Concluding, the sampled areas were almost exclusively constituted by pastoral land-uses. The year following forest disturbance was subsequently interpreted as the onset of pastoral land-use in the respective pixel. Pasture age was derived by subtracting the year of disturbance from the year of the dataset under investigation.

The potential complexity of the trajectories suggests calculating a useful measure to allow for comparative interpretation of different median trajectories. Therefore, definite integrals were derived for each median trajectory to express potential temporal changes in the regional trends as a single measure. The definite integrals were defined as

$$\int_b^a \gamma(x) = \sum_i^n \gamma(x_i) \bigtriangleup x$$

where a and b limit the included range of x (the pasture age), and $\gamma(x)$ is a non-continuous functional relationship. The number of years under investigation is represented by n, x_{i} is the value at a given year and $\bigtriangleup x$ is the interval between $x_{\text{i-1}}$ and x_{i}. Since $\bigtriangleup x = 1$, the integral can be defined as the sum of all values of $\gamma(x_{\text{i}})$ within the given time period. The observed trends in the integrals of median trajectories were cross-checked with literature on the effects of national policy interventions and market dynamics on animal husbandry in the Brazilian Amazon region.

3. Results

3.1. Phenological behavior of pasture types

Phenological profiles of grass-dominated pastures and wood-encroached pastures were investigated to better understand their spectral behavior (see fig. 4). Differences are visible from the beginning of the dry season, where higher values (TCW -1200 to -600) are given with increased fractions of woody vegetation, compared to grass-dominated pastures (TCW -1500 to -1000). These differences propagate towards the end of the dry season, whereas they show to be highest during the period after DOY 200. At DOY 223, the TCW of woody encroached pastures ranges from -1600 to -1000, whereas TCW on grass-dominated pastures decreased to values between -2700 and -2300.

The overall patterns of the observations from the LULC dataset match the findings based on field data. A stable phenology in wood-encroached pastures is visible, compared to grass-dominated pastures with higher variability of TCW throughout the dry season. Whereas grasses senesce in the dry season (Numata et al., 2007b), larger shrubs and single trees show increased resilience towards drought-stress, thereby potentially reducing the variability of TCW throughout the dry season. The high standard deviation (fig. 4, polygon outlines) suggests high a variation in the pixel profiles. The overlap between both derived phenologies, especially within the existing LULC dataset, suggests a gradual transition, rather than discrete separation between the two pasture classes.

Dry-season metrics derived from the phenologies demonstrate the separability of the pasture types in both metrics. TCW_{min} values of grass-dominated pastures range from -2700 to -2400, whereas pastures with increased fractions of woody vegetation show values between -1700 and -1100. TCW_{σ} values over grass-dominated pastures range between 400 and 600, while significantly lower TCW_{σ} values from 100 to 300 occur when woody vegetation dominates pastures.

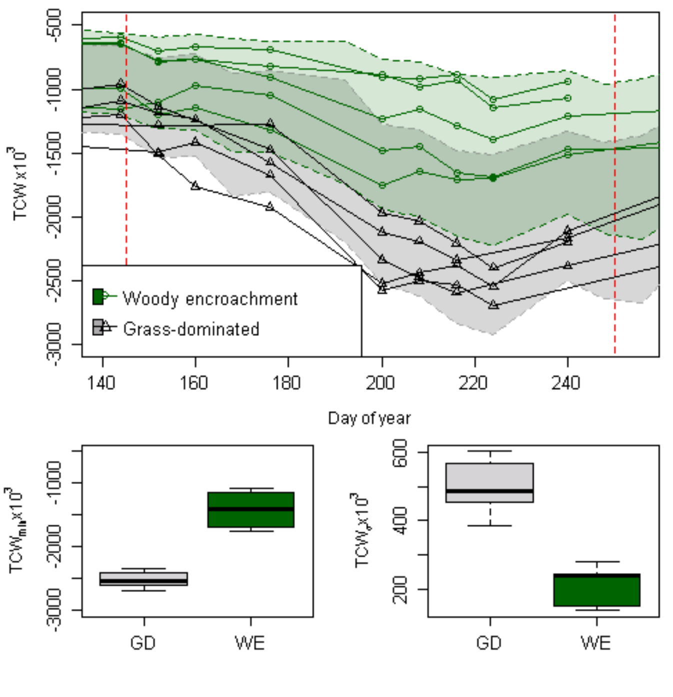

Figure 4: Phenological profiles of 10 field plots (lines) representing woody encroachment (green) and a grass-dominated pasture (black). Each point represents a cloud-free observation of 2011 TM / ETM+ data. Colored polygons represent the median +/-1 standard deviation of the respective pasture types as determined from a n=2000 random sample from TerraClass 2010. Dashed red lines delineate on- and offset of the defined dry season (left). Boxplots of the TCW_{min} and TCW_{σ} metrics, derived from the phenological profiles (middle, right).

3.2. Relationship between woody encroachment and pasture age

A chronosequence was created to analyze the regional relationship between pasture age and the respective metrics which indicate woody succession. Higher TCW_{min} values, as well as lower TCW_{σ} values (see fig. 5) indicate a tendency towards higher vegetation cover and lower dynamics on pastures of one to seven years of age. Medians in this period show a nearly linear decrease of TCW_{min}, and an increase of TCW_{σ}, respectively. This trend saturated at pasture ages of approximately eight years in both metrics. Median values throughout the TCW_{min} chronosequence range from -1000 on one year old pastures until -2300 on eight year old pastures, from where on they remain between -2000 and -2500 in the subsequent years. The TCW_{σ} chronosequence median rises from 100 in the first year until 400 in year eight, with oscillations of less than +/-50 in the following years. A growing value range with increased age was observed that also tends to stabilize at approximately six to eight years. The 99% margins (boxplot whiskers) reach TCW_{min} and TCW_{σ} values that approach values ranges of forests after only few years.

The chronosequence reveals two attributes of the relationship between pasture age and woody encroachment. Firstly, the variation in the value ranges of both metrics in each pasture age class is large. Pasture areas are therefore assumed to be dynamic in terms of vegetation structure, whereas the maximum variability is reached after seven years. Secondly, 50% of the sampled pastures follow a trend that shows a decline in TCW_{min} and an increase in TCW_{σ} until the age of eight. Given the findings on the spectral-temporal behavior of pastures, a gradual shift from areas which spectrally resemble pastures with woody encroachment towards grass-dominated pastures can be identified for the major portion of sampled pasture areas. This suggests the fraction of woody vegetation on the pastures in our study area to decline within the first eight years. Afterwards, 50% of the sampled pastures show a value range which spectrally approximates grass-dominated pastures.

3.3. Comparison of trajectories with varying establishment year

Shifts in median trajectories were found, when pastures of varying establishment years were compared (see fig. 7, a and b). Each trajectory in itself shows a decrease of TCW_{min} and an increase of TCW_{σ}, similar to the above findings. The years subsequent to disturbance are characterized by TCW_{min} values between -1000 to -1300, followed by a steady decrease, until these trends saturate. Again, the inverse was shown for the TCW_{σ} metric, whereas the values shortly after disturbance range between 100 and 300 with an increasing trend towards later pasture ages. Comparing several trajectories with the difference being the year of pasture establishment, a shift in the trajectory is visible, whereas periods with higher vegetation cover

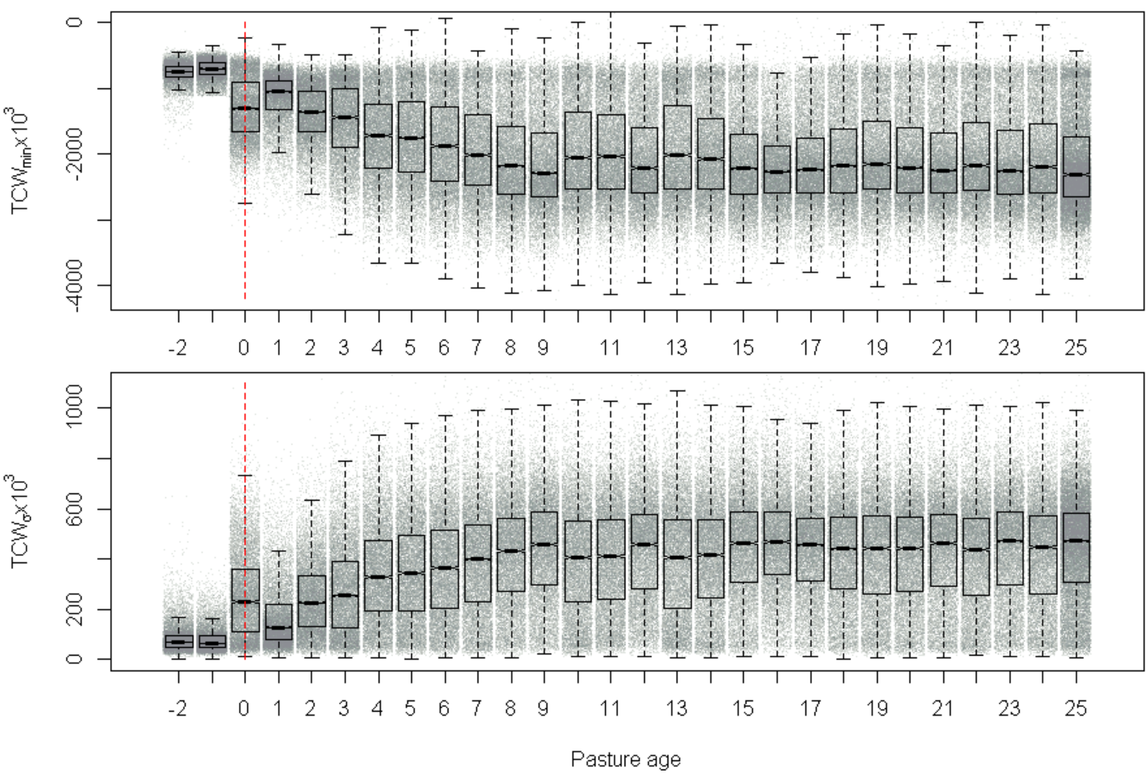

Figure 5: Chronosequence of TCW_{min} and TCW_{σ} sampled from dataset 2010, boxplots grouped by pasture age.

(TCW_{min}) and less vegetation dynamics (TCW_{σ}) become shorter over time. Single peaks and troughs are occurring in few years, specifically in the trajectories of TCW_{σ}.

The differences in trajectories were also expressed by definite integrals, suggesting variation in the relationship between pasture age and woody encroachment to occur (fig. 7, c and d). Integrals were derived for the interval of pasture age one to seven. The TCW_{min} integrals show a non-linear behavior over time. When separating the study period into smaller segments, linear trends can be seen. Increasing TCW_{min} integrals until the year 1988, followed by a steady linear decrease until 1995 can be observed. Two outliers mark the years 1996 and 1997, followed by relatively stable values in 1998-2000. A sudden drop in TCW_{min} integral values in 2001 is followed by a slight increase. In the TCW_{σ} integrals, the longer periods linear of in- and decreases as well as the outliers after 1995 coincide with the observed patterns of the TCW_{min} integrals, yet with inverse tendencies (increase in TCW_{min} integrals corresponds to a decrease in TCW_{σ} integrals).

4. Discussion

4.1. Dry-season metrics

Given the phenologies for different pasture types, we can identify some benefits when applying dry-season metrics for remote sensing of woody encroachment. The data enabled to capture the regionally prevalent trends of woody encroachment on pastures by the provision of information on the annual minimum vegetation cover, and the variation of vegetation cover during the dry season using TCW_{min} and TCW_{σ} metrics. Independent from single date imagery, the metrics allow to generate a dense time-series of cloud-free metric datasets, while annually integrating the seasonal spectral variations of given ground features. Thereby, phenological parameters, which have shown to contain valuable information in the present research context can be integrated.

Despite these advantages, a number of critical issues unfold the necessity of performing further research on Landsat-based dry-season metrics. A number of TCW images showed significantly deviating image statistics, compared to the majority of images of the same year. Causes behind these outlier images remain unclear, yet, atmospheric correction procedures might have caused some variation in surface reflectance values (see Appendix B.2), which possibly introduce a bias into the metrics. Alternatively, the sensitivity of TCW to soil moisture (Crist and Cicone, 1984) could have biased TCW values towards higher ranges after heavy precipitation events. Some outlier pixels were visible within the metric images, which can be largely attributed to cloud remnants and undetected clouds, as well

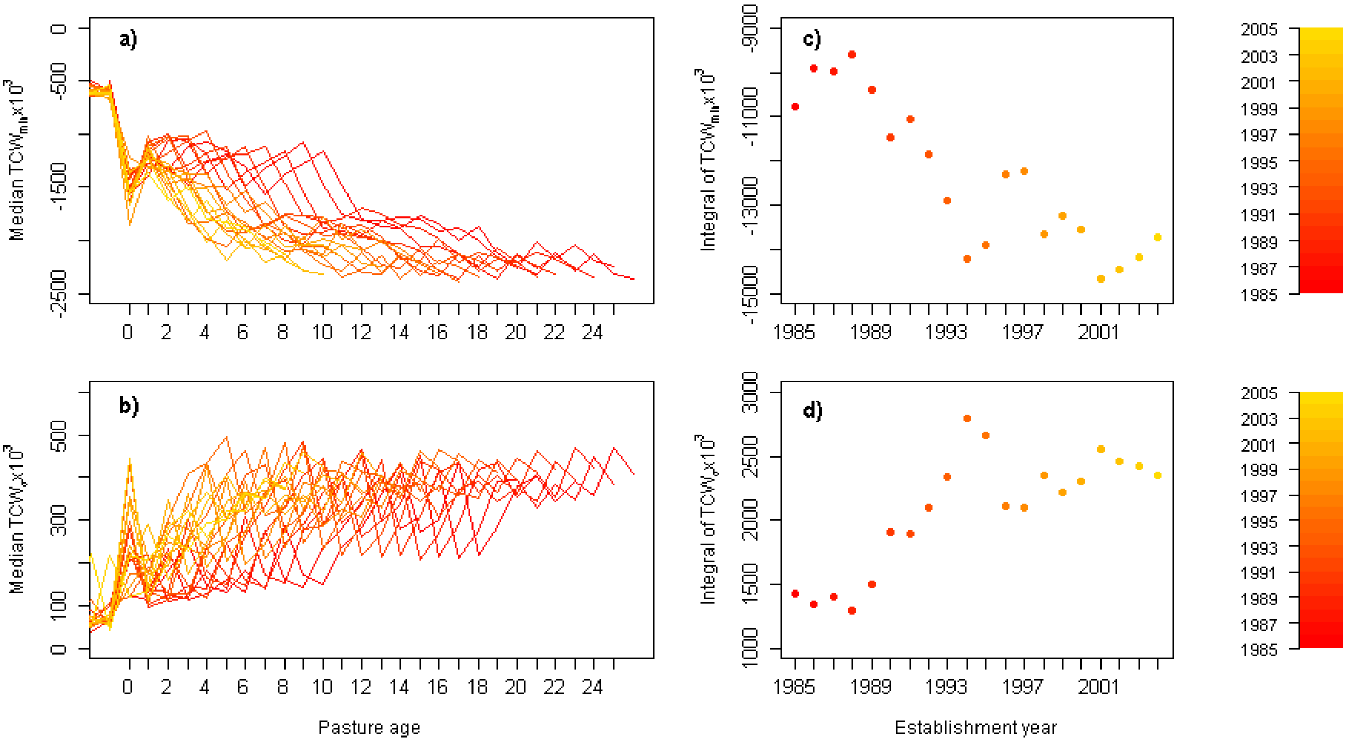

Figure 6: Pasture trajectories (a, b), each line represents the trajectory for a single year of pasture establishment (1985-2005). The x-axis shows the amount of years after disturbance, where 0 represents the disturbance year. The y-axis represents median values of a random sample (n=10,000) drawn from the TCW_{min} (a) and TCW_{σ} (b) metrics in each respective year. Integrals of trajectories (c, d) for the period of pasture ages of one to eight years.

as cloud shadows. These were especially abundant within the TCW_{max} metric. For future applications it is to note that cloud pixels have TCW values well above forests, which makes it possible to detect and exclude them. Cloud shadow remnants show reduced reflectance, which remain in a realistic range of values and are therefore harder to detect.

To inspect the inter-annual stability of the metric dataset, a comparison of pseudo-invariant features was performed. A secular negative trend was found over the entire period, when investigating averaged TCW_{min} metrics. The causes behind this trend remain unclear, but are unlikely to occur due to differences in the annual distribution of images (see Appendix B.2). It shall be noted that the amplitude of the observed decrease in mean values comprises a small range (TCW_{min} -450 to -600) over 29 years, hence, the inter-annual variation in the datasets is too small to cause the observed temporal changes in trajectories. Therefore, further evaluation of the quality of Landsat-based dry-season metrics is considered advantageous. This involves a sensitivity analyses towards the impact of annual distribution of observations, a mechanism to exclude cloud and cloud-shadow remnants, possibly using distance measures (Griffiths et al., 2013b) and exclusion of images with largely deviating image statistics (see Appendix B.2) prior to metrics computation.

4.2. Woody encroachment and pasture age

Some characteristics were identified when observing pasture areas of increasing age. The investigated relationship between pasture vegetative structure and age shows two main features, a decrease in woody vegetation throughout the initial years of pasture use and a large variability of values.

The median values of the chronosequences shift from the value ranges of a pasture with woody vegetation towards values that are approaching the presented values of grass-dominated pastures. Accordingly, woody vegetation is highly prevalent during the initial years after pasture establishment. Presumably, a high amount of plant remnants and denser seed banks remain on the pastures after forest clearing, causing this initial regrowth of woody plants. The observed decrease in woody vegetation is confirmed by findings of other authors which found the duration of land use to be negatively related to the speed and amount of vegetation succession (Alves et al., 1997; Brown and Lugo, 1990; Uhl et al., 1988). The length of the period until stabilization was found to range between seven and eight years in the chronosequence of 2010. Uhl et al. (1988) found pastures with less than eight years of use to be repopulated with trees within a short period of time. Seed banks in the soil can be diminished due to burning practices, mechanized clearing and herbivore, additionally limiting the successful regrowth of native species (Nepstad et al., 1996). Additionally, depletion of plant available nutrients leads to declining soil fertility (Buschbacher et al., 1988) and might contribute to the observed reduction of woody vegetation. In subsequent years, medians of $\mathrm{TCW_{min}}$ and TCW_σ stabilize, suggesting the onset of a pasture regime with less woody encroachment. This suggests that either seed banks are diminished to a degree which does not allow successful regrowth, or, nutrient pools are depleted, impeding natural succession.

The high range of annually observed values indicates a high structural heterogeneity, which contributes to the variance in values that was observed in each year. Several authors discussed the complexity of managed grazing lands, which results from the complex interplay of environmental and anthropogenic factors (Asner et al., 2004a; Bowman et al., 2012). A fraction of the areas spectrally resembles the forested state only few years after the disturbance. This indicates the fast recovery potential in the area. Furthermore, this suggests that a fraction of the sampled areas was abandoned in earlier years and secondary succession transforms these areas into secondary forests (Feldpausch et al., 2004). Inversely, a share of the observed areas responds with very low vegetation fractions. These can be explained by soil compaction which hampers vegetation growth (Asner et al., 2004b; Buschbacher et al., 1988). These areas either emerge spatially extensive due to overstocking, or spatially clustered, when areas are heavily frequented by cattle, for instance paths or areas surrounding ponds or drinking troughs.

4.3. Contextualization of trajectory changes

Median trajectories varied over time, suggesting that pathways of pastoral land-use in the study region are altered with varying year of pasture establishment. It is hypothesized that management regimes, which were prevalent during the time of pasture establishment, determine the future characteristics of respective areas. Despite the symptomatically low productivity in the region, variations in the input of manual labor or the frequency of burning can alter the success rate of woody vegetation growth over time (Uhl et al., 1988). Additionally, increasing stocking rates can contribute to lower levels of woody encroachment (Krummel et al., 2008). A trajectory with lower fractions of woody vegetation was consequently interpreted as intensified production system, even though pasture productivity remains far from the productivity of modern high-input production systems and the sustainability of the mentioned management practices remains questionable (Hohnwald et al., 2010). Comparatively higher integral values were thereby interpreted as more extensive type of pasture management due to longer periods of raised levels of woody vegetation. Four distinct segments were identified which suggested a discussion of the political and economic frameworks at the time. These are namely: an increase of $\mathrm{TCW_{min}}$ integrals until 1988, followed by a near-linear decline until 1995, a spike over the years 1996 and 1997, as well as a sequence of generally low, but scattered integral values until 2004.

Pasture establishment has been extensively used as a mean for land appropriation and land valorization (Fearnside, 2001). Pasture land could be sold by 5-10 times the price of forested land and is therefore an efficient method to increase land value (Mertens et al., 2002). Given this insight, it can be assumed that extensive forms of pastoralism are prevalent, unless certain incentives for intensification are given. During the initial three years of the study period, environmental laws were few, and extensive land-uses were subsidized by the Brazilian government (Bowman et al., 2012). This period coincides with an increase in the $\mathrm{TCW_{min}}$ integral since the beginning of the time series until the year 1988.

Enforcement of environmental law can decimate rationales for extensive management, or high fractions of woody vegetation on pastures, respectively. Mechanisms of this kind could reduce the profitability of extensive management schemes with means of penalization and therefore promote intensive use of newly cleared lands. In the context of the new national constitution of Brazil which came into effect in 1988, environmental laws, which explicitly demanded for the preservation of Amazon forests, were put into force. The simultaneous establishment of the environmental protection agency IBAMA and the launch of the deforestation monitoring program PRODES in 1989 rendered illegal deforestation increasingly fraught with risk. Mattos and Uhl (1994) discuss the decreasing impact of land tenure from 1987, due to the increasing profitability of beef production. These factors support a trend towards more intensive management schemes on newly cleared lands, and therefore could serve as explanatory factor for the observed decrease in the integral until 1994/95.

Two outliers with higher $\mathrm{TCW_{min}}$ integrals in 1996/97 temporally coincide with a change in the national forest code, which obligated land owners to maintain 80% of their land as a legal reserve (Bowman et al., 2012). This fraction previously accounted for 50%, according to the old forest code law from 1965. There is no intuitive rationale that could explain why especially the newly cleared lands should be abandoned in those years. Nevertheless, the change in forest code promotes the abandonment of selected areas to increase the share of secondary vegetation on private lands.

With the onset of the new millennium, the relative importance of steering frameworks for Amazon cattle ranching shifted from national policies towards international commodity markets (Nepstad et al., 2006). An increasing number of studies undermine the hypothesis that indirect land-use change was recently contributing to the growth of pastoral activities in the Amazon (Arima et al., 2011; Barona et al., 2010; Barretto et al., 2013). The edaphic conditions in the neighboring state of Mato Grosso increase agricultural suitability and thereby land value. This diminished the profitability of pasture areas, which were then increasingly replaced by highly demanded export crop monocultures (Macedo et al., 2012). Barona et al. (2010) found a replacement of pastoralism from northern Mato Grosso state into the south-west of Pará, starting in the early 2000s. Coupled with a generally rising national demand for animal products (Bowman et al., 2012), indirect LUC possibly contributed to the increase in head of cattle in the study area. This in turn possibly led to an increase in stocking rates, impeding the encroachment of woody vegetation. Additionally, the eradication of foot and mouth disease in the early 2000s opened up export markets for animal products with origin in southern Pará (Nepstad et al., 2006). Simultaneously, the devaluation of the Brazilian Real until 2003 lowered prices for Brazilian beef on global commodity markets, which raised the attractiveness of cattle ranching in the Amazon. This was also reflected in a skyrocketing trend in export quantities in the early 2000s (Bowman et al., 2012). These events increased the profitability of pastoralism and therefore possibly served as an incentive to direct production systems towards higher levels of intensity. Interestingly, these market developments coincide with a sharp drop in the TCW_{min} integrals in 2001, followed by slightly increasing, but low values in the following years.

The discussed coincidences would support the observed sequence of integrals changes. Nevertheless, quantification of the relationships in terms of their strength and statistical confidence has not been done. The enforcement strategies and the effectiveness of governmental policies are widely discussed in the Amazon context (Verburg et al., 2014), embedding the discussion of the integrals into a wealth of contradictory points of view. Nevertheless, given the assumption of functioning law enforcement, the integrals showed some plausible changes of trends in pasture vegetation structure, which encourage further research on this matter.

5. Conclusions

In this study, annual time series of Landsat dry-season metrics were employed to investigate the regional trends of woody encroachment on pastures in southern Pará. The main findings of this study can be summarized as follows:

- The minimum TCW value in each respective dry season has been shown to be suitable to distinguish wood-encroached and grass-dominated pastures in the Novo Progresso region. Moreover, the annual variation in vegetation was well captured by the standard deviation metric. Consequently, the TCW_{min} and TCW_{σ} metrics were appropriate in the research context.

- A chronosequence was created from a regional sample of pastures of different age classes. This method revealed that the fraction of woody vegetation is increased in the initial years of the regional pastures. In the following years, the fraction declines until it reaches an age of approximately eight years. Subsequently the larger share of pastures in the region spectrally resembles a grass-dominated pasture. The structural complexity of pastures was repeatedly reflected by a high range of values in the chronosequence.

- A comparison between median trajectories of pastures with different year of establishment suggests that the year of pasture establishment is of relevance for the future trajectory of vegetation cover on pastures in the region. Incentives for increasing land productivity and forest conservation possibly lead to varying trajectories of pasture vegetation cover. Concluding, the relationship between pasture age and fractions woody vegetation is non-stationary, whereas the political and economic context during pasture establishment was suggested to be contributing to the observed variations.

For future applications of Landsat-based metrics, further research on quality and biasing factors is recommended. This concerns the sensitivity towards irregularities in annual distribution of Landsat observations which are used to compute metrics. The metrics-based chronosequence method promises important insights into spatial determinants of woody encroachment on pastures, which help to better understand the locally operating processes. It is proposed to include the size of clearing as well as the distance to forest edges in future analyses of woody encroachment processes (see Appendix C). The proposed trajectory method could be applied to locally estimate the effects of economic changes and policy interventions, if statistically valid relationships can be determined.

Literature on Amazonian pastoral systems reveals a scientific dispute about the potential effects of intensification on Amazon pastures. Governmental guidelines suggest a reduction in deforestation processes by intensifying pasture areas, whereas several authors oppose this argumentation. In either case, management schemes for sustainable intensification are being continuously improved by federal agricultural research institutes and the scientific community. A widespread application of these schemes, coupled with facilitated access to financial loans can help to convert Amazon pastures into more productive pastoral systems.

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Appendix A. Ancillary Data

Appendix A.1. Field Data

Field data was collected in the Novo Progresso area during the onset of the wet season in October 2013. A total of n = 108 points were visited using a Garmin handheld GPS device. For each plot, 4 photographs were taken in north, south, east and west directions. Ground cover was divided into fractions of soil, rocks, herbaceous vegetation (including pasture grasses, height <1m), shrubs (height 1-2m) and trees (height >2m). According to species composition, percentage of shrubs and trees, the respective ground plot was attributed to one of the classes grass-dominated pasture, woody encroachment and biological degradation(see fig. A.7).The spatial distribution of the sample points is clustered and does therefore not cover the entire study area due to low accessibility of cattle ranches distant from main roads. The majority of the plots is located on the "Fazenda Paraiso", a 2200ha cattle farm east of Novo Progresso town, which was established in the 1980s. Since its establishment, the ranch expanded continuously; hence it contains a variety of pasture age classes and comprises the relevant pasture types (see fig. A.8, middle zoom chip).

Appendix A.2. Forest Disturbance Map

The dataset containing the disturbance year (Müller, unpublished) (see fig. A.8) was derived using an automated pixel-based multi-criteria thresholding approach on annual metric time series. Metrics describing the minimum in TCW values were computed annually, whereas all available cloud-free observations of a given year were included in the analyses. Pre-processing routines and metrics computation were identical with the procedures described in this study, with the difference being the limiting temporal window, which was not applied when computing annual metrics.

A linear model was created to transform TCW minimum values into percentage vegetation cover. A randomly sampled forest population was used to derive the 100% vegetation cover values, accordingly values were rescaled between 0% vegetation (TCW minimum = -2200) and 100% vegetation (TCW minimum = -550) values.

Two criteria defining maximum vegetation cover in the disturbance year and the maximum vegetation cover in the post-disturbance year were defined to account for several disturbance types and minimize commission errors due to outliers. Vegetation cover in the disturbance year has to be below 65% for the pixel to be labeled as disturbance. The post-disturbance year criterion does not allow values above 75% vegetation cover in the following year, thereby eliminating potential commission errors due to outliers. In case both criteria were fulfilled, the pixel was labeled as disturbed in the appropriate year.

The map has been validated with the PRODES deforestation product (Instituto Nacional de Pesquisas Espaciais, 2013) and has an overall accuracy of 83%, where mismatches in the disturbance year were mainly caused by cloud remnants. In comparison to the PRODES deforestation product, the disturbance dataset has two characteristics which are beneficial in the research context of this study. First, the dataset includes disturbance years back to 1985, expanding the temporal extent of the analyses. Secondly, the pixel-based approach does furthermore provide higher spatial detail and hence allows for the inclusion of areas smaller than the minimum mapping unit of the PRODES product (6.25 ha).

Appendix B. Additional Analyses

Appendix B.1. Dry Season Definition

The definition of the dry-season temporal window for the calculation of the according metrics was done in a two-step approach. First, precipitation estimates were used to calculate monthly averages of cumulative precipitation. This served as a basis to delineate the dry season temporally. Subsequently, the influence of an expansion or reduction of the temporal window on the image availability was investigated to minimize data loss. TRMM3B43 V7 monthly precipitation estimates (Tropical Rainfall Measuring Mission Project, 2013) for the period of 2000-2010 were transformed from mm/h into mm/month by multiplication of each dataset by 24 and the number of days for each month. In a next step, monthly averageswere calculated. Lastly, the 11-year monthly mean precipitation values were spatially averaged over the extent of the Landsat footprint (path 227, row 65). Dry season definitions in the Amazon typically use a threshold of 100mm cumulative monthly precipitation (Saatchi et al., 2007). Using this threshold, the derived dry season within the 227/65 footprint lasts from the beginning of June until the end of August (DOY 152-243). To minimize data loss, this period was extended for one week on both ends, which lead to the inclusion of a total of 21 additional scenes. The final dry-season period falls between DOY 145 and 250.

Appendix B.2. Data Mining

To investigate causalities of variation in metrics datasets, a preliminary outlier analysis was performed. A sample of 100,000 forest pixels was created to compare the distribution of TCW values between all TC-transformed Landsat images which constitute the basis for the metrics computation. Forests can be assumed to be phenologically stable and are therefore considered as pseudo-invariant features in this context. Accordingly, the histograms of all images in a given year should match approximately. Several outlier images were included in the metrics computation (see fig. B.9) and therefore might introduce a bias.

To inspect the inter-annual stability of metrics datasets, a comparison based on pseudo-invariant features was performed. Due to the negligible phenology of tropical forests-forest populations (n = 100,000) were sampled annually.

Figure A.7: Woody encroachment (left), grass-dominated pasture (center), biological degradation (right). Images captured during field visit in October 2013.

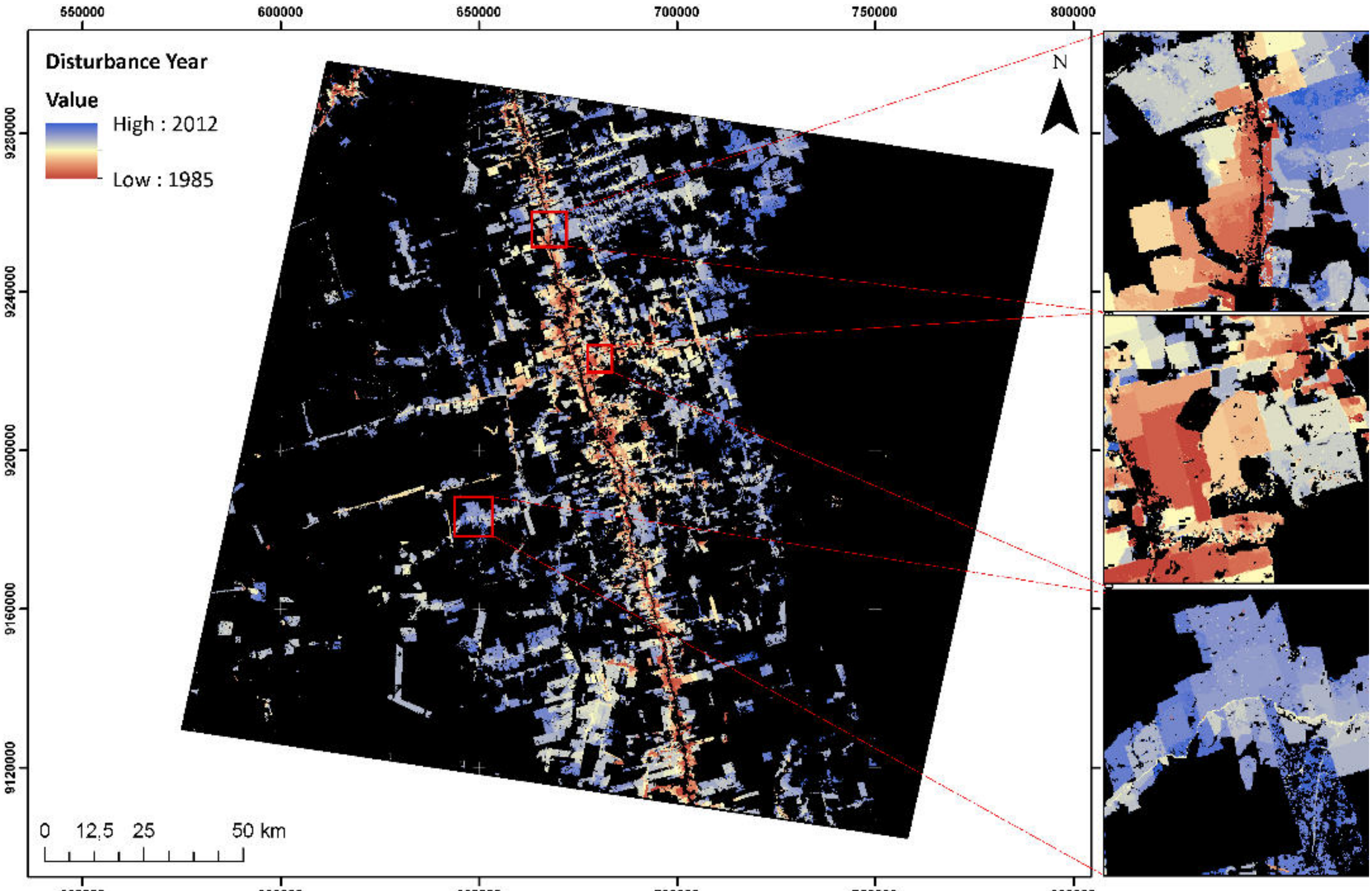

Figure A.8: Disturbance year dataset, black areas represent undisturbed areas and include disturbance previous to 1985. Zoom chips show exemplary areas of successive disturbance. Map projection UTM zone 21 south.

Averages of the TCW_{min} metric in forests show a decreasing secular trend over the entire period (see figure B.10). Presumably this trend is related to either (1) differences in the annual data distributions, where observations later in the year (drier period of the temporal window) are outweighing earlier (wetter) observations, (2) a climatic trend over the years, i.e. a decrease in precipitation, leading to natural degradation of forests, or (3) changes in forest structure related to anthropogenic activities, such as selective logging. Additionally, (4) sensor degradation can possibly cause a decrease in sensitivity, leading to a reduction in data values.

To account for (1), dependencies between metrics and metadata describing the observation distribution were investigated further. A moderate negative correlation between the year under investigation and the DOY_{min} ($\rho =$

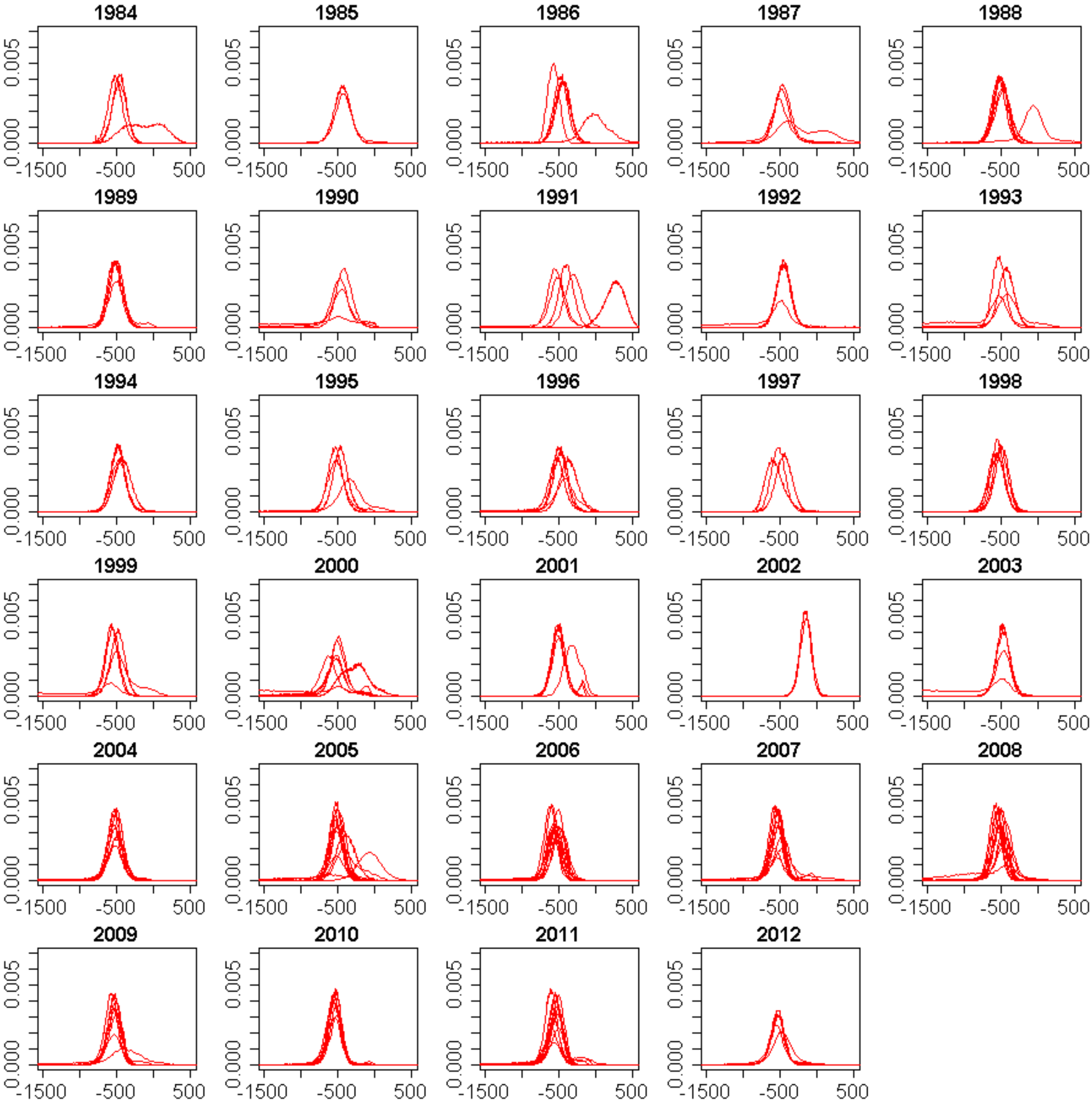

Figure B.9: Distributions of wetness values of 100,000 forest pixels. Only cloud-free pixels were considered, hence the actual number of pixels per scene varies. X-axis values range from -1500 to 500, whereas the Y-axis (0-0.7%) denotes the frequency in the respective bin.

$-.54, p < 0.001$) suggests that metrics in later years include observations earlier in the dry season, which does not support the trend showing a decrease in TCW. Similarly, a weak negative correlation between year and $\mathrm{DOY}_{\bar{x}}$ ($\rho = -.25$) indicates a temporal shift from later towards earlier observations later in the time series. Furthermore, weak insignificant correlations between $\mathrm{DOY}_{\bar{x}}$ and $\mathrm{TCW}_{\mathrm{min}}$ ($\rho = -.30$) were found. These findings imply that the data distribution does not bias the metrics time series heavily. Accounting for these findings it is concluded that the decreasing trend within the phenological metrics is not caused by the data distribution, but is rather related to climatic trends, human-induced phenomena or sensor degradation. It shall furthermore be noted that the amplitude of the observed decrease in mean values comprises a small range ($\mathrm{TCW}_{\mathrm{min}}$ -450 to -600) over 29 years, hence, the interannual variation in the datasets is too small to cause the temporal changes in trajectories.

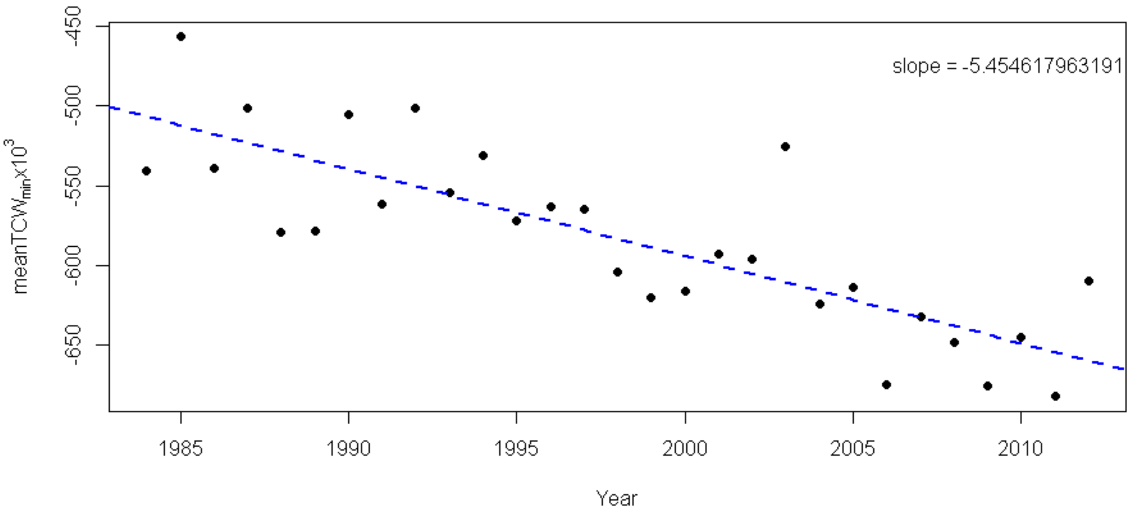

Figure B.10: Mean values of TCW_{min} metric in forests ($n = 100,000$) for each year, blue line represents linear regression line.

Appendix C. Case Study: Forest Proximity as Spatial Determinant of Woody Encroachment

Appendix C.1. Background

Biophysical determinants of pasture productivity have been studied widely (Asner et al., 2004; Buschbacher et al., 1988; Carreiras et al., 2006; Moran et al., 2000; Numata et al., 2007). Seed availability is determining vegetation succession on Amazonian pastures (Uhl et al., 1988), whereas seed dispersal has previously been found to be spatially clustered among primary forest edges (Alves et al., 1997). This case study aims to apply the methods proposed in the previous study to explore the relationship between chronosequences of woody vegetation on pastures towards the distance to forest edges.

Appendix C.2. Data & Methods

To account for the proximity to forests, a PRODES (Instituto Nacional de Pesquisas Espaciais, 2013) forest mask of the year 2010 has been used to calculate the euclidean distance to forests in ArcGIS Spatial Analyst. The relationship between distance to forests and vegetation succession was first investigated using a Spearman correlation analyses. Subsequently, chronosequences were created. This was done due to the non-stationarity of the variable distance to forest. The disturbance-year stratified point sample (n=290,000) was, further separated into 10 strata of distances to the primary forest edge, where each strata comprises a distance range of 60m. TCW_{min} values were extracted for each of the age/distance classes. Similar to the approach above, the median of the sampled values for each age and distance class was used to shape a trajectory. This resulted in 10 different trajectories, each showing a chronosequence of median values of the sampled metric per distance class. The definite integral of each chronosequence was calculated, where the temporal interval was limited to 0-25 years.

Appendix C.3. Results

Low correlation was detected between distance to forest and TCW_{min} ($\rho = -.31$) and TCW_{σ} ($\rho = -.30$). Median chronosequences of the TCW_{min} metric continuously show elevated values and a high variability of TCW_{min} (fig. C.10 left, light blue) throughout pasture ages, whereas more distant pastures (fig. C.10 left, purple) show a more rapid decrease in TCW_{min} within the first years and then remain stable in lower value ranges. Elevated integral values (fig C.10, right) of the chronosequences of lower distance classes were observed. The integral values are decreasing with an increase of the distance to the forest edge. This decrease saturates at distances between 360-420m, from which on the integrals remain stable.

Appendix C.4. Discussion & Conclusion

Vegetation succession is highly dependent of the availability of seeds (Asner et al., 2004; Uhl et al., 1988). Presumably, higher woody vegetation cover is persistent throughout time in areas with a low distance to forests. Correlation analyses overall showed a weak correlation between distance to forest and metrics. Chronosequences enabled to differentiate the development of vegetative cover for pasture areas in varying distances to forests. The integrals of the median curves suggest a shorter distance to forests contributes to higher vegetative cover which remains over longer periods of time. The integral values are decreasing with increasing distances until the 360-420m distance class.

Nepstad et al. (1996) conducted a detailed study of forest regrowth on an abandoned pasture in Paragominas. The investigated pasture showed a diminished amount of sprouting material, which suggests seed dispersal by wind

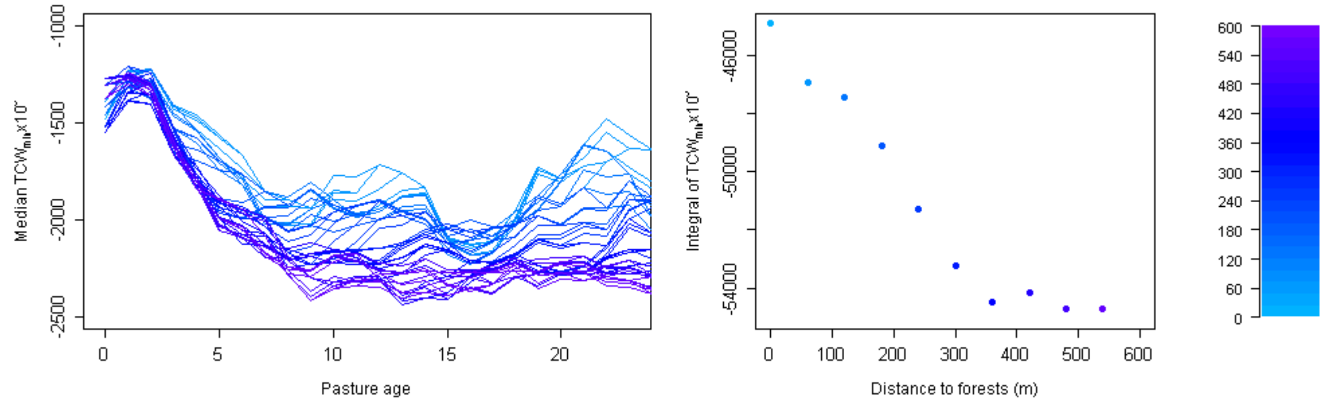

Figure C.11: Chronosequence of the TCW_{min} metric for pastures in proximity to forests (light blue) and more distant to forest borders (purple) (left, curves are smoothed for better visualization using a running mean with k=3). Integrals of chronosequences in dependence to forest proximity (right).

and animals to be mainly responsible for succession of tree species. The author further remarks that only 11% of the forest species are wind-dispersed and for these a maximum distance of 100m is assumed, suggesting a high degree of animal seed dispersal on Amazonian pastures. Birds and bats were found to carry seeds which germinate on pasture areas and despite having a low chance of survival due to destruction by herbivores and ants, contribute to succession on pastures. Since the investigated pasture was abandoned, effects of cattle in the context of animal seed dispersal were not considered in the study. However, the speed and success of regrowth were found to be significantly higher in tree-fall gaps compared to pastures, supporting the findings in the presented research.

Generally, the reliability of the approach suffers from the high number of classes, when stratifying ten distance classes by 25 years of age creates imbalances in sample size of each combined distance/age class. Possibly, this causes the observed drop in chronosequences of high proximity to forests at ages 14-19. Nevertheless, the findings suggest that distance to forest does exert an influence on the behavior of vegetation succession on pastures. Future investigations of regionally contributing factors to woody encroachment on pastures might furthermore investigate size of the pasture or ranch as a factor. Larger paddocks are hard to maintain (Landers, 2007), whereas seed availability is generally reduced due to increased distance to forests. Additionally, terrain might contribute to vegetation succession since clearing is more difficult on slopes.

The spatial stratification of chronosequences by distance to forest edge showed, that pasture areas proximate to forests tend to show elevated values of vegetation cover, which persist throughout the entire chronosequences. It can be assumed, that the factor distance to forest edge contributes to spatial heterogeneity in pasture vegetative structure.

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