Institut für Erd- und Umweltwissenschaften
Arbeitsgruppe Ökohydrologie

The Brazilian Cerrado: Ecohydrological assessment of water and soil degradation in heavily modified meso-scale catchments

Dissertation
zur Erlangung des akademischen Grades
"doctor rerum naturalium"
(Dr. rer. nat.)
in der Wissenschaftsdisziplin Geoökologie/Ökohydrologie

eingereicht an der
Mathematisch-Naturwissenschaftlichen Fakultät
der Universität Potsdam

von
Philip Paul Hunke
aus Marburg

Potsdam, August 2015

Author: Philip Paul Hunke
Email: hunke@posteo.de

Supervisors: Dr. habil. Eva Nora Müller
Referee *University of Potsdam, Institute of Earth and Environmental Sciences, Hydrology*

Prof. Dr. Boris Schröder
Technical University of Braunschweig, Environmental Systems Analysis
Berlin-Brandenburg Institute of Advanced Biodiversity Research

Referee Prof. Dr. Britta Tietjen
Freie Universität Berlin, Institute of Biology, Biodiversity and Ecological Modelling

Referee Prof. Dr. Jose Carlos Araújo
Federal University Ceara, Department of Agricultural Engineering, Ceara, Brazil

Submitted: 05.August.2015
Defended: 27.November 2015

Published online at the
Institutional Repository of the University of Potsdam:
URN urn:nbn:de:kobv:517-opus4-85110
http://nbn-resolving.de/urn:nbn:de:kobv:517-opus4-85110

To my wife Johanna, my son Emil, my parents Bettina and Joachim and my sisters Anna and Ellen.

Acknowledgements

I would like to express my gratitude to all those who have contributed to this thesis.

First, I want to thank my advisors Eva Nora Müller and Boris Schröder.

I would like to thank Eva for giving me the opportunity to work on an inspiring subject, her continuing support und understanding even when progress was slow, for improving my scientific skills and for long and helpful discussions even in her parental leave. She gave me all the scientific freedom one could hope for and placed great trust in me.

I would like to thank Boris for his support and for improving the first drafts of all papers (especially the first one), his valuable comments and availability before deadlines throughout the entire thesis.

I am grateful to Peter Zeilhofer for his warm welcome in Brazil, for the fruitful scientific collaboration at all stages of my dissertation and for friendship beyond academia. Thank you for the scientific and logistic support, but also for introducing me to Brazilian specialities and making possible great trips to Lago Manso, the Chapada, the Pantanal and Florianópolis.

I would like to thank Prof. Jose Carlos de Araújo for taking the time to work through the thesis. Prof. Eliana Dores provided the laboratory for water quality analysis at the University Cuiabá (UFMT). During the stays in Brazil several students of the UFMT supported me. I thank Adelaine Cezar for helping to organise suitable field sites and Roberto Souto, Thatiane Leite, Rebekka Roller and Paulo Goncalves who assisted with the fieldwork for several weeks. Suzy Klemp carried out qualitative interviews with farmers on land management in the catchment and Wagner was the best discussion partner to figure out available geodatabases to parameterize the SWAT model.

Roberto who accompanied me on all of my field stays over the last years became a friend. Thank you for the great time and teaching me Portuguese and introducing me to your family. I am still hoping that he will come to Germany one day to give me the opportunity of giving something back. I thank Gilson for his hospitality and providing me a home in Cuiabá. Very special thanks to the owners of the Fazendas for providing me the opportunity and support to work on their properties. I would like to thank Sophie Bormann who helped me with data preparation and setting up the SWAT-model. A special thanks to Jana for going through the papers.

My gratitude also refers to my colleagues in Potsdam, namely Andreas Bauer, Frank Bäse, Daniel Bazant, Peter Biro, Axel Bronstert, José Miguel Delgado, Thomas Gräff, Maik Heistermann, Mathias Reiche and Florian Stein.

I also want to thank my school friends Basti, Henning, Dennis, Jona, Luke, Malte, Moritz and Timo from Marburg for staying close despite the distance. Our annual “Männer im Wald” meeting is always a highlight.

I am most grateful to my parents and sisters for supporting me in many ways. This doctoral thesis could not be done without the love and patience of my wife and son in that challenging time of life.

The research was financed by the Deutsche Forschungsgemeinschaft (DFG MU2986) and partly supported by the DAAD (German Academic Exchange Service, Grant No. D/11/46339) and the POGS (Potsdam Graduate School). I also thank the anonymous reviewers and Dr. Rossiter (Chapter 3) for their helpful comments on the papers which improved previous versions substantially.

Abstract

The Brazilian Cerrado is recognised as one of the most threatened biomes in the world, as the region has experienced a striking change from natural vegetation to intense cash crop production. The impacts of rapid agricultural expansion on soil and water resources are still poorly understood in the region. Therefore, the overall aim of the thesis is to improve our understanding of the ecohydrological processes causing water and soil degradation in the Brazilian Cerrado.

In order to fulfil the overall aim, I first present an extensive literature review to provide quantitative evidence and to identify the main impacts of soil and water alterations resulting from land use change.

Second, field studies were conducted to (i) examine the effects of land use change on the soils of natural cerrado transformed to common croplands (soybean/cotton/maize rotation and sugarcane) and pasture and (ii) indicate how agricultural production affects water quality across a meso-scale catchment (850 km²). Third, the ecohydrological process-based model SWAT (soil water assessment tool) was tested with different data inputs as well as simple scenario analyses to gain insight into the impacts of land use and climate change on the water cycling in the upscaled, heavily modified upper São Lourenço catchment (7072 km²) which experienced decreasing discharges in the last 40 years.

In a first study, the thesis reviews the history of land conversion in the Cerrado. Soil and water quality parameters from different land uses (cerrado, pasture, croplands and plantations) were extracted from 89 soil and 18 water studies in different regions across the Cerrado. Following the conversion of native Cerrado, significant effects on top-soil pH, bulk density and available P and K for croplands and less-pronounced effects on pastures were evident. Soil total N did not differ between land uses because most of the sites classified as croplands were nitrogen-fixing soybean cultivations, which are not artificially fertilized with N. By contrast, water quality studies showed nitrogen enrichment in agricultural catchments, indicating fertilizer impacts and potential susceptibility to eutrophication. Regardless of the land use, P is widely absent because of the high-fixing capacities of deeply weathered soils and the filtering capacity of riparian vegetation. Pesticides, however, were consistently detected throughout the entire aquatic system. In several case studies, extremely high-peak concentrations exceeded Brazilian and EU (European Union) water quality limits, which pose serious health risks.

Consistent with the findings of the literature review, my second field study revealed that land conversion caused a significant reduction in infiltration rates near the soil surface (0–40 cm depth) of pasture (–96 %) and croplands (–90 % to –93 %). Soil aggregate stability was significantly reduced in croplands than in cerrado and pasture. Topsoil pH and nutrient concentrations were high in croplands and pasture. Soybean crops had extremely high extractable P concentrations (80 mg kg^{-1}; 9 times greater than the natural background), whereas pasture N levels declined. Nutrient accumulation of N and P did not occur at deeper horizons for any land use type which is consistent with the findings of the review study on the entire Cerrado. A snapshot water sampling showed strong seasonality in water quality parameters. Higher temperature, oxi-reduction potential (ORP), NO_2^-, and very low oxygen concentrations (<5 $mg \cdot l^{-1}$) and saturation (<60 %) were recorded during the rainy season. By contrast, remarkably high PO_4^{3-} concentrations (up to 0.8 $mg \cdot l^{-1}$) were measured during the dry season. We found, that water quality parameters were affected by agricultural activities at all sampled sub-catchments across the catchment, regardless of stream characteristics (stream order, percentage of riparian vegetation, sub-catchment size); thus, no spatial patterns were identified. Direct NO_3^- leaching appeared to play a minor role; however, water quality is affected by agricultural non-point sources, due to topsoil fertiliser inputs affecting the entire catchment, from small low order streams to the larger rivers of the modified catchment. The results in this thesis show that land use conversion has degraded soil physical properties, leaving cropland soils more susceptible to surface erosion by increased overland flow events and potential lateral nutrient transport to the stream network.

In a third study, the collected field data were used to parameterise and apply SWAT at the daily and monthly time-steps in the upper São Lourenço catchment. The model was tested with different input data (satellite vs. measured precipitation inputs) and different infiltration approaches (G+A–Green and Ampt vs. CN–Curve Number) and calibrated and validated with SWAT-CUP using the SUFI-2 (Sequential Uncertainty Fitting) algorithm. It turned out that the model parameterisation with satellite-based rainfall data was unsatisfactory due to a large underestimation of streamflow for several years. The G+A approach resulted in a better model performance, but also exhibited incorrect process representations for other primary water components. Therefore, the CN model was judged more reliable to simulate the water balance in the Cerrado. A complete cerrado, pasture and cropland cover was used to analyse the impact of land use on water cycling as well as three climate change projections (for 2039–2058) of various conditions (temperature increase, adjusted precipitation pattern, increased atmospheric CO_2 level of 500 ppm) according to the projections of the RCP 8.5 high emission scenario. The comparison of primary water components of the pasture and crop scenario with a complete cerrado land cover showed that percolation, aquifer recharge and total water yield was reduced by 5 % for croplands and about 11 % for pastures. The actual evapotranspiration (ET) for the cropland scenario was higher compared to the cerrado cover (+~100 mm a^{-1}). Land use change scenarios confirmed that deforestation caused higher annual ET rates explaining partly the trend of decreased streamflow. However, there might also be other factors responsible for the observed decreases in streamflow. The findings also revealed that it is highly relevant how the cerrado vegetation is parameterised because the default forest parameters of the SWAT database might imply an overestimation of ET for the area. The climate change high emission scenarios showed for drier conditions lower discharges with critical dry seasonal water availability when baseflow is the main contributing source. The ET response (–7.5 % to –15 %) is mainly attributed to elevated CO_2 levels. Taking all high emission simulation scenarios into account, the most likely effect is a prolongation of the dry season (by about one month), with higher peak flows in the rainy season. The combined effects of further land use intensification and climate change are uncertain, but both stressors imply higher peak flows in the rainy season. Consequently, potential threats for crop production at the beginning of the crop cycle with lower soil moisture and increased erosion and sediment transport during the rainy season are likely and should be considered in adaption plans.

Land use intensification is likely to continue, particularly in regions where less annual rainfall and severe droughts are projected, for instance in the northeastern and western Cerrado. Thus, the leaching risk and displacement of agrochemicals are expected to increase, particularly because the current legislation has caused a reduction in riparian vegetation. From the three studies of the thesis I conclude that land use intensification is likely to seriously limit the Cerrado's future regarding both agricultural productivity and ecosystem stability. Because only limited data are available for the vast biome, we recommend further field studies to understand the interaction between terrestrial and aquatic systems. This thesis may serve as a valuable database for integrated modelling to investigate the impact of land use and climate change on soil and water resources and to test and develop mitigation measures for the Cerrado in the future.

Zusammenfassung

Das Hauptziel dieser Dissertation ist es, die weit reichenden Umweltveränderungen des Landnutzungswandels auf die Boden- und Wasserdegradierung im Cerrado zu quantifizieren und damit zum ökohydrologischen Prozessverständnis beizutragen. Ökohydrologische Interaktionen in Folge von exzessiver Bodenerosion auf landwirtschaftlich stark modifizierten Flächen können speziell in tropischen Gebieten einen großen Einfluss auf die Fruchtbarkeit und zukünftige Nutzbarkeit der Böden haben, wie dies z.B. im Cerrado geschieht. Der brasilianische Cerrado ist eine neotropische Savanne und durch semiaride bis tropisch gemäßigte Gras-, Strauch- und Waldsavannen gekennzeichnet. Er stellt mit 2 Mio. km² das zweitgrößte Biom Südamerikas dar und wird global unter den bedeutendsten aber auch meist gefährdetsten 25 Biodiversitätshotspots gelistet. Ein extremer Landnutzungswandel führt seit den 1980er Jahren dazu, dass der Cerrado zu den weltweit bedeutendsten landwirtschaftlichen Gebieten zählt und mittlerweile > 50 % des Bioms abgeholzt sind. Durch staatliche Subventions- und gezielte Pflanzenzüchtungsprogramme, Aufkalkung und Düngung der sauren und nährstoffarmen Böden werden mehrere Ernten (v.a. Soja, Mais, Zuckerrohr und Baumwolle und Energieplantagen) pro Jahr bei hohem Ertrag realisiert.

Aufgrund weniger Untersuchungen ist bisher völlig unklar, wie sich die enorme Landnutzungsintensivierung mit dem Einsatz hoher Mengen an Agrochemikalien auf die Boden- und Wasserressourcen auswirkt. Um die Zielsetzung zu erreichen, wurden in einer umfassenden Literaturstudie Boden- und Wasserqualitätsparameter von mehr als 100 Einzelstudien analysiert, mehrere Feldkampagnen zur eigenen Erhebung bodenphysikochemischer und Wasserqualitätsparameter für unterschiedliche Landnutzungen durchgeführt und Modellierungen mit SWAT zur Abschätzung des Landnutzungs- und Klimawandels vorgenommen.

Die Literaturanalyse konnte zeigen, dass Erosion, Veränderungen des Nährstoffkreislaufs, Nährstoffanreicherungen und sehr hohe Pestizidkonzentrationen in den Gewässern des gesamten Cerrado auftreten, mit stärkster Ausprägung für Ackerflächen. Trotz hoher Düngemengen wird für den Cerrado konsistent festgestellt, dass P nur in sehr geringen Konzentrationen in den Gewässern nachgewiesen wird, welches auf die P-Fixierung der Böden und die Filterleistung der Uferrandstreifen zurückzuführen ist. In meiner Feldstudie bestätigen sich die Ergebnisse der Literaturanalyse, dass der Landnutzungswandel zu deutlichen Änderungen der boden-physikochemischen Parameter führt, wie z.B. einer signifikanten Abnahme der hydraulischen Leitfähigkeit (> –90 %) und der Bodenaggregatstabilität. Außerdem werden erhöhte pH-Werte (um ein bis zwei Einheiten) und Überdüngung anzeigende P und K-gehalte im Oberboden (9-fach natürlicher Hintergrund) mit der stärksten Ausprägung unter Soja festgestellt. Die gemessenen Niederschlagsintensitäten überschreiten die Infiltrationskapazität der landwirtschaftlich genutzten Böden, wodurch es zu erhöhtem Oberflächenabfluss, Bodenerosionsereignissen mit Gullyformierungen kommt und der Eintrag von Agrochemikalien in die zuvor pristinen Gewässer begünstigt wird. Verglichen mit natürlichen Gewässern konnten im gesamten Einzugsgebiet niedrigere O_2-Werte (< 5 mg l^{-1}) sowie erhöhte NO_3^- (0.5 mg l^{-1}), NO_2^- (0.1 mg l^{-1}) und in der Trockenzeit auf direkte Düngung zurückzuführende sehr hohe PO_4^{3-} (0.8 mg l^{-1}) Konzentrationen festgestellt werden. Da in den Bodenprofilen keine Tiefenakkumulation von NPK nachgewiesen wurde ist davon auszugehen, dass Dünger durch Oberflächenabflussprozesse in das Flusssystem gelangen. Auch wenn die Nährstoffkonzentrationen nach europäischen Maßstäben gering sind, ist anzunehmen, dass in einem nährstofflimitierten System wie dem Cerrado die um ein vielfach erhöhte Konzentration der natürlichen Hintergrundwerte den Metabolismus der Gewässer negativ beeinflusst.

In einer dritten Studie wird mit dem „Soil Water Assessment Tool“ (SWAT) untersucht, ob dieses weltweit angewandte ökohydrologische Modell im datenlimitierten Cerrado Zentralbrasiliens anwendbar ist und abzuschätzen wie sich der Landnutzungs- und Klimawandel auf die Wasserbilanz auswirkt. In Testläufen zeigt sich, dass sowohl die verwendeten Niederschlagseingangsdaten (gemessen vs. satellitenbasiert) als auch die Vegetationsparameterisierung des natürlichen Cerrados von hoher Relevanz sind, um die Wasserbilanz plausibel zu simulieren. Die Simulation verschiedener Landnutzungsszenarien hat aufgezeigt, dass die im Gebiet beobachteten abnehmenden Abflüsse auf die Zunahme landwirtschaftlicher Produktion und einer damit einhergehenden Zunahme der Evapotranspiration zurückzuführen sind. Von besonderer Bedeutung sind eine ungünstige, über dem globalen Durchschnitt liegende Erwärmung und ein verändertes Niederschlagsregime. Die Simulation extremer Klimaszenarien (RCP 8.5) für die Jahre 2039-2058 verdeutlicht, dass sich die Trockenzeit verlängert, welches Auswirkungen auf die Aussaattermine haben könnte. Gleichzeitig zeigen die Szenarien eine Zunahme der Spitzenabflüsse in der Regenzeit, welches ohne entsprechende Gegenmaßnahmen zu erhöhter Erosion und gesteigertem Nähr- und Schadstofftransport in die Gewässer führt.

Kombiniert mit einer weiteren Landnutzungsintensivierung wird für die zukünftige Entwicklung des Cerrado geschlussfolgert, dass die aufgezeigten Veränderungen des Wasser- und Nährstoffhaushalt durch die Landwirtschaft und die damit einhergehenden Degradierungserscheinungen die Produktivität und Ökosystemstabilität nicht dauerhaft gewährleisten werden können und das Biom ein nachhaltiges Flußgebietsmanagement benötigt. Die vorliegende Dissertation liefert einen zentralen Beitrag zur ökohydrologischen Bewertung des Status quo und der zukünftigen Entwicklung des brasilianischen Cerrados. Sie kann einen Ausgangspunkt für weitere Forschungen und Modellierungen darstellen, um die in dieser Arbeit benannten offenen Fragen hinsichtlich der ökohydrologischen Interaktionen zu klären.

Contents

1 General Introduction and objectives

1.1 The Brazilian Cerrado, a forgotten Biome?

The Brazilian Cerrado, the second-largest biome in South America, has experienced excessive and continuous expansion of agriculture over the last 30 years, whereby the natural savannah has been replaced by monocultures of soybean, sugar cane, corn, coffee, and cotton (cash crops), as well as by energy plantations and pastures (Marris 2005; Klink and Machado 2005; Sano *et al.*, 2008; Sano *et al.*, 2010; Redo *et al.*, 2012; Grecchi *et al.*, 2013). The current increase in crop production in Brazil has been concentrated in the Cerrado region (La Rovere *et al.*, 2011) and the adjacent transitional and forest ecosystems. Today, the Cerrado is considered Brazil's most threatened biome (Sano *et al.*, 2010). By the end of the 1990s, the natural Cerrado vegetation retained only 50 % of its original extent (Machado *et al.*, 2004) (Figure 1-1). Since the revision the Forest Code (Government of Brazil, Law No. 12.727) in 2012, it is even easier to convert native vegetation outside the Legal Amazon (encompassing 9 states; Marris, 2005; Sparovek *et al.*, 2012). Machado *et al.,* (2004) estimated that the natural Cerrado outside of protected areas may disappear by 2030. Current deforestation rates of the Cerrado as given by the FAO (Food and Agriculture Organisation) (2009) are highly variable, but confirm this trend. The accelerated expansion of agricultural activities has led to a significant increase in crop yields and economic wealth in the region over a short time, but it has also contributed to serious environmental problems associated with soil degradation, water shortages, pesticide contamination and increasing costs to control pests and diseases (Lopes *et al.*, 2004; Martinelli *et al.*, 2010; Schiesari and Grillitsch 2011; Schiesari *et al.*, 2013).

In the scientific literature, many ecological studies focus on singular taxonomic groups or endemic species (Nogueira *et al.,* 2011; Zimbres *et al.,* 2013; Carmignotto *et al.,* 2014). Studies on the impacts of rapid agricultural expansion on soil and water degradation and the functioning of coupled hydrological and ecological processes in this vast biome, which is three times the size of France, are surprisingly rare (but see Haridasan 2001; Review on knowledge gaps by Ferreira *et al.*, 2012; Grecchi *et al.*, 2013). The Cerrado experienced an even more dramatic change regarding ecosystem function and use; meanwhile, the severity of this change is less recognised than that of the Amazon (Sawyer 2008; Janssen and Rutz 2011; Barreto *et al.*, 2013), even though the deforestation rate in the Cerrado was twice as high as in the Amazon Basin between 2008 and 2010 (Lambin *et al.*, 2013). Findings relating to environmental changes resulting from Amazonian deforestation are unlikely to be transferable to the Cerrado due to the dissimilarity of the environmental and climate conditions of the two biomes (Figure 1-1).

Impact studies on how current and future land use intensification affects land and water resources are pivotal to assess the Cerrado's potential for the continued provision of its ecosystem services. Available hydrological, ecological and soil studies merely focus on a singular aspect of the ecosystem (e.g., the studies by Eiten 1972; Lopes and Cox 1977a; Goedert 1983; Hoffmann 1996; Klink and Machado, 2005). Several studies have demonstrated the effects of increasing agriculture in the Cerrado, but most have focused on specific aspects of land use change (e.g. pesticide transport: Laabs *et al.*, 2000; soil fertility change: Lilienfein *et al.*, 2003; change in soil organic carbon content: Corbeels *et al.*, 2006; micro-aggregation of one soil type: Balbino *et al.*, 2002; tillage effects on soil biological activity: Green *et al.*, 2007). Other studies have assessed natural Cerrado soils (Goedert, 1983; Lopes and Cox, 1977) or focus on how to increase soil productivity, rather than investigate the negative impacts of land modification (de Sousa and Rein, 2011; Fageria *et al.*, 2014).

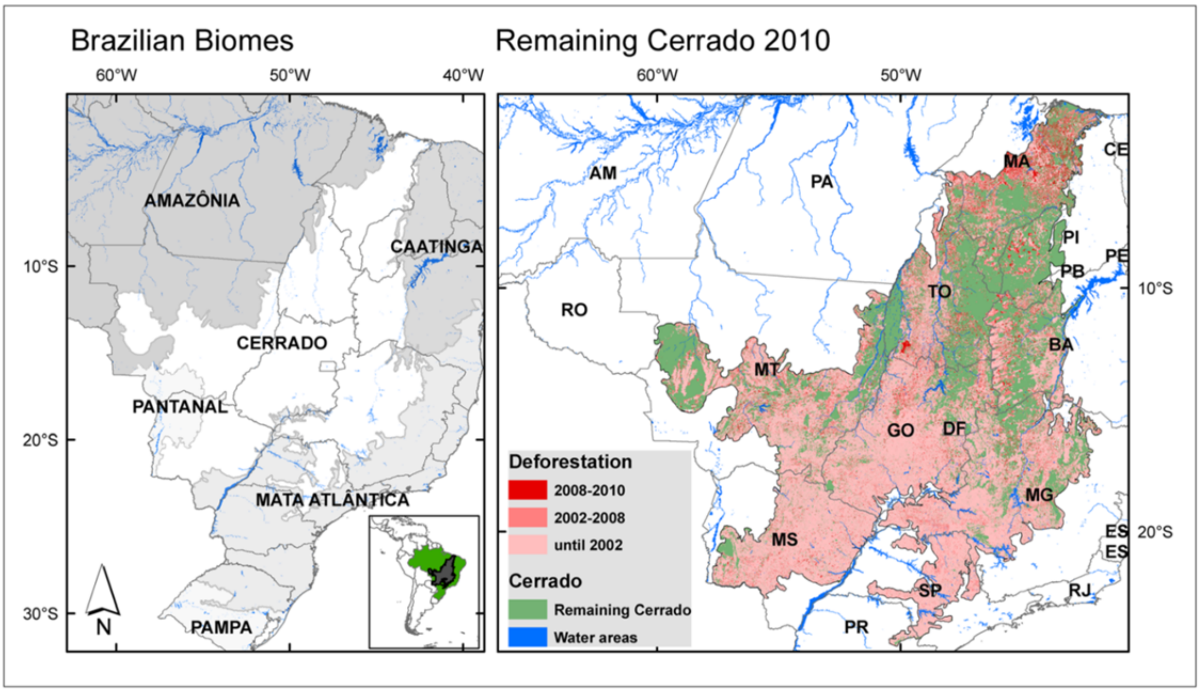


Figure 1-1: The Brazilian biomes and remaining Cerrado with deforestation areas up to 2002, 2002–2008 and 2008–2010 (data sources: IBAMA, Ministério do Meio Ambiental (MMA 2013))

The review study by Klink and Machado (2005) focused on the biodiversity aspects of land use change and stated that increased soil erosion and poor water quality are major threats for the conservation of the ecosystem. A large number of field case studies over the last 10 to 30 years investigated mechanisms of land use change on soil or water parameters at different sites (e.g., Carvalho *et al.*, 2007; Dores *et al.,* 2008; Gücker *et al.*, 2009; Silva *et al.*, 2010; Torres *et al.*, 2011), but no study has compiled and integrated these results to provide a comprehensive understanding of the state of land and water degradation phenomena due to land use change in the Cerrado. Specifically, the changes in soil hydraulic and biogeochemical properties of agricultural fields compared with natural Cerrado regions and the degree of nutrient and pesticide contamination in adjacent surface waters have not been quantified for different land uses. Therefore, it is rather unclear if and how soil and water resources of the Cerrado are already negatively impacted and how the entire region is likely to develop under current and future land use intensification as well as climate change.

1.2 Aim, key research questions and objectives

The overall aim of the thesis is to improve our understanding of ecohydrological processes causing water and soil degradation in the Brazilian Cerrado biome which has experienced an excessive expansion of agriculture. As noted above, many studies focus on one aspect of water or land degradation, but no coherent overview of the impacts of the rapid agricultural expansion exists for the entire Cerrado. There is also only a very limited database on soil-hydrological properties of regions under heavily modified land-use. And currently, there are no tools available which would allow for a catchment-scale quantification and prognosis of water and land degradation. To overcome these limitations, I employ a three-method approach:

- Literature review with an in-depth assessment and analysis of water and soil degradation in heavily modified catchments in the Brazilian Cerrado
- Field study to quantify soil and water degradation under different land uses in a meso-scale catchment in the Cerrado of Mato Grosso, Brazil.
- Modelling study to assess past and future effects of land-use change on the runoff regime of a meso-scale Cerrado catchment.

In order to fulfil the aim of this thesis and to tackle the three specific research aspects, the key research questions and objectives of this thesis have been identified as follows:

Objective 1: Assessment and analysis of water and soil degradation in heavily modified catchments in the Brazilian Cerrado.

- The key research questions for characterizing water and land degradation of the *entire* Cerrado are:
- To what degree does land use change influence soil and water properties and functioning in the Cerrado?
- What main impacts on soil and water resources can be highlighted?
- How good is the data availability for water and soil resources?
- How is the Cerrado likely to change under future land use and climate change?

The research questions are addressed by the following objective:
The Brazilian Cerrado, the second-largest biome in South America, has experienced an excessive and continuous human-induced expansion of agriculture over the last 30 years. The natural savannah has been replaced by monocultures of soybean, sugar cane, and cotton (cash crops), as well as energy plantations and pasture. Several comprehensive soil studies from the 1970s and 1980s (e.g., Lopes and Cox 1977a,b; Goedert 1983) study the natural Cerrado, but no recent complete soil review for the Cerrado investigates the effects of land use change on soil properties and functioning.
The goal of the review study is to give quantitative evidence how the water and soil resources of the Cerrado ecosystem have been altered under heavily modified land use. This thesis reviews the literature on environmental stressors regarding past and projected human land use and climate change. This gives a comprehensive review of available field studies of the Cerrado that investigate the impact of different land uses (crop, pasture and energy plantation) on soil-hydraulic and biogeochemical properties and changes to the quality of surface and groundwater for nutrients and pesticides. The compilation attempts to give a starting point to determine the change of soil and water resources in the Cerrado under stress by identifying the current impacts of land use change.

Objective 2: Quantification of soil and water degradation under different land uses in a meso-scale catchment in the Cerrado of Mato Grosso, Brazil.

More specific research questions to understand the dynamics and processes on the plot and meso-scale agricultural used catchments are:

- What is the effect of different agricultural land uses on soil physical and chemical properties in the Cerrado?
- To what degree do agricultural activities affect water quality?
- How do soil changes affect hydrological flow paths and water quality?
- Are there any spatial and seasonal patterns of water quality evident?

These questions are addressed by Objective 2:

The goal of the field study is to assess in the field how land use change from natural Cerrado to agricultural production that emerged during the last 30 years has affected soil physical, hydrological and biogeochemical properties and processes on the hillslope scale and subsequently water quality on the meso-scale. Specifically, it is aimed to examine (1) the effects of changes in land use from natural Cerrado to planted pasture, soybean-cotton rotation, and sugarcane on a range of parameters (soil aggregate stability, infiltrability, saturated hydraulic conductivity, pH, and soil nutrients [NPK]) and (2) to provide insights into the processes by which agricultural production affects water quality, by examining the seasonal patterns in water quality parameters across a heavily modified catchment. We hypothesise that an increase in soil nutrient concentrations, due to the extensive fertilisation of agricultural land, is correlated with increased nutrient concentration in streams across altered meso-scale catchments, especially in the rainy season.

Objective 3: Ecohydrological modelling to assess past and future effects of land use and climate change with SWAT (Soil Water Assessment Tool)

The main research questions to improve process understanding in the Cerrado by using the ecohydrological model SWAT are:

- Can SWAT be applied successfully in the Cerrado?
- How meaningful are the model results when using different driver inputs? Where are the limitations?
- What is the impact of land use and climate change on the primary water components in the upper São Lourenço catchment?
- Can SWAT help to explain with simple land use scenarios why the discharges have decreased in the last 40 years in the study area?

To answer these questions Objective 3 of this thesis is formulated as follows:

The main goal of the modelling study is to test the ecohydrological process-based model SWAT in data-sparse areas of the Cerrado. For performance testing of SWAT, different input data (satellite precipitation data vs. measured) and infiltration approaches in the upper São Lourenço catchment are considered. Applying SWAT, this chapter will quantitatively determine the primary water balance components in order to investigate the observed reduction in discharges and provide insight into how land use change and climate change impact the water balance (viz. disrupt the water cycle). The specific objectives are:

(1) to test the applicability of the SWAT model in a savannah watershed of Brazil,
(2) to test different weather input data and infiltration methods for SWAT modelling.

However, assuming a satisfactory working model, SWAT is applied for simple scenario simulations of land use change and climate change. It is intended to:

(3) explore the impacts of land use changes (LUC) on discharge, ET and soil water storage, and
(4) to simulate the impacts of climate change (CC) on components (Q, ET, SW) of the water balance.

1.3 Introduction to the study sites

The central geographical position in South America gives the Cerrado Biome importance to environmental change as it connects the major biomes and covers the headwater areas of the largest watersheds in Brazil (Figure 1-2). Especially the federal state of Mato Grosso is heavily affected by landscape scale conversion, and has the highest deforestation rates in Brazil for conversion to pastures and cash crops (Sano *et al.*, 2010). The focus area of this thesis lies on the Planalto (Brazilian high plains) of the Cerrado of Mato Grosso, which represents the agricultural activity on the dominating well drained Latosols (Ferralsols). Almost all of the Latosols of the high plains in that area are subject to agricultural use for intensive cash crop production.

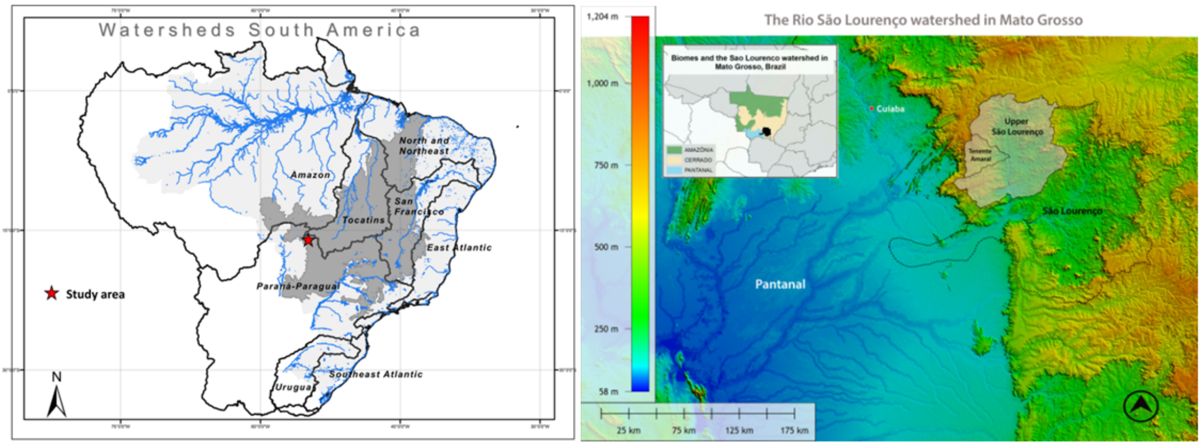


Figure 1-2: The main watersheds of South America (left) and the São Lourenço study area draining into the Pantanal floodplain of Mato Grosso (right).

The upper São Lourenço catchment (~7000 km²) is situated ca. 120 km southeast of the capital Cuiabá in Mato Grosso. For the application of SWAT (Chapter 4) the catchment is well suited because it combines different geophysical and geoecological characteristics of the Cerrado to study the effects of land conversion for agriculture. It covers a wide range of different soil types and vegetation formations of the Brazilian Cerrado and streamflow validation data are available. The river São Lourenço drains the Brazilian highlands as a major feeder of the Pantanal. The climate type is classified as Aw according to the Köppen classification, with a distinct dry season between May and September. Mean annual precipitation is 1500 mm, of which about 80 % falls as heavy rain from October to April. Also low-order streams in the area never dry up. However, in the last 40 years, the flow of the Rio São Lourenço and tributaries have decreased and it remains unclear if the loss of natural vegetation has caused these flow alterations.

Figure 1-3: The Tenente Amaral catchment with soybean production on the high plains (above) and the main stream with natural riparian vegetation (lower left). The typical cerrado vegetation (lower right).

In a nested approach field campaigns were conducted in the Tenente Amaral sub-catchment. The study area is situated on the Planalto and gives an excellent opportunity to work on agricultural fields which are cultivated under economic considerations by optimising yields of various crop rotations (mainly soybean, maize, sugarcane and cotton) and planted pastures (Figure 1-3). Additionally, the land owners gave us the permission to install measurement plots and to take water samples even at times of harvest; thus, giving us realistic ("real-world") insights into the impacts of mechanised agriculture. In the early 1990s, studies looked at stream valley systems and physical pollution in the same catchment (Wantzen 2006, Wantzen *et al.,* 2006) – we build on this valuable information.

A detailed description of the upper São Lourenço catchment can be found in Chapter 2.1 and the Tenente Amaral sub-catchment sampling sites are described in Chapter 3.2.

1.4 Overview of the thesis

In line with the objectives, the thesis can be roughly divided into three main parts (Chapters 2, 3 and 4). A multi-methods approach by conducting a comprehensive literature analysis, collecting different field data and performing process-oriented modelling is used to gain insight into the ecohydrological interactions of the Brazilian Cerrado. In each chapter, the impact of land use change on soil and water resources is addressed. However, they all use a different approach as illustrated in Figure 1-4.

Chapter 2 comprises a comprehensive review of available field studies on the Cerrado that investigate the impact of different land uses (crop, pasture and energy plantation) on soil-hydraulic and biogeochemical properties and changes in the quality of surface and groundwater for nutrients and pesticides. After providing a detailed account of the geophysical characteristics of the natural savannah system, a review of the environmental stressors regarding past and projected human land use activities and climate change is conducted. The synthesis of existing field data attempts to offer a starting point for determining the changes in soil and water resources in the Cerrado that are under stress by identifying the current and future impacts of land use change.

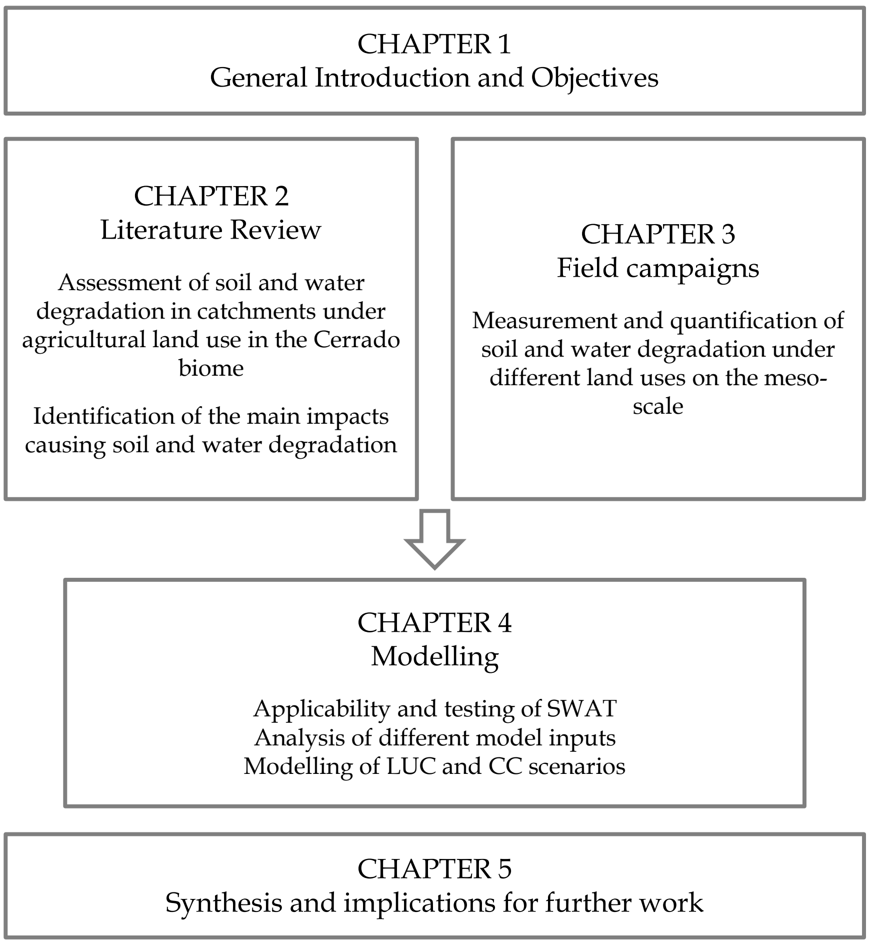


Figure 1-4: Overview of the thesis.

Chapter 3 considers the problem of lacking data on the quantification of soil and water degradation. A field study on the impact of different land uses on soil physical and chemical properties as well as on water quality is carried out in a meso-scale intensively agriulturally used catchment. The collected data are a substantial prerequisite to enable the parameterisation of the ecohydrological model SWAT.

Therefore, Chapter 4 considers whether the ecohydrological model SWAT can be applied successfully in the Cerrado environment. The model is tested with different input data and infiltration approaches to assess whether the model is performing satisfactorily predicts runoff volumes with the appropriate calibration. Land use change and climate change scenarios are used to simulate the primary water components. These scenarios can be contrasted to the observed reduction in streamflow.

Finally, Chapter 5 provides a general conclusion and outlines interesting directions for further research.

1.5 List of publications

During my Phd-studies the following article and book chapters were published:

Hunke, P., Roller, R., Zeilhofer, P., Schroeder, B, Mueller, E.N. 2015. Soil changes under different land-uses in the Cerrado of Mato Grosso, Brazil. Geoderma Regional. (4) 31–43.

Hunke, P., Mueller, E.N., Schroeder, B., Zeilhofer, P. (accepted). The Brazilian Cerrado: assessment of water and soil degradation in catchments under intensive agricultural use. Ecohydrology. 2014. DOI 10.1002/eco.1573. early view.

Müller E.N., van Schaik N.L.M.B., Blume T., Carus J., Fleckenstein J., Fohrer N., Geißler K., Gerke H.H., Graeff T., Hesse C., Hildebrandt A., Hölker A., Hunke P., Körner K., Lewandowski J., Lohmann D., Meinikmann K., Schibalski A., Schmalz B., Schröder B., Tietjen B. 2014. Skalen, Schwerpunkte, Rückkopplungen und Herausforderungen der ökohydrologischen Forschung in Deutschland / Scales, topics, feedbacks and key challenges of ecohydrological research from a German perspective. Hydrologie & Wasserbewirtschaftung (HYWA). 58 (4), 221–240.

Couteron P., Hunke P., Bellot J., Estrany J., Martinez N., Mueller E. N., Papanastasis V., Parmenter R. R., Mohutair H., Wainwright J. Characterizing patterns, Book chapter in Mueller, E.N., Wainwright J., Turnbull L., Parsons A.J. 2014. Patterns of land degradation in drylands: Understanding self-organized ecogeomorphic systems. 211–245, Springer, Utrecht

2 Assessment of water and soil degradation in heavily modified catchments in the Cerrado biome – A review

Abstract:

The Brazilian Cerrado is recognized as one of the most threatened biomes in the world, as the region has experienced a striking change from natural Cerrado vegetation to intense cash crop production. This paper reviews the history of land conversion in the Cerrado and the development of soil properties and water resources under past and ongoing land use. We compared soil and water quality parameters from different land uses considering 89 soil and 18 water studies conducted in different regions across the Cerrado to provide quantitative evidence of soil and water alterations from land use change. Following the conversion of native Cerrado, significant effects on soil pH, bulk density and available P and K for croplands and less-pronounced effects on pastures were evident. Soil total N did not differ between land uses because most of the sites classified as croplands were nitrogen-fixing soybeans, which are not artificially fertilized with N. In contrast, water quality studies showed nitrogen enrichment in agricultural catchments, indicating fertilizer impacts and potential susceptibility to eutrophication. Regardless of the land use, P is widely absent because of the high-fixing capacities of deeply weathered soils and the filtering capacity of riparian vegetation. Pesticides, however, were consistently detected throughout the entire aquatic system. In several case studies, extremely high-peak concentrations exceeded Brazilian and EU (European Union) water quality limits, which were potentially accompanied by serious health implications. Land use intensification is likely to continue, particularly in regions where less annual rainfall and severe droughts are projected in the northeastern and western Cerrado. Thus, the leaching risk and displacement of agrochemicals are expected to increase, particularly because the current legislation has caused a reduction in riparian vegetation. We conclude that land use intensification is likely to seriously limit the Cerrado's future regarding both agricultural productivity and ecosystem stability. Because only limited data are available, we recommend further field studies to understand the interaction between terrestrial and aquatic systems. This study may serve as a valuable database for integrated modelling to investigate the impact of land use and climate change on soil and water resources and to test and develop mitigation measures for the Cerrado.

2.1 Geophysical characteristics and vegetation formation

The Cerrado biome is a neotropical savannah that comprises ca. 2 million km². The area is the second-largest biome in South America, after the Amazon. The Cerrado region includes parts of 11 Brazilian federal states and extends from the equator to the Tropic of Capricorn (Figure 1-1).

According to the Köppen classification, the Cerrado exhibits a typical Aw climate (humid tropical savannah) with a distinct dry season between May and September. The temperature and precipitation varies with latitude (south-north) and altitude, which ranges between 300 and 1800 m a.s.l. The annual average rainfall and evapotranspiration rates in the wet season are 750–2000 mm and 900–1100 mm, respectively. More than 80 % of the precipitation falls in the rainy season between November and April, and the smallest amount falls in the north-eastern part of the biome (Cochrane and Jones, 1981; Oliveira-Filho and Ratter 2002). The rainfall erosivity increases from east to west (Oliveira *et al.*, 2013). Dry spells of one to three weeks, which are associated with high evapotranspiration rates (5.8 mm d^{-1} Oliveira *et al.*, 2005), frequently occur during the rainy season. The runoff regime is driven by rainfall, with a marked difference in discharge between the dry and wet seasons (Figure 2-1).

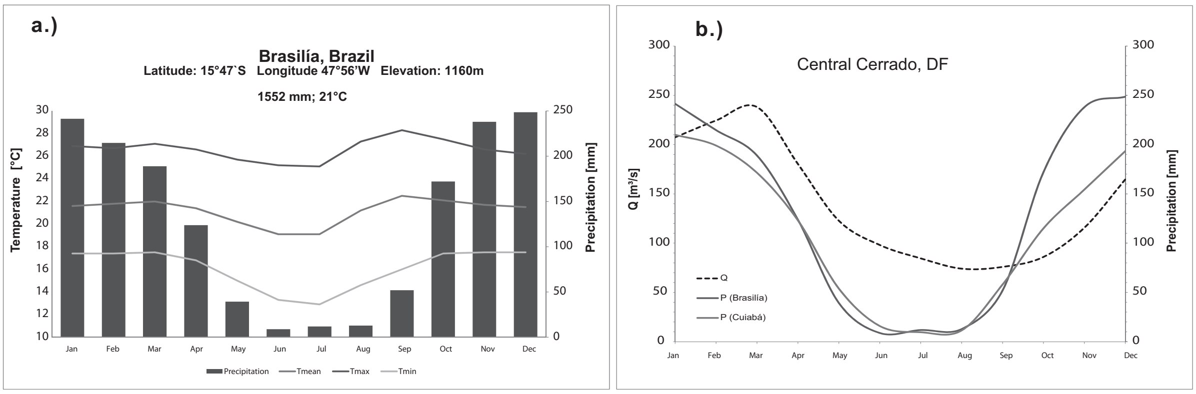


Figure 2-1: Climate chart of Brasília (a.)) and runoff (Q) of the São Lourenço River, Mato Grosso (catchment area of 5,407 km² averaged over time period 1965–2006) with monthly precipitation from Cuiabá and Brasília (b.)).

The Brazilian Cerrado savannah is a complex neotropical plant community (Pinheiro and Monteiro 2010). The savannah ecosystems have an unusually high level of endemism, complex habitats and a high ß-diversity (Olson and Dinerstein 2002); thus, it is ranked among the 25 most important terrestrial biodiversity hotspots (Myers *et al.*, 2000). The area is characterised by scattered trees and shrubs, small palms and a ground layer of grasses (Quesada *et al.*, 2008). The natural Cerrado ranges from deeply rooted savannah woodlands (*cerradao*, dense-forest type, 8–15 m tall, and a completely closed canopy), progressively less arboreal formations (*cerrado sensu stricto* and *campo cerrado*, closed scrub, and more scattered trees, 5–8 m tall), to nearly treeless grasslands (*campo sujo* and *campo limpo*) (Eiten 1972; Ribeiro and Walter 1998; Furley 1999). The persistence of patchy vegetation patterns seems to be related to the different phenological adaption strategies due to complex interactions of climatic conditions during the wet and dry seasons, soil properties and the re-occurrence of wild fires (but see Ferreira and Huete 2004; Miranda *et al.*, 2009; Pinheiro and Monteiro, 2010). The rainfall variability strongly influences the composition of the Cerrado vegetation, whose herbaceous component is during the dry season dead or dormant until the next wet season (Quesada *et al.*, 2008); the dormancy also maintains regeneration after fires (De Castro and Kauffman 1998). Tree density and diversity is related to spatial and temporal variations in water table depth (groundwater) than to soil and groundwater nutrient variations (Villalobos-Vega *et al.*, 2014). Because the woody vegetation has access to soil moisture in deeper soil layers during the dry season, these species' expand their leaves, flower, and fructify during the dry season (Meinzer *et al.*, 1999; Oliveira and Gibbs 2000). Frequent fires in the dry season play a fundamental role in balancing the shrub-grass-tree composition: unrestricted fires reduce the woody component of the vegetation and increase the density of the herbaceous layer, whereas fire elimination has the opposite effect (Coutinho 1990). Because the Cerrado vegetation has highly variable nutrient resorption capacities, the dependence on soil nutrients is lowered (Vourlitis *et al.*, 2014).

Cerrado soils are among the oldest on Earth. The soils are mainly derived from the Brazilian shield (Marques *et al.*, 2004; Zinn and Lal 2013), and they are deeply weathered (up to 50 metres or more) and well drained. The landforms include flatlands and plains, hilly areas and high plateaus (Silva *et al.*, 2006).

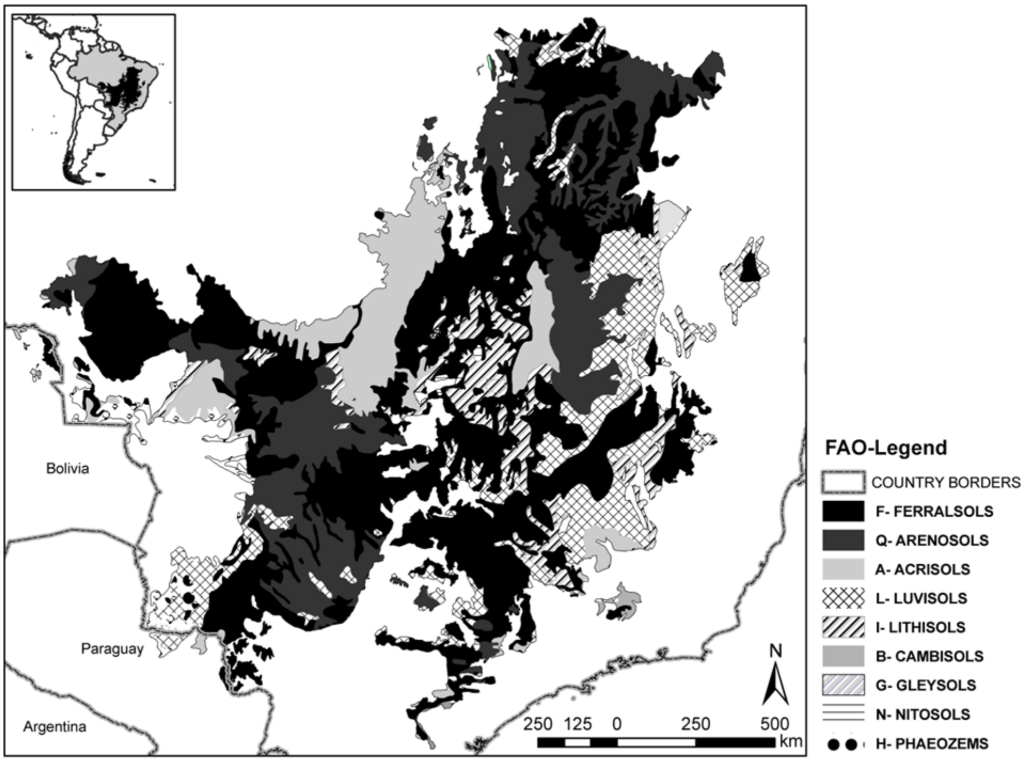


Figure 2-2: Distribution of the main soil types in the Cerrado region (derived from the digital FAO-UNESCO Soil Map of the World, FAO-UNESCO 2003)

Approximately 50 % of the soils are Ferralsols according to the FAO classification (Latosolos in the Brazilian soil classification and Oxisols in the USDA– United States Department of Agriculture taxonomy), while 21 % are Arenosols and 12 % are Acrisols, which seriously limit crop production because of their very low natural soil fertility (see Figure 2-2 for the spatial extent). The soils are acidic and have low nutrient availability (Lopes and Cox 1977a; Lopes 1996; Lopes *et al.*, 2004). The total P content for typical Ferralsols is 250–350 mg kg^{-1} soil, whereas the available P is much lower (Goedert 1983). Lopes and Cox (1977a) found a median concentration of available P of 0.4 mg kg^{-1}, whereby more than 92 % of their samples exhibited values less than 2 mg kg^{-1}. The soils have a low effective cation exchange capacity (ECEC < 1.5 $cmol_c$ kg^{-1} clay), high aluminium (Al) saturation (Lopes and Cox 1977a) and high P fixation capacities (Ayarza *et al.*, 2007). The soils of the Cerrado are normally not prone to crusting or compaction, and they exhibit a good soil structure for satisfactory crop growth (Goedert 1983). These soils, including the clayey varieties, are characterised by low a water-holding capacity. The limited rooting depth of many crops is suggested to be a function of Al toxicity and/or Ca and Mg deficiency in subsurface soil layers (Lopes 1996; Joris *et al.*, 2012).

Low soil pH values, deficiency in plant-essential soil nutrients (e.g., P), adverse soil chemical conditions for root growth, low soil-water retention capacity, and extended dry spells during the rainy season have been detrimental to crop growth (Oliveira *et al.*, 2005). To remove the low soil fertility as a limiting factor for crop production, the land was excessively limed (Yamada 2005), which increased the soil pH by up to 0.25 pH-units per year (Carvalho *et al.*, 2009). Breeding tropically adapted cash crops, applying agrochemicals, and liming practices greatly improved the soil conditions to intensify agricultural land use in the Cerrado (Lopes 1996; Roscoe and Buurman 2003; Jepson *et al.*, 2010).

2.2 Environmental stressors

2.2.1 Land use change (human stressors)

Cerrado in Portuguese translates as ‘closed’ or ‘dense’, and until the 1970s the Cerrado region was considered to be rough, inaccessible terrain. Before the mid-1970s, the Cerrado was characterised by a low population density. Cattle ranching and some subsistence agriculture were concentrated in the most fertile soils along the rivers (Ayarza *et al.*, 2007; Jepson *et al.*, 2010). The transfer of the Brazilian capital to Brasília in the 1960s and the construction of roads and railways contributed significantly to the region’s development. During the 1970s, occupation of this area was encouraged by the Brazilian government through the PROÀLCOOL Programme, POLOCENTRO, and the PRODECER Development Projects (Pires 2000; Soccol *et al.*, 2005; Ayarza *et al.*, 2007; Ferreira and de Deus 2011; Pereira *et al.*, 2012). These programs led to an expanding deforestation and occupation of the Cerrado (Jepson *et al.*, 2010; Grecchi *et al.*, 2013) to use it both for grazing and crop production (Marris 2005).

In the 1990s, the amelioration of subsoil acidity led to a release of phosphate and sulphate from Al/Fe-hydroxides, thus increasing soil fertility (Joris *et al.*, 2012). The implementation of adapted crop rotation and intercropping with legumes for fixing atmospheric nitrogen increased progressively (Lopes 1996; Mattsson *et al.*, 2000). The Brazilian Agricultural Research Corporation (EMBRAPA: Empresa Brasileira de Pesquisa Agropecuária) led the breeding of tropical crops (see Lopes *et al.*, 2012). They improved tolerance against dry climate and acid soil conditions (FAS, Foreign Agricultural Service, USDA 2003) and significantly reduced the growing period. For example, they cut eight to twelve weeks off the usual life cycle of soybeans. This now allows double or even triple cropping per year, with the potential to increase soybean yield from 3 t/ha to 5 t/ha (FAS-USDA, 2003). Brazil’s planted area for soybeans increased to 30 Mha in 2013 with simultaneously increased productivity which resulted in a production of 90 million tons of soybeans per year (Figure 2-3). Genetically modified crops are also widely used. In 2012, 71 % of Brazil’s total soybean growth of was genetically modified (Marinho *et al.*, 2012) making Brazil the second-largest producer of genetically modified crops (Melo *et al.*, 2010). The Cerrado is now among the world's top regions for the production of soybeans (IBGE 2013, Smaling *et al.*, 2008; Batlle-Bayer *et al.*, 2010).

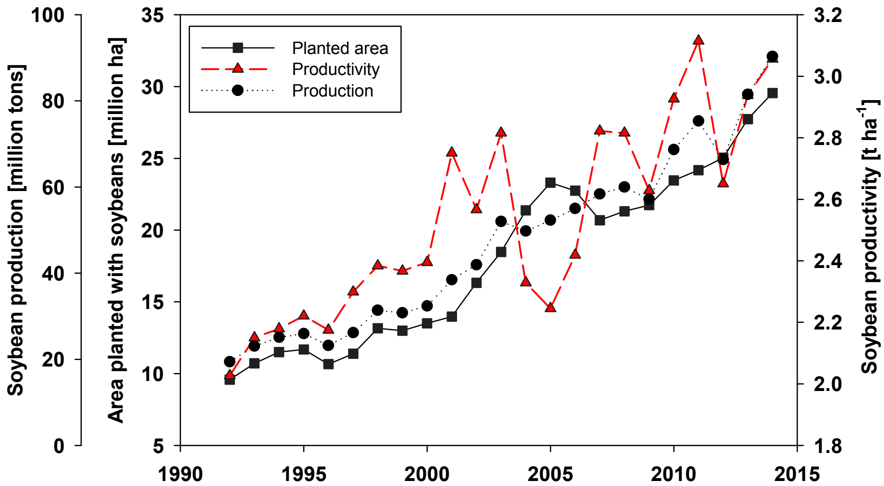


Figure 2-3: Soybean production, productivity and area planted for soybeans in Brazil (calculated with data of Conab 2015).

For the years 2008–2010, deforestation rates were more than twice as high as in the Amazon basin (Sawyer 2008; Lambin *et al.*, 2013). Only 2 % of the biodiversity hotspot regions are preserved in strictly protected areas (after World Conservation Union Categories I to III) (Myers *et al.*, 2000; Jepson 2005; Klink and Machado 2005; Silva *et al.*, 2006). The conservation effort in the Cerrado is always secondary to that in the Amazon (Barreto *et al.*, 2013), and deforestation is easier realisable (Mittermeier *et al.*, 1999; Klink and Machado 2005; Sparovek *et al.*, 2010) as the new Forest Code (Government of Brazil 2012, Law No. 12.727/2012) implies reductions of legal requirements for both permanent protection areas (PPA) and legal reserve areas (LRA). Important changes include the exclusion of the PPA-class ''hill tops'' and the reduction of buffer strips for small rivers. On private land in the Cerrado regions outside the Legal Amazon Region a reduction of LRA to 20 % is allowed, as opposed to only 35 % of allowed clear-cutting after the legislation until 2012 (Sparovek *et al.,* 2012; Stickler *et al.*, 2013). In the Amazon Basin, in contrast, 6 % of the area is strictly protected, and an additional 17.7 % is preserved as indigenous lands (Klink and Machado 2005).

The rapid agricultural development is being enhanced by infrastructure developments in the formerly remote areas (Rada 2013). The construction of the transregional BR-163 highway from Cuiabá, capital of Mato Grosso in the western Cerrado, to the most important industrial harbour of the Amazonas River in Santarem, for instance, opens up an export corridor for cash crops to international markets (Fearnside 2007)

Projections of future land use show that the trend towards intensive agricultural use is likely to continue for the entire Cerrado region (Janssen and Rutz 2011). Soares-Filho *et al.*, (2004) developed a land-cover change model estimating that until 2036 the total forested area in the region will decline by 35 % for the scenario with high population growth and by 13–16 % for governance scenarios. Projecting deforestation trends until 2050, Ferreira *et al.,* (2012) estimate an increase in deforested areas of 13.5 % which is 40,000 km² per decade mainly in the states Bahia, Maranhão, Mato Grosso and Tocantins. Moreover, Soares-Filho *et al.,* (2014) found that the revision of the Brazilian Forest Act (Sparovek *et al.,* 2012) will allow additional deforestation in the Cerrado. As much as 600,000 km² unprotected vegetation could be converted according to the current legislation (reviewed by Lambin *et al.*, 2013).

2.2.2 Climate Change

The climate of the Cerrado region is controlled by the inter-tropical convergence zone (ITCZ) and the South Atlantic convergence zone (SACZ). The South Atlantic monsoon system occurs east of the Andes, with precipitation maxima in the convergence zones in summer. The monsoon season is influenced by the El Niño Southern Oscillation (ENSO) (IPCC 2013; WG1).

Past and future climate trends for the Cerrado are available through trend analysis of the SREX region VII covering the upper-central part of South-America (SREX: Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation, SREX region numbering according to IPCC-WG1 report, 2013). Furthermore, projections with regional models are available through the studies conducted by Marengo *et al.,* (2009, 2010).

Past climate trends across central and northern Brazil show a general temperature increase at a rate of 0.08 to 0.2 °C per decade; opposite trends regarding precipitation range between –50 % and +20 % of the annual rate over the last 50–100 years (IPCC 2007a, WG1). In the southern Amazon, the mean temperature increased by 0.08 °C per decade during 1901–2001. During 1948–1999, the precipitation trends exhibited changes between –23 % and +18 % (Marengo 2004). The IPCC (2013, WG1) reports an increased occurrence of extreme rainfall events, but the lack of long-term records make robust trend analysis impossible (Liebmann and Mechoso 2011). However, Assad *et al.,* (1993) analysed 100 rainfall stations over a minimum of 20 years (1940–1970) across the Cerrado to identify a return period of 10–30 consecutive dry days during the rainy season. The authors found that for a 5 year return period, 25 days without rainfall occurred in the states of Piauí, South Maranhão, and the northern Minas Gerais. In contrast, Mato Grosso, Goiás, and the triangle of Mineiro showed shorter dry spell lengths of 10 days. Carvalho *et al.,* (2013) repeated the analysis with a time series of 70 years and provided evidence for the intensification in the dry spell length. For the Midwest region, dry spells of 5–25 days were observed with a one-year return period and 40–50 days without rainfall were observed for return periods of 4 to 5 years. In addition, in the last 30 years, El Niño (ENSO) has occurred more often in the southern Amazon Basin and has resulted in an increased susceptibility of wild fire occurrence (Nepstad *et al.*, 2004). However, La Niña has also increased due to climate change and has caused natural wildfires in the wet season via lightning strikes, which doubled between 2005 and 2008 (Pivello 2011).

Future predictions of temperature trends for the large SREX regions comprising the Cerrado, as derived by a set of 42 global models (CMIP5), estimate a temperature increase of 0.5 –1.8 °C by 2035 (2016–2035) for the new RCP4.5 scenario. In a regional analysis (A1B emission scenario, Eta-CPTEC) of the Paraná Basin, which covers parts of the central Cerrado, Marengo *et al.,* (2012) similarly estimated a temperature increase of 1.8 °C between 2011 and 2040. Global circulation models (GCM) project a warming of up to 3.3 °C in the region in both seasons by 2065 (2046–2065) and a warming of up to 4 °C by 2100 (IPCC, 2013), which is also projected for the Cerrado based on regional models (Marengo *et al.*, 2010); therefore, the Cerrado is predicted to warm faster than the global average (Marengo *et al.*, 2011). Using deforestation scenarios from Soares-Filho *et al.,* (2006), Costa and Pires (2010) demonstrated that the concurrent deforestation in the Cerrado directly affects the future climate of the Amazon rainforest. Deforestation will reduce rainfall in April and September-November and prolong the dry season from five to six months in the Cerrado.

In Brazil, droughts are very likely to substantially increase (IPCC 2013, WG1), particularly in the NE-Cerrado (Marengo *et al.*, 2010). GCM precipitation projections for NE-Brazil are variable, ranging from -19 % to +17 % for 2016–2035; however, in the long-term, it is very likely that less rainfall will occur in the eastern Cerrado in the dry season (high confidence for 2081–2100, IPCC 2013). In the Paraná River Basin, Marengo *et al.,* (2012) projected a slight precipitation decrease of 2.1 % between 2011 and 2040 for both seasons using regional models. The decrease is projected to be as high as 12 % in winter; the summer precipitation will remain approximately the same (–0.7 %). In the simulations for 2071–2100 under the A2 scenario, Marengo *et al.,* (2010) found that rainfall will decrease in NE-Brazil; in the central Cerrado area, one model shows increases while others project reductions. However, heavy rainfall events greater than 10 mm are very likely to increase in the Cerrado (Marengo *et al.*, 2009, Marengo *et al.*, 2010, IPCC 2013).

Because of inconsistencies between the different climate models, both the IPCC reports (2007, 2013) and Marengo *et al.,* (2010) conclude that current GCMs and RCMs are not able to project changes in future rainfall regimes at regional scales for the west-central region in Brazil. Most of the climate change prediction models neglected to include future land use dynamics, which potentially have a significant effect on the future micro-climate (Costa and Pires 2010). For example Loarie *et al.,* (2011) reported for the Cerrado that the conversion of natural vegetation to crop/pasture had led to a warming of in average 1.55 °C whereas the conversion of crop/pasture to sugarcane caused a cooling of 0.9°C. Projections of the future temperature and rainfall regimes are crucial to develop management plans for future agricultural practice; however, all in all, current climatic trend projections for the region appear to be highly insufficient to do so.

2.3 Analysis of ecohydrological change: land and water degradation in the Cerrado

This section first reviews the impact of land use change on soil physical and biogeochemical properties. Soil organic carbon studies are excluded because very recent comprehensive reviews are already available (Bernoux *et al.*, 2006; Carvalho *et al.*, 2009; Batlle-Bayer *et al.*, 2010). Then, we evaluate degradation in the water quality, including nutrient and pesticide contamination in surface waters of meso-scale catchments that have undergone land use change over the last 30 years; a comparison with unaltered catchments is also conducted.

Database compilation of soil and water studies

The analysis focuses on three clusters within the Cerrado: the states of Mato Grosso, Minas Gerais, and the Federal District, where most of the experimental stations and reserves are located. Several additional studies originate from various regions across the Cerrado.

We reviewed 80 soil studies over 1977–2012 to assess the impacts of land use change from natural Cerrado to pasture, cropping, and energy plantations on soil texture, infiltration, bulk density, pH, soil nutrients (NPK), and cation exchange capacity (CEC). All of the data were selected from the major soil type (Ferralsol). Four major land use classes were defined: (1) *cerrado*, containing all sub-forms; (2) *cropland*, including till and no-till soybeans, sugar cane, corn, sorghum, cotton, and rice; (3) *pasture*, i.e., natural, planted (with invasive species) and fertilised pastures; and (4) *Eucalyptus* and *Pinus* energy *plantations*. Because of non-normality, we employed Kruskal-Wallis tests (α=0.05) with post-hoc Bonferroni correction for multiple comparisons to analyse the differences in the soil physical and chemical properties due to altered land use (Figure 2-4).

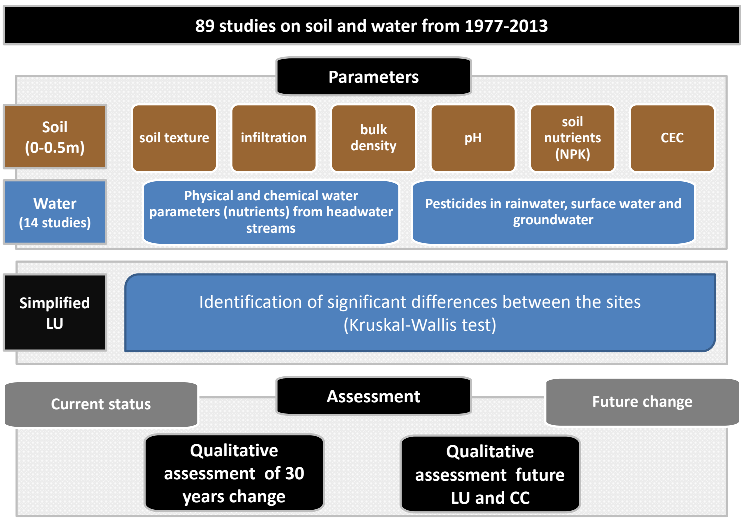


Figure 2-4: Methodology of the reviewed case studies of the Cerrado with the focus of the current status on soil parameters up to 0.5 m, physical and chemical water parameters and pesticides in rainwater, surface water and groundwater. The future change is qualitatively assessed by the likely development of future land use and climate change

Significantly less studies are available on water quality than on soil conditions, and the water quality studies clustered at only a few locations within the Cerrado during the time period 2002–2014. We reviewed 16 water quality studies on river nutrients and biogeochemistry with a focus on the central and south-eastern Cerrado (Table 2-2). Studies on the influence of pesticides were conducted in southern Mato Grosso (Table 2-3)

2.4 Results of ecohydrological change: land and water degradation in disturbed systems

2.4.1 Results on alterations of soil physical and biogeochemical properties in the Cerrado

2.4.1.1 Infiltrability and saturated hydraulic conductivity (Ks)

Several field studies quantified infiltrability and saturated hydraulic conductivity within different land use classes in the Cerrado biome (Table 2-1). The sampling depths were 60–140 cm for the cerrado sites studied by Reatto *et al.*, (2007) and 0–0.55 m for other studies.

Table 2-1: Infiltration and Ksat measurements for different land uses from studies across the Cerrado.

Study	Vegetation	Location and soil type	Soil Depth [m]	Infiltration [mm h^{-1}]	Ks [mm h^{-1}]	Method
Balbino *et al.*, 2004	Cerrado	Goiás, Red Latosol	0 – 0.07		102	Constant head
	Pasture		0 – 0.07		49	
	Cerrado		0.25– 0.4		175	
	Pasture		0.25– 0.4		231	
Bono *et al.*, 2012	Cerrado	Mato Grosso do Sul, Red Latosol		888		Double ring infiltrometer
	Soybean (1a) – Pasture (3a)			153		
	Agric. (4a) – Pasture (4a)			275		
	Direct seeding soybean			249		
	Pasture			337		
Borges *et al.*, 2009	Cerrado (strictu sensu)	District Federal, Red Latosol	0.1 – 0.55		117	Guleph permeameter
	Cerrado anthropogenic		0.1 – 0.55		127	
	Pasture		0.1 – 0.55		50	
Fontenele *et al.*, 2009	Cerrado	Piauí, Yellow Latosol		356		Double ring infiltrometer
	Cropland (NT)			86		
	Cropland (CT)			57		
	Deforested area			281		
Hunke *et al.*, 2015	Cerrado	Mato Grosso, Red Latosol	0; 0.14 – 0.4	1047	43	Single ring (infiltration) and Amoozemeter (Ksat)
	Pasture		0; 0.14 – 0.4	48	8	
	Soybean		0; 0.14 – 0.4	250	6	
	Sugarcane		0; 0.14 – 0.4	157	6	
Reatto *et al.*, 2007	Cerrado (7 locations)	Red and Yellow Latosol	Bw 0.6–1.4		99	Guelph permeameter
da Silva *et al.*, 2006	Cropland (NT)	Red Latosol	0.1 – 0.4		4	Guelph permeameter
	Cropland (CT)		0.1 – 0.4		1	
Souza and Alves 2003	Cerrado	Mato Grosso do Sul, Red Latosol	0; 0.14 – 0.4	330	102	Guelph permemeter
	Pasture		0; 0.14 – 0.4	190	21	
	Cropland (NT)		0; 0.14 – 0.4	228	38	
	Cropland (CT)		0; 0.14 – 0.4	221	23	
	Rubber plantation		0; 0.14 – 0.4	162	10	
Torres *et al.*, 2011	Cerrado	Minas Gerais, Red Latosol	0 – 0.4		56	Constant head permeameter
	Pasture		0 – 0.4		23	
	Cropland (NT)		0 – 0.4		59	
	Cropland (CT) > 20a		0 – 0.4		24	

Infiltrability and saturated hydraulic conductivity (Ks) are important soil-hydraulic parameters that strongly influence storm runoff generation and soil moisture dynamics. Studies have employed different sampling techniques (Amoozemeter, Guelph permeameter, or the constant head method); thus, a direct quantitative comparison of the sampled values is not possible.

Nevertheless, one can observe a clear qualitative alteration of the soil-hydraulic behaviour as a function of land use. Most studies have shown the highest infiltration rates for the Cerrado sites and the lowest rates for pastures and croplands. For example, land use change reduced the permeability by 73.6 % in pastures (Borges *et al.,* 2009) and by more than 90 % in the study of Hunke *et al.,* (2015) in various croplands and pastures. The direct effect of decreasing soil permeability after deforestation was documented by Fontenele *et al.,* (2009), with the lowest rates in croplands. Extremely low Ks values were presented by Silva *et al.,* (2006) for croplands with almost no water input to the soil. Only Balbino *et al.,* (2004) found varying Ks values at pasture sites; however, if only the upper surface layer (0–7 cm) is considered, their average Ks is reduced and their rates are considerably lower than those at the Cerrado sites. All of the authors attributed the reduced infiltration to the loss of macroporosity by soil compaction (e.g., due to cattle and machinery).

2.4.1.2 Texture and bulk density

Texture sampling studies across the Cerrado biome show relatively small variations among the land use classes in Cerrado, including crops and pastures (Figure 2-5). The upper and lower quartiles and the mean values of the sand and clay fractions do not significantly differ. The clay contents of the Cerrado sites show the widest range (16.5 % to 88 %), reflecting the Ferralsol varieties. The mean silt content is significantly higher for croplands than for the other three land use classes (p=0.038), and pastures exhibit the smallest value.

For the bulk density, 26 studies on the upper soil layer (0–50 cm; 60–140 cm for the Cerrado sites of Reatto *et al.*, 2007) were considered. Croplands have significantly higher bulk densities than the Cerrado sites, and the bulk density (p<0.001) of pastures are significantly larger than those of the Cerrado sites (Figure 2-6). The depth profiles of the chemical properties show that differences between the croplands and cerrado can be detected up to a depth of approximately 25 cm below the surface for bulk density. Pasture and Cerrado sites have similar, but less pronounced, characteristics (Figure 2-8).

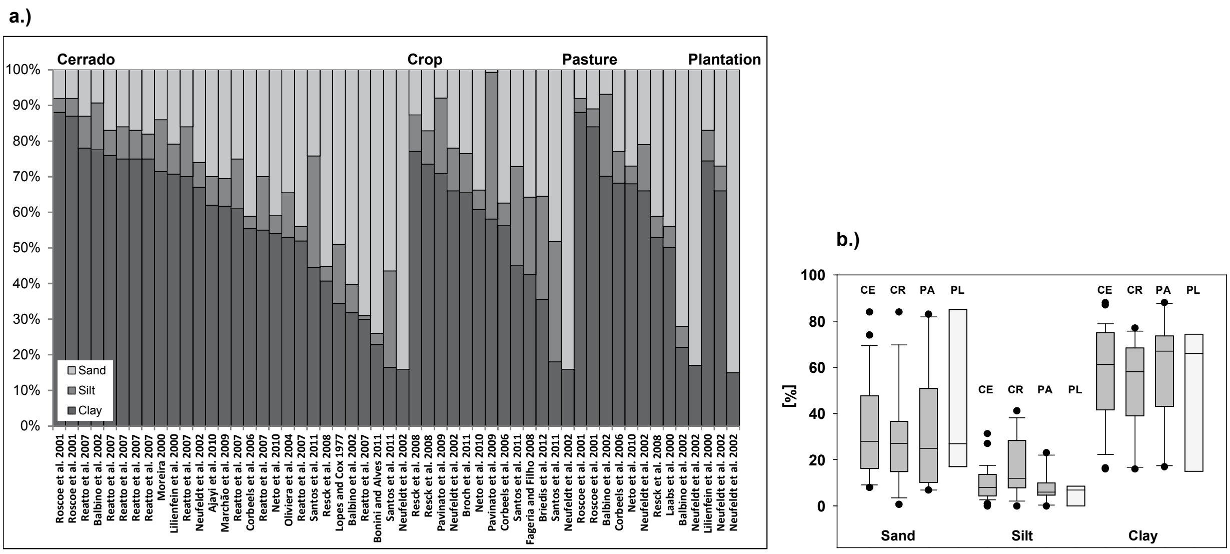


Figure 2-5: Texture of Ferralsols under different land uses (cerrado, crop, pasture and energy plantation) in the Brazilian Cerrado (sorted by clay content from 20 studies at 54 locations at a soil depth of 0–60 cm, and 0–140 cm at the Cerrado sites): a) Percentage distribution per study and location; and b) box-plot representation of sand, silt and clay fractions (the grey boxplot for plantations means that only two studies were available).

2.4.1.3 Soil chemical and physical properties

We used the results of 65 studies to assess effects related to land use change on the soil chemical and physical properties of Ferralsols by employing Kruskal-Wallis multi-comparison tests. For soil pH, 34 studies were considered. For the cation exchange capacity (CEC), total N, available P, and available K, 51 studies on the upper soil layer (0–50 cm for the Cerrado sites of Reatto *et al.*, 2007; otherwise, 60–140 cm) were considered (Figure 2-6).

The soil pH (average: 5.03 (pH_{H2O})) is lowest at the Cerrado sites and energy plantations (where only two studies are available). On croplands and, to a lesser extent, pastures, the pH of the topsoil significantly ($p<0.001$) increased (average: 5.7 (pH_{H2O}), max.:7.0). The pH for the natural Cerrado increases with soil depth but decreases for the other land use categories due to topsoil liming. Although the clay content in Ferralsols under cerrado is often high, the average effective cation exchange capacity (ECEC) as measure of fertility is low for the Cerrado sites (mean 2.05 $cmol_c\ kg^{-1}$). The ECEC is on average more than double for the cropland sites, slightly higher for pastures, and low for plantations (Figure 2-6). The mean concentrations of available K for the croplands (95.81 mg kg^{-1}) are twice as high as those for the Cerrado. The highest mean concentrations are found in energy plantations. For total N, the pattern is different; the highest mean N content and ranges are for the Cerrado sites (0.06–6.7 g kg^{-1}), while slightly lower mean values occur in croplands and pastures. Notably, the available P is low, with small ranges for the Cerrado sites (mean: 2.4 mg kg^{-1}). However, a ~5-fold increase (up to 40 mg kg^{-1} at the surface) occurs in the croplands, and a ~2-fold increase occurs in the pastures; the values decrease to very low values of 0.3 to 2 mg kg^{-1} below 30 cm for all land uses.

A non-parametric multi-comparison based on Kruskal-Wallis showed that land use had a significant impact on a whole range of soil-chemical properties: 1) the mean values of the pH ($p<0.001$), cation exchange capacity ($p<0.001$), available P ($p<0.001$), and available K ($p<0.001$) in croplands are significantly higher than those at Cerrado sites, 2) the pH ($p<0.001$) of pastures is significantly larger than that of Cerrado sites, and 3) the pH ($p=0.012$) and available K ($p=0.0019$) of plantations are significantly higher than those at the Cerrado sites, while the total N ($p<0.001$) is lower than that at the Cerrado sites.

The depth profiles of the chemical properties showed that differences between the croplands and cerrado can be detected to a depth of approximately 30–40 cm for the pH, available P, and available K. The differences between the pastures and cerrado show similar, but less pronounced, pH characteristics (Figure 2-8). In contrast, no statistically significant differences exist between the total N-content of Cerrado, crop and pasture soils; the depth distribution of the nitrogen for the three land uses is similar (Figure 2-7).

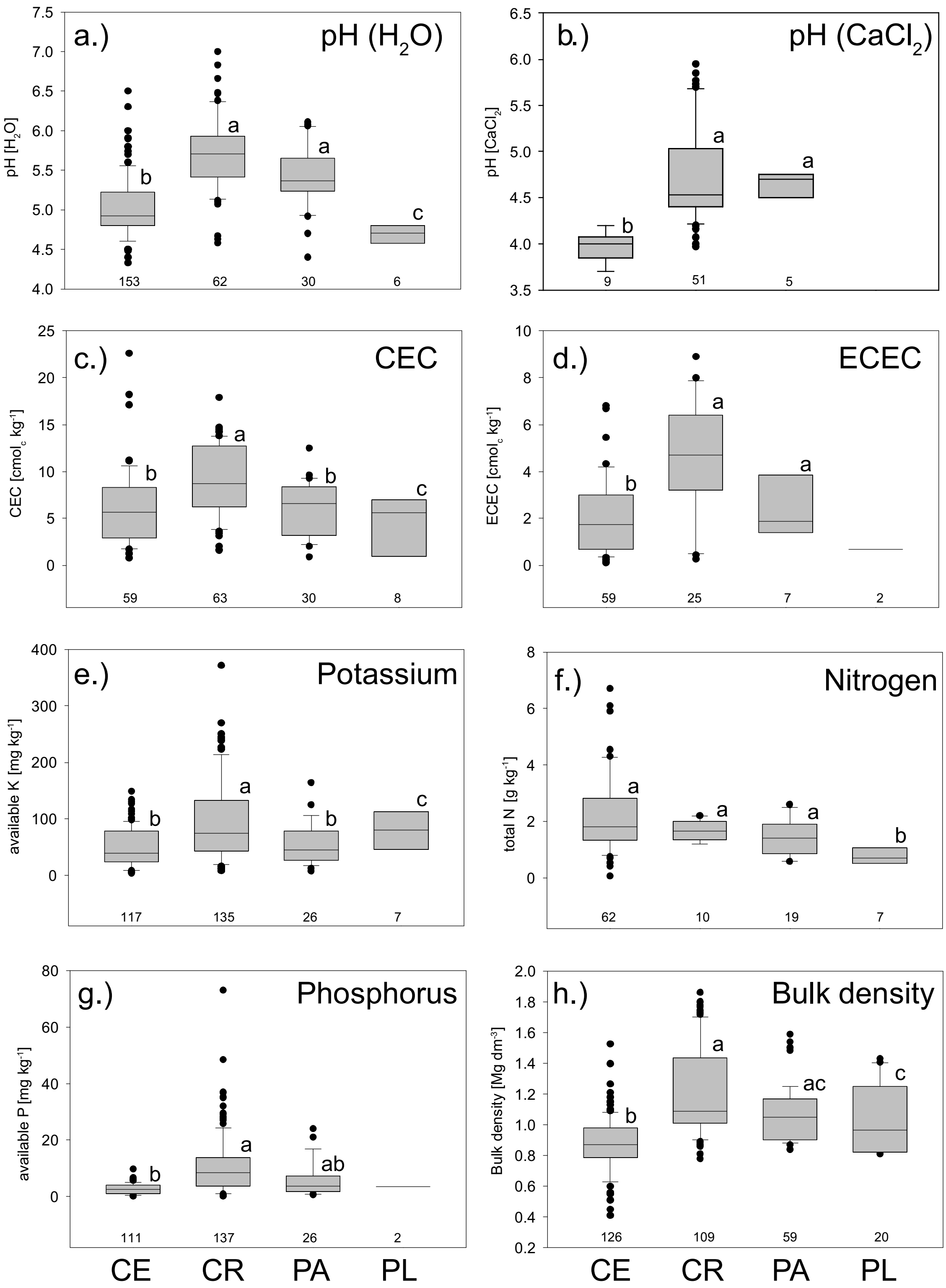


Figure 2-6: Soil chemical properties (pH, cation exchange capacity and nutrients) and bulk density for different land uses (CE: Cerrado, CR: crop, PA: pasture, and PL: energy plantation) with all available measurements (study references given in Figure 2-7and Figure 2-8; n per land use is given in the box plot) in the upper 50 cm Ferralsol soil layer (the pH values were measured in H_2O or $CaCl_2$; therefore, the values are depicted in two separate plots). Three different methods were used to detect the available P in the soil (Mehlich1, Mehlich3, and resin according to the Brazilian and international standards). The box plots that do not share a letter are significantly different ($\alpha = 0.05$) (after Bonferroni adjusted the Kruskal-Wallis test).

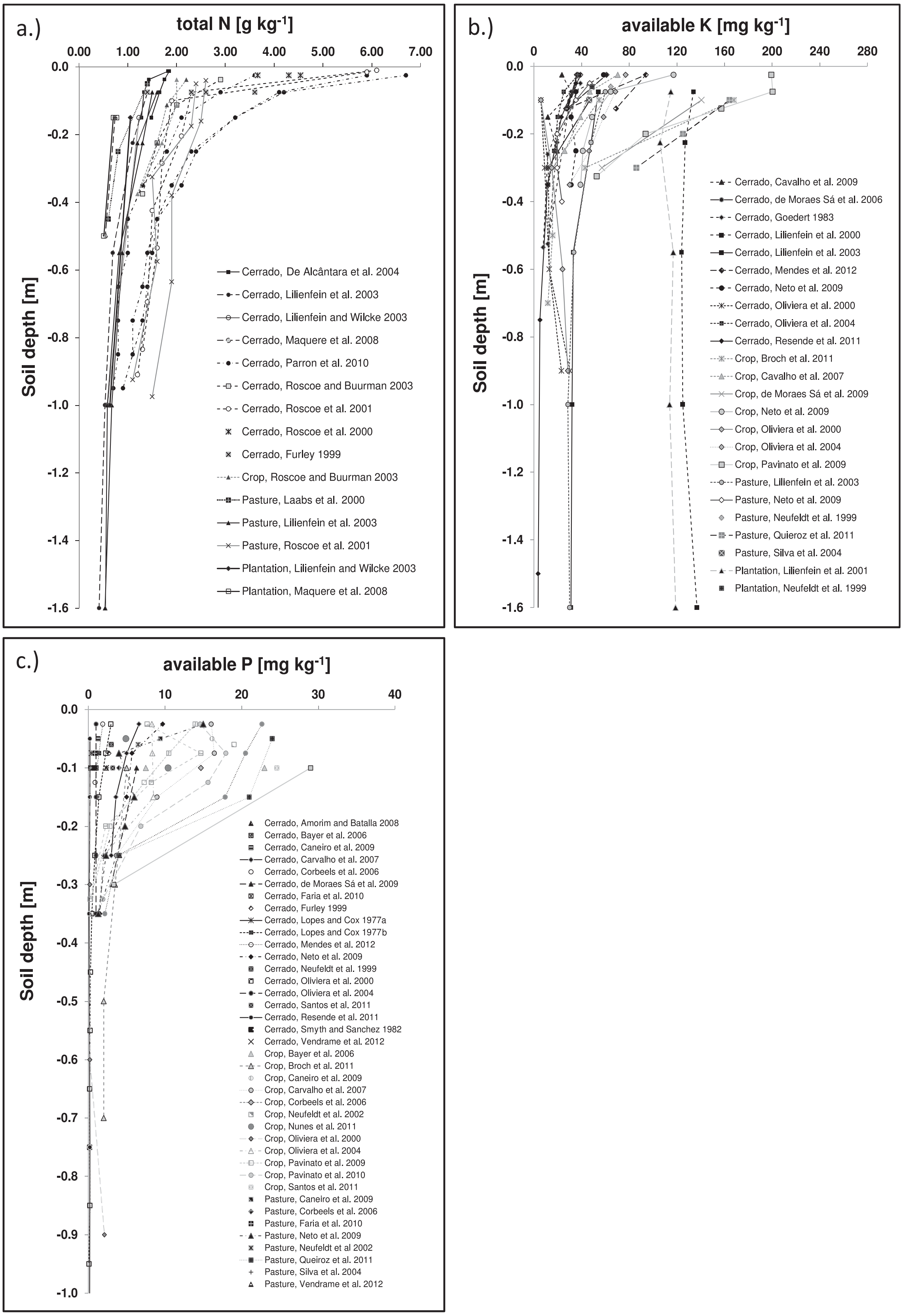


Figure 2-7: Comparison of the soil profiles for total N, available K and available P among different land uses (CE: Cerrado, CR: crop, PA: pasture, and PL: energy plantation) and the studies (the different locations within one study are shown by an averaged soil profile). The published value is averaged over the depth.

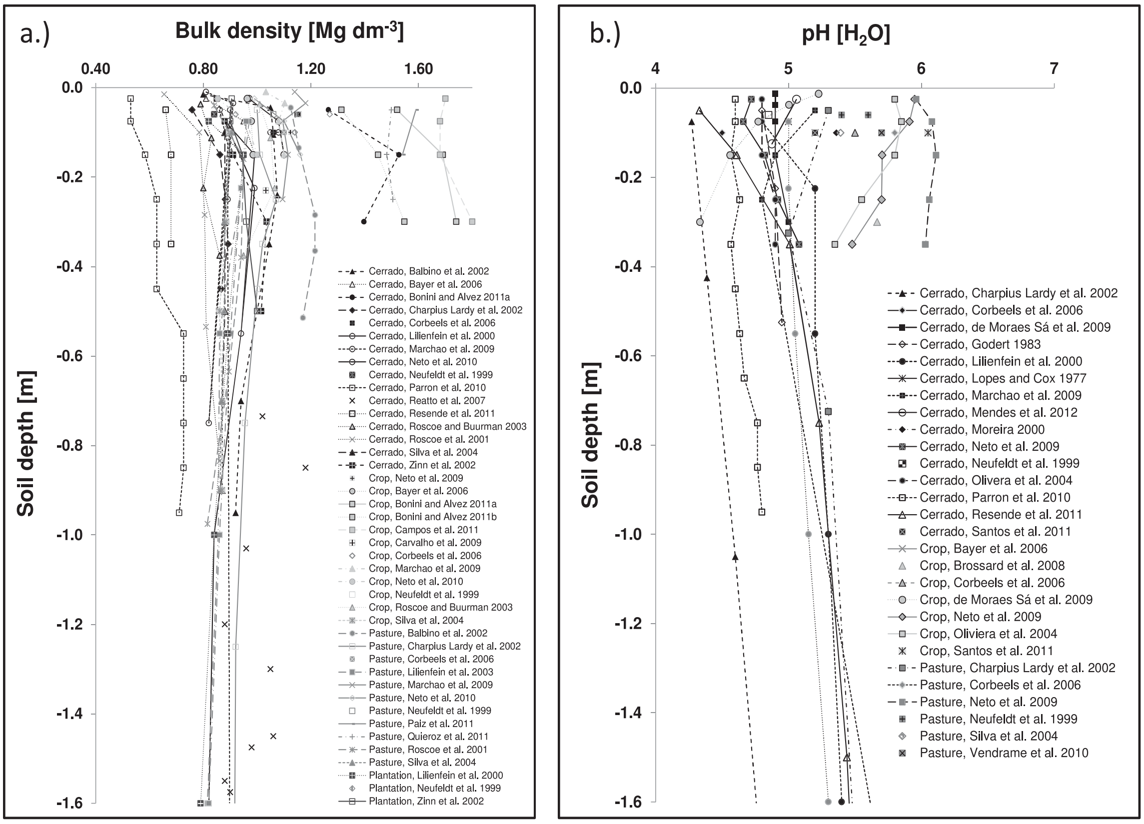


Figure 2-8: Comparison of soil profiles for the bulk density and pH among the different land uses (CE: Cerrado, CR: crop, PA: pasture, and PL: energy plantation) and the studies (the different locations within one study are shown by an averaged soil profile). The published value is averaged over the depth.

2.4.2 Results on alteration of water quality across the Cerrado

2.4.2.1 Nutrients in the river system

Several studies have only analysed the nutrient content in undisturbed low-order (1^{st}-3^{rd}) Cerrado systems (Markewitz *et al.*, 2006; Goncalves *et al.*, 2007; Parron *et al.*, 2010). In a gallery forest within an ecological reserve near Brasilía, Parron *et al.,* (2010) found only very low N and P concentrations in a stream, with mean total N concentration of 0.08 mg l^{-1} and a maximum concentration of 0.15 mg l^{-1} in the dry season. The mean NH_4^+-N was 0.03 mg l^{-1}, while NO_3-N was not detectable; thus, the gallery forest has a high filtering capacity. Likewise, the total P concentrations in the stream water were < 40 µg l^{-1}, which is similar to other findings in natural systems within the Cerrado biome (e.g., Resende *et al.*, 2011). In addition, Silva-Junior *et al.,* (2014) found very low soluble reactive P concentrations in streams of well-preserved catchments. Extremely weathered, undisturbed watersheds are characterised by very low in-stream ionic concentrations often dominated by Ca^{2+} and by electrical conductivities <10 µS cm^{-1} that are negatively correlated to stream discharge; this finding is characteristic of regions with groundwater contributions from weathered aluminiosilicate rocks in the Brazilian shield under baseflow conditions (Markewitz *et al.*, 2006). Thus, Markewitz *et al.,* (2006) showed for second-order streams that most measured ionic components (Ca^{2+}, Mg^{2+}, K^+, Na^{2+}, Cl^-, SO_4^{2-}, and alkalinity), excluding NH_4^+-N and NO_3^--N, show a seasonal variation: high values in the dry season were at least three times larger in the wet season. For pristine Cerrado streams, Fonseca *et al.,* (2013) and Fonseca and Mendonça-Galvão (2014) found very low nutrient baselines for 1^{st} to 3^{rd} streams compared with other natural areas in Brazil or temperate regions. The authors concluded that the response to anthropogenic impacts was slower in these regions than in the Amazon. Silva *et al.,* (2010) discussed for 1^{st}-3^{rd} order streams three to 40-fold lower nutrient concentrations in the Cerrado as an indication of more conservative nutrient cycling and fluxes. This finding was supported Davidson *et al.,* (2004), who showed that Cerrado stream conductivity is extremely low compared with the Amazon. Cerrado streams are supposed to be N-limited (Silva-Junior *et al.*, 2014). This supposition was highlighted by Goncalves *et al.,* (2007), who found in third-order streams slow leaf breakdown rates in Cerrado compared with those in temperate streams when conducting litter decomposition experiments; they attributed these findings to low nitrate concentrations, which caused a slowdown in the fungal activity.

In contrast, agriculturally modified catchments showed nutrient enrichment. Silva *et al.,* (2007) reported that streams draining sugar cane areas displayed significantly higher concentrations of all of the analysed biogeochemical properties compared with undisturbed streams. The water conductivity was ~ten-fold greater for sugar cane (55.9 and 58.8 $\mu S\ cm^{-1}$) and ~two-fold higher for *Eucalyptus* than for the Cerrado stream. In agricultural streams, nitrate concentrations were increased by approximately 4–19 times. A similar pattern was found for potassium in a stream that drains a sugar cane area (increase of approximately 4 to 8 times), whereas *Eucalyptus* showed only a marginal increase. For small 1^{st}- order pasture catchments, Gücker *et al.,* (2009) found significantly higher electrical conductivities and NO_3^- compared with natural streams. Silva *et al.,* (2010) found the highest concentrations in urban streams, followed by rural watersheds (pasture, soybean, and maize), and the lowest concentrations in pristine streams (Table 2-2). The concentrations of NO_3^- and NO_2^- in rural streams were as much as 1.5-times higher, and they differed significantly from natural streams in terms of seasonal flux patterns. Fonseca *et al.,* (2013) presented similar findings in low-order pristine streams.

Silva *et al.,* (2010) did not find higher PO_4^{3-} concentrations in rural streams, although large amounts of fertilisers (up to 150 kg $P_2O_5\ ha^{-1}\ a^{-1}$) were applied. This finding is supported by other studies that found only low variability and concentrations (5–15 $\mu g\ l^{-1}$) of SRP in stream water, regardless of the land use (Silva-Junior *et al.*, 2014), or only slight increases in rural areas (Fonseca *et al.*, 2013). A common trend in the Cerrado is that P is not enriched in fertilised agricultural areas, unlike in temperate regions, where a relationship between P in the soil and high losses to the stream is well documented and reviewed by Schoumans *et al.,* (2014). The absence of P is consistent with findings in the Amazon, where agricultural (Neill *et al.*, 2013) and pasture (Davidson *et al.*, 2004) headwaters do not have P pollution, probably due to the high adsorption capacities of the Fe-Al-rich Ferralsols, the deposition with sesquioxides and organic matter or uptake by plants and algae. Another hypothesis for the small quantities of P in streams in heavily fertilised regions is that the filtering capacities of the riparian vegetation might mitigate diffuse N and P contributions from agricultural fields (Parron *et al.,* 2010).

Table 2-2: Physical properties and biogeochemistry of Cerrado streams under different land use

Land use	Sampling	WT °C	pH	EC µS cm^{-1}	DO mg l^{-1}	TN µg l^{-1}	NO_3^-N µg l^{-1}	NO_2^- µg l^{-1}	NH_4^+ µg l^{-1}	TP µg l^{-1}	PO_4^{3-} µg l^{-1}	SRP µg l^{-1}	BMB g m^{-2}	Chl–a µg g^{-1}	Reference	Location
Cerrado	Samplings of seven 1st to 3rd order streams from 2006–2009, n= 39	19.6–23.04	5.68–7.2	3.03–24.41	4.9–5.85		14–213	2–348	9–97	<1–22		<1–7			Fonseca *et al.*, 2013	Federal District
Rural	Samplings of four 2nd to 4th order streams, n=73	20.78–23.25	6.16–6.85	17.99–63.3	4.24–5.55		76–365	8–48	72–265	11–79		3–24				
Cerrado *Campo rupestre*	Twelve 1st order streams	19.8–21.5	5.8–6.6	20–34	6.7–7.2	<100			3–9	<50					Gücker and Boëchat 2004	Minas Gerais, Serra do Cipó National Park
Cerrado Grassland	3 samplings biweekly (January, May and December 2006), three small 1st order headwater streams per land use	21.4 ± 1.9	6.2 ± 0.4	30.9 ± 4.6	2.6 ± 0.8		4.2 ± 0.3		2.1 ± 0.7			2.5 ± 1.0	16.4 ± 4.9	15.1 ± 11.6	Gücker *et al.*, 2009	Minas Gerais Rio São Francisco
Pasture (pasture >80 %)		22.6 ± 1.8	6.5 ± 0.3	57.2 ± 16.6	2.2 ± 0.3		51.3 ± 13.3		6.8 ± 1.6			7.2 ± 2.4	2.2 ± 1.1	171 ± 96		
Cerrado	May–July 2003 3rd order stream	14.5–16.5	4.6–6	5–7	8.6		5				2.5				Goncalves *et al.*, 2007	Minas Gerais Serra do Cipó National Park
Cerrado	May 1998–1999, n=168, 2nd order		5.54	6.1			49.59		9.1						Markewitz *et al.*, 2006	Federal District IBGE Ecological Reserve,
	May 1999– 2000 biweekly, n=56, 2nd order		6.03	5.6			6.2		7.2							
Cerrado Gallery forest	n=29, one year biweekly 1st order stream	–	5.2±0.3	3.1 ± 1.2	–	80 (mean) –150 (max)	>dl		30 (mean)	<40 – 188	>dl				Parron *et al.*, 2010	Federal District IBGE Ecological Reserve
Rural (34–54 % pasture, crops<15 %)	June and September 2010, November 201. Three 2nd to 3rd order streams upstream and downstream of fishfarm effluents	14.9–19.1	6.5–7.1	13.7–28.9	7.6–9		22–41		17–174			6–19			Rosa *et al.*, 2013	Minas Gerais Cerrado-Atlantic rainforest transition
Rural impacted by fishfarm (34–54 % pasture, crops<15 %)		14.8–19.0	6.4–6.8	13.9–28.3	7.4–8.7		20–54		31–170			11–17				
Cerrado dry season	mean values of three small streams (1st to 3rd order, from 13.3–45.8 km²) per land use. 2 years sampling, biweekly wet season, monthly dry season		4.98	3.99	7.79		30.38	39.56	54.66		2.84				Silva *et al.*, 2010	Federal District
Cerrado wet season			4.79	4.03	6.98		41.54	99.36	74.14		19.94					
Crop dry season			5.16	6.72	6.72		45.26	44.16	67.83		35.13					
Crop wet season			5.0	7.38	6.09		60.76	143.06	103.73		16.14					
Cerrado (*sensu strictu*)	Five small (two cerrado, two sugar cane, one platnation) catchments (423–1750 ha), monthly one year,n=12 (1st to 2nd order)	22.2	5.3	6.1	7.6		301	117	<48.7						Silva *et al.*, 2007	São Paulo state
Crop (*sugar cane*)		22	6.4	57.4	7.9		2213	446	<48.7							
Plantation (*Eucalyptus*)		21.7 ± 1.9	5.2 ± 0.4	10.3 ± 2.4	6.7 ± 0.5		2089.4 ± 508	96.6 ± 23	<48.7							

For purpose of comparison the nutrient concentrations from the studies of Markewitz *et al.*, 2006; Silva *et al.*, 2007; Silva *et al.*, 2010 were converted to µg l^{-1}

WT water temperature, EC electrical conductivity, DO dissolved oxygen, TN total nitrogen, TP total phosphorus, SRP soluble reactive phosphorus, BMB benthic microbial biomass

Microbiological studies by Gücker *et al.,* (2009) and Boëchat *et al.,* (2011) examined first-order stream catchments dominated by pastures (>80 % of catchment area) to investigate the effects of grazing on nutrients, benthic microbial biomass (BMB) and chlorophyll *a*. They found lower BMB and impacts on the entire stream metabolism due to stream channelisation and to increased bottom shear stress. Stream morphology is directly affected by agricultural land use, which leads to faster drainage, altered hydrodynamics and direct impacts on ammonium retention (most retentive in swamps and step-pool reaches) (Gücker and Boëchat 2004; Gücker *et al.*, 2009; Boëchat *et al.*, 2011). Contrary to Gücker *et al.,* (2009), Silva-Junior *et al.,* (2014) related higher gross primary production to stream morphology and greater light exposure in clear-cut agricultural streams, rather than nutrient enrichment. Analysing the effects of fish farms on water quality, Rosa *et al.,* (2013) showed that even small increases of inorganic nutrients (1.3 to 2.1 higher) changed the ecosystem metabolism with an increased community respiration and gross primary productivity. Although nutrient fluxes from fish farming is not readily transferable to nutrient imports from agricultural fields, their study gives a first, quantitative measure on the vulnerability of the system.

All studies from agricultural areas showed in low-order streams enriched inorganic N-forms and higher solute loads. These results indicate that land cover change has a clear effect on the hydrochemistry in the Cerrado. Although Fonseca *et al.,* (2013) attributed water quality deterioration to point source inputs, diffuse pollution from agriculture also plays a major role in highly nutrient-limited ecosystems, such as the Cerrado, which is therefore susceptible to eutrophication (Gücker *et al.*, 2009; Nascimento *et al.*, 2012, Rosa *et al.,* 2013). Changes in hydrochemistry and siltation processes appear to directly affect benthic invertebrates (Wantzen *et al.*, 2006; Gücker *et al.*, 2009), thereby affecting food webs and the whole-stream secondary productivity. All cited authors stressed the importance of using continuous high-resolution monitoring approaches to confirm long-term trends in the effects of land use changes on water quality in the Cerrado.

2.4.2.2 Pesticides in surface water, groundwater and rain water

In Brazil, legal concentration limits have been established only for a few pesticide ingredients in drinking and surface water (e.g., 2 $\mu g\ l^{-1}$ for atrazine, 10 $\mu g\ l^{-1}$ for metolachlor, and 20 $\mu g\ l^{-1}$ for endosulfan (alpha, beta and sulphate)) (Reg No. 2914/2011, Res. No. 357/2005). Contaminant levels in groundwater levels are less strict, depending on the potential water use (see Res. No. 396/2008 for more details). The Brazilian limits for pesticide concentrations are considerably less strict than the limits for the EU Drinking Water Directive (Council Directive 98/83/EC, 1998), which are set to 0.1 $\mu g\ l^{-1}$ for any one pesticide and 0.5 $\mu g\ l^{-1}$ for the maximum total pesticide concentration.

Most of the reviewed studies detected a wide range of agricultural-related substances in the aquatic system of headwater catchments (Table 2-3). The main factors that affect pesticide inputs to surface and groundwater are wind drift from agricultural fields after plane applications (Laabs *et al.*, 2002), direct water runoff from agricultural fields (Casara *et al.*, 2012) and leaching through macropores (Dores *et al.*, 2009). High surface water concentrations are often related to missing riparian buffer strips (Nogueira *et al.*, 2012). For a typical agricultural field in Mato Grosso, Dores *et al.,* (2008) showed that pesticides are common groundwater and surface water pollutants, particularly from non-point sources such as croplands.

Nogueira *et al.,* (2012) found very high maximum concentrations of atrazine in groundwater (18.9 $\mu g\ l^{-1}$) and surface water (9.3 $\mu g\ l^{-1}$).

Table 2-3: Detected pesticide concentrations and deposition rates of five studies in the Cerrado region.

References	Location and land use	Sampling	Substance	Type	Min conc	Max conc	Mean conc*	positive detection	Max deposition
					--------------------[µg l^{-1}]-----------			[%]	[µg m^{-2}]
Casara *et al.*, 2012	headwaters São Lourenco, MT								
	Cotton and soybean	Surface water	Atrazine	H	0.18	0.35		7.2	
		one year, six location, monthly, n=72	Metolachlor	H	0.5	0.82		4.3	
			Flutriafol	F	0.04	0.46		7.2	
		Groundwater	DIA		0.64	0.91		9	
		one year, six location, monthly, n=72	Atrazine	H	0.2	0.28		3	
			Metolachlor	H	0.02	1.16		40	
			Flutriafol	F	0.15	0.75		6	
			ß-Endosulfan	I	0.02	0.33		13	
			Endosulfan-sulfate		0.22	0.62		13	
		Rainwater	DEA		1.48	3.31		11	
		one year, two location, every event	Atrazine	H	0.02	8.2		50	
			Metolachlor	H	0.02	0.3		39	
			Flutriafol	F	0.05	0.12		16	
			Endosulfan-sulfate		0.09	0.14		33	
		Runoff water	DIA		0.33	1.53		44	
		one year, six location, every event	DEA		1.24	3.74		11	
			Atrazine	H	0.02	28.2		44	
			Metolachlor	H	0.02	0.85		14	
			Flutriafol	F	0.05	0.92		28	
			Endosulfan-sulfate		0.2	8.02		63	
Carbo *et al.*, 2008	Primavera do Leste, MT								
	Cotton	Groundwater	Acetamiprid	I	nd	6.31		4	
		14 month, 2 farms, five wells, monthly, n=110	Carbofuran	I	nd	68.79		9	
			Diuron	H	nd	0.78		1	
			Methomyl	I	nd	22.81		1	
			Teflubenzuron	I	nd	2.62		3	
Dores *et al.*, 2008	Primavera do Leste, MT								
	Cotton	Drinking well	Atrazine	H	0.063	0.063	0.063	5	
		three sampling periods, n=23	DEA		0.048	0.69	0.158	25	
			Simazine	H	0.042	0.138	0.064	26	
			Metribuzin	H	0.07	0.882	0.151	65	
			Trifluralin	H	< 0.102	0.182		5	
			Metolachlor	H	< 0.206	0.838		17	
		Open well	Metribuzin	H		< 0.106	< 0.106	20	
		n=6	Metalochlor	H	< 0.206	1.732		60	
		Irrigation well	Atrazine	H	0.078	0.856	0.152	100	
		n=6	DEA			0.206	0.206	33	
			Simazine	H	0.075	0.085	0.08	67	
			Metribuzin	H		0.129	0.129	33	
			Trifluralin	H		< 0.102	< 0.102	33	
		River (n=3)	Simazine	H	0.045	0.047	0.046	67	
		Dam (n=3)	Metribuzin	H	<0.106	0.138		50	
Laabs *et al.*, 2002	near Cuiabá, MT								
	Pasture (soy, sugarcane, cotton)	Rainwater	Alachlor	H	0.006	0.672	0.105	48.9	43
		one rainy season (Nov–March), thrice a week, n=45	Cypermethrin	I	0.032	0.376	0.204	4.4	15
			α-Endosulfan	I	0.014	0.322	0.065	51.1	37
			ß-Endosulfan	I	0.013	0.722	0.131	77.8	108
			Metolachlor	H	0.008	0.866	0.089	33.3	50
			Monocrotofos	I	0.06	2.23	0.334	28.8	94
			Profenofos	I	0.187	2.27	0.674	26.7	141
	Soybean, cotton, sugar cane	Stream water	Ametryn	H	0.002	0.009	0.004	12.8	
		one rainy season (Nov–March), weekly, n=94	α-Endosulfan	I	0.003	0.032	0.012	13.8	
			ß-Endosulfan	I	0.002	0.03	0.009	13.8	
			Endosulfan-sulfate		0.002	0.038	0.012	31.9	
			Metolachlor	H	0.002	0.007	0.003	25.5	
			Metribuzin	H	0.003	0.007	0.005	20.2	
		biweekly River (n=26)	Malathion	I	0.01	0.174	0.042	26.9	
			Profenofos	I	0.187	2.27	0.674	26.7	141
	Soybean, cotton, sugar cane	Stream water	Ametryn	H	0.002	0.009	0.004	12.8	
		one rainy season (Nov–March), weekly, n=94	α-Endosulfan	I	0.003	0.032	0.012	13.8	
			ß-Endosulfan	I	0.002	0.03	0.009	13.8	
			Endosulfan-sulfate		0.002	0.038	0.012	31.9	
			Metolachlor	H	0.002	0.007	0.003	25.5	
			Metribuzin	H	0.003	0.007	0.005	20.2	
		biweekly River (n=26)	Malathion	I	0.01	0.174	0.042	26.9	
Nogueira *et al.*, 2012	Campo Verde, MT								
	Soybean, cotton, maize	Surface water	Atrazine	H	0.25	9.3	0.68	14	
		one hydrological year (Oct–May), bimonthly	DEA		dt			7	
			α-Endosulfan	I	nd	0.5	0.04	7	
			ß-Endosulfan	I	nd	0.94	0.07	7	
		Groundwater	Atrazine	H	nd	18.9	0.7	4	
		one hydrological year (Oct–May), bimonthly	α-Endosulfan	I	0.45	0.561	0.06	11	
			ß-Endosulfan	I	0.18	0.54	0.03	7	
			Flutriafol	F	0.23	57.1	2.21	19	
			Metolachlor	H	0.26	1.48	0.08	11	

Type of pesticide: F-Fungicide, H-Herbicide, I-Insecticide; Atrazine metabolites: DIA (desisopropyl-atrazine), DEA (desethyl-atrazine) nd: not detected

Atrazine is a substance that has been banned in the EU since 2004 for being an endocrine disruptor and a persistent groundwater polluter. Similarly, Casara *et al.,* (2012) detected atrazine in water runoff samples, with an extremely high maximum concentration of 28.3 µg l^{-1}; most frequently, the substance was detected in rainwater samples, as supported by the study of Moreira *et al.,* (2012) in which extremely high concentrations of atrazine (75.43 µg l^{-1}), monocrotofos (41.35 µg l^{-1}) and flutriafol (29.64 µg l^{-1}) were detected. Because of the higher volatilisation rates, the atmospheric input of pesticides may be more relevant in tropical areas than in temperate regions (Laabs *et al.*, 2002).

Pesticide concentrations and detection frequencies were highest for atrazine and flutriafol from March to May, when a second crop (soybean, corn or cotton) is typically grown (Casara *et al.*, 2012). Dores *et al.,* (2008) temporarily linked the highest detection frequencies of herbicides in groundwater and surface water samples to the application dates of pesticides in the rainy season. In particular, metribuzin and metolachlor, which are commonly applied to soybean, corn and cotton areas, exceeded the threshold of the EU Directive by a factor of 17 (Dores *et al.*, 2008).

Dores *et al.,* (2009 and 2013) analysed the leaching potential of metolachlor and diuron for Ferralsols in a lysimeter field study and in an undisturbed soil column in laboratory experiments. The study showed that groundwater contamination was caused by a downward displacement of substances through the soil profile; metolachlor leached into the groundwater via matrix flow and preferential flow. Conversely, Reichenberger *et al.,* (2002) found that the downward movement of pesticides was characterised by preferential flow only through macropores in a lysimeter study near Cuiabá (Mato Grosso). This later finding was confirmed by the field study of Casara *et al.,* (2012), who detected substances with low water solubility (in this case, ß-endosulfan and endo-sulfate) in groundwater that were related to leaching through macropores. Similarly, Nogueira *et al.,* (2012) detected flutriafol (57.1 µg l^{-1}) in groundwater at depths to 120 metres. At five monitoring wells on two farms, Carbo *et al.,* (2008) found the insecticide carbofuran in 9 % of samples, with a very high maximum concentration of 68.79 µg l^{-1} in shallow groundwater. Similarly to atrazine, the insecticide carbofuran has been illegal in the EU since 2007 (Council Directive 91/414/EEC, Annex I 2007). Moreira *et al.,* (2012) documented drinking water pollution and detected that the fungicide flutriafol was 500-fold higher than the EU limits.

Overall, the pesticide concentrations presented here often complied with the limits of the Brazilian legislation but considerably failed to comply with the stricter EU thresholds. Even with the low detection frequencies, all studies found pesticides contamination in surface water, groundwater, or rainwater in agricultural fields.

2.5 Discussion and conclusion of the combined effects of water and land degradation

2.5.1 Qualitative assessment of ecohydrological change: To what degree does land use change influence soil and water properties and functioning in the Cerrado?

For a qualitative assessment of change, we summarise key findings of the reviewed field studies of the last 30 years and indicate which soil and water parameters have been altered under land use intensification for crop production, pasture or plantation. Most soil and water parameters are affected by land use change to crop, especially parameters related to soil-hydraulic properties, soil pH, soil P content, as well as nutrient and pesticide contaminations in surface waters. The impact is less pronounced for pastures. Data availability from field studies on energy plantations is considered too sparse to give a clear picture of change for the investigated parameter range (Table 2-4).

Table 2-4: Impacts (Impact 1–Increased occurrence of overland flow, erosion and gully transformation; 2– Nutrient accumulation in land and water resources; 3– Pesticide contamination in the water cycle) and potential consequences for soil and water parameters after land use change from Cerrado to crop, pasture and energy plantation. CEC, cation exchange capacity; ECEC, effective CEC; SRP, soluble reactive phosphorus. X= changes evident, O=no changes, ?=changes uncertain; in parantheses + = increase, – = decrease

Parameter	Land use change to			Impact	
	crop	pasture	plantation		
Soil					
Infiltration, Ks	X (– –)	X (– –)	?	Impact 1	Increased overland flow, ponding, soil loss, lateral agrochemical displacement and potential gully formation
Bulk density	X (+ +)	X (+)	X (+)	Impact 1	Compaction, increased overland flow, erosion and potential gully formation
pH	X (+ +)	X (+)	X–O (–)		Soil dispersion, losses of aggregates, decreased infiltration, increased nutrient availability
CEC/ECEC	X (+ +)	X (+)	?–O (–)	Impact 2	Topsoil nutrient accumulation from fertilisation and liming
total N	O	O	X–O (–)	No impact identified	
available P	X (+)	X–O (+)	?	Impact 2	Topsoil P-accumulation and overfertilization in some cases
available K	X (+)	O	?–X (+)	Impact 2	Topsoil K-accumulation
Water					
pH	X (+)	X (+)	?		
Temperature	?	?	?	Impact is uncertain	Insufficient data
Dissolved oxygen	X–O(–)	X–O(–)	X(–)	Impact 2	Increase of suspended loads and nutrient accumulation
Electrical conductivity	X (+)	X (+)	X (+)	Impact 2	Increase of total dissolved solids, anthropogenic inputs from agriculture
NO_3^-, NO_2^-, NH_4^+	X (+)	X (+)	X (+)	Impact 2	Nutrient enrichment and increase of inorganic N–forms from agriculture
TP, SRP	O–?	O–?	?	No impact identified	(Insufficient data)
Pesticides	X (++)	?–X (+)	?	Impact 3	Leaching from agricultural fields, surface runoff, wind drift of agrochemicals in the water cycle

Impact 1: Increased occurrence of overland flow, erosion and gully transformation

Soil compaction with increased bulk density, increased silt content and decreased infiltration rates due to the combined effects of machine traffic, cattle trampling and liming were identified for croplands and pastures. Substantial increases in pH values were recorded in all sampled soils and surface water within croplands and pastures (Figure 2-6, Table 2-2) due to extensive liming that is meant to increase biomass yields (Fageria and Barbosa Filho 2008). For Brazilian Ferralsols, Haynes and Naidu (1998) showed that increased soil pH values were related to clay dispersion and decreased the infiltration rates in accordance with our findings (Table 2-1). The loss of aggregates with land use change is documented by Resck *et al.,* (1999), who found that after 9 years of soybean growth, the percentage of topsoil aggregates > 2 mm had decreased by 30 %. The highest aggregate stability was related to Cerrado, pastures and eucalyptus plantations; interestingly, the stable aggregates were not related to no-till soybean systems (although no-till accumulated the most organic carbon).

The combined effects of changes to the soil structure and the very high rainfall erosivity factors (Oliveira *et al.*, 2013; also see Chapter 2.1) commonly cause more frequent overland flow due to high-intensity storms in the rainy season (Figure 2-9); as a result, extensive soil erosion may occur and gullies may form (*voçoroca*) (Wantzen *et al.*, 2006; Vrieling and Rodrigues 2004; Nascimento *et al.*, 2012). According to our findings, accelerated erosion is likely to occur in the future.

Barreto *et al.,* (2013) used soil erosion modelling to show that high erosion and sedimentation are directly linked to land use changes. Favis-Mortlock and Guerra (1999) observed that merely ten years of conventional soybean cultivation resulted in the entire loss of the A-horizon (up to 20 cm) through soil erosion at a study site in Mato Grosso. No-tillage systems were largely implemented in the Cerrado in the early 1990s (FAO 2001; reviewed by Bernoux *et al.,* 2006); these systems are well known for their positive effects on C-storage (e.g. Carvalho *et al.*, 2009; Neto *et al.,* 2010; Pinheiro *et al.,* 2014) and for stabilising aggregates (Green *et al.*, 2007). However, even with common no-till practices, high soil erosion and gully formation were directly linked to agriculture (Didoné *et al.*, 2014). Likewise, Wantzen and Mol (2013) pointed out that despite of direct planting and other measures (e.g. construction of contour lines) erosion is still a problem. The study of Jesuz *et al.,* (2013) associated the occurrence of 39 active gullies in a meso-scale catchment to no-tillage soybean-maize/cotton areas, rather than to pasture areas. Their studies investigated active gully systems under agricultural practice but there were no information available if the gullies were initially developed under the current land use or existed before the implemenation of no-tillage. The application of geo-radar (GPR) data established a relationship between piping and gullies (Augustin and Aranha 2006); this link was also found in field studies for pastures (Castro 2005). Based on SAR (Synthetic Aperture Radar) imagery, Vrieling and Rodrigues (2004) assessed similar effects for degraded pastures, which experienced the highest soil losses in the rainy season. Vrieling *et al.,* (2008) found that pasture areas have the highest erosion risk in November and December, when the vegetation cover is reduced, and directly after the application of agrochemicals.

Plantations are considered to have a smaller erosion risk than annual crops (Smith *et al.*, 1999). In field experiments, Wantzen (2006) showed that the increased sediment loads from gully erosion significantly reduced benthic invertebrate populations. Wantzen (2003) measured fluxes of up to 60 tons of sediments per day at the outlet of a gully after heavy rainfall. Our own observations in Mato Grosso confirm that gullies more than 10 metres deep and several hundred metres long are common at pasture and crop sites in the Cerrado; these gullies form rapidly, even in fairly flat landscapes.

Figure 2-9: Overland flow on a soybean field shortly before harvest in Mato Grosso, near the city of Jaciará (15°56'46.1"S 54°58'26.1"W)

Impact 2: Nutrient accumulation in land and water resources

Croplands showed an accumulation of P and K in the upper soil layer (30 cm, see Figure 2-7); the accumulation was less pronounced for pastures and plantations. The accumulation suggests that there is an increased chance of leaching into deeper soil layers or even into groundwater, but it remains unclear at which concentration the extractable P exceeds to begin to leach. Resende *et al.,* (2011), for instance, provided some evidence of P-leaching into deeper horizons in the Cerrado. In several cases, the results from the soil studies indicated over-fertilisation compared with the soil P concentrations of 8 mg kg^{-1} recommended by EMBRAPA (2003) for Cerrado soils (Figure 2-7).

The surplus of P for the displacement to surface water is not related to P pollution in the reviewed water quality studies. Instead, the filtering capacity of the riparian vegetation seems to be high (Chapter 2.4.2.1). For instance, Boëchat *et al.,* (2013) found that the intactness of the riparian zone determines habitat integrity and sediment quality more than the entire watershed's land cover.

A soil accumulation trend has not been detected for nitrogen. The result is not surprising because most of the areas classified as croplands are nitrogen-fixing soybean sites that require little nitrogen fertiliser (Sousa and Rein 2011; Brando *et al.*, 2013). However, the role that nitrogen leaching plays in agricultural Cerrado is inconclusive. Other crops (e.g., cotton, sugar cane, coffee, and maize) with the highest nitrogen demands in Brazil (FAO 2004) are grown in the Cerrado, which may explain the increase in inorganic nitrogen observed in the surface water for all altered land use classes (Table 2-2). Most commonly, nitrogen fertiliser (for cotton up to 180 kg ha^{-1} N and maize ~90 kg ha^{-1}) is applied as urea with 1/3 of the total N rate during the seeding stage of the second crop (usually maize or cotton) after the soybean harvest. Ammonification and subsequent nitrification of urea to nitrate in combination with low plant uptake at the beginning of the growth cycle may promote fast leaching of highly mobile nitrates to the groundwater. Additionally, nitrate fertiliser is also applied directly to crops, and higher levels of inorganic nitrogen forms in surface waters may originate from granular fertiliser applications on bare soil between the seedling rows (pers. obs.). These nitrates can easily be displaced towards surface waters through overland flow in dissolved or particulate-bound transport. Thus, rapid transport to the stream network may occur via overland flow, infiltration and interflow. Again, this emphasises the importance of overland flow and erosion processes in the altered system (see Impact 1). Gücker *et al.,* (2009) provided evidence for nitrate leaching, i.e., significantly high levels, in groundwater samples influenced by agriculture. In the eastern Cerrado, Bortolotto *et al.,* (2012, 2013) reported by extremely high N-applications during fertigation (irrigation combined with fertiliser application) in coffee plantations at a rate of up to 800 kg N ha^{-1} a^{-1}. In field experiments they confirmed that nitrate leaching and groundwater pollution would occur.

An increase in electrical conductivity and inorganic N-forms in surface water was detected in most reviewed studies due to anthropogenic inputs from fertilisation and liming (Table 2-2). In absolute terms, nitrate concentrations in surface water were low compared with concentrations measured in European rivers; in relative terms, however, the nitrate values of the rivers in catchments under land use change are orders of magnitude greater than those found in natural Cerrado streams. Allan (2004) showed that even modest increases in nutrient concentrations can cause eutrophication. Indeed, Gücker *et al.,* (2009) and Boëchat *et al.,* (2011) found higher chlorophyll levels and primary productivity in agricultural streams, and most of the studies reviewed in the section 4.3.1 revealed nitrogen enrichment. Therefore, this naturally nutrient-limited aquatic system of the Cerrado, as a whole, might be affected by this increase.

Impact 3: Pesticide contamination in the water cycle

According to several studies available for the Cerrado region (Chapter 2.4.2.2), pesticides have been detected throughout the entire hydrosystem. Some substances exceed both Brazilian and European legal water quality limits. This excess reflects the potential overuse of toxic substances by smallholders, as documented for the Amazon (Schiesari *et al.*, 2013). As most of the studies were conducted in the southern part of Mato Grosso, an extrapolation of the findings on the pollutant level to the entire Cerrado region must be performed carefully. However, the national data on pesticide consumption (ANVISA 2012) show a large increase in pesticide consumption in the Cerrado states with agricultural production.

Figure 2-10: Pesticide spraying in the Tenente Amaral catchment

Pesticides are detected consistently in all components of the hydrological cycle; this finding implies non-random contamination is occurring, with unknown impacts on the aquatic habitat in surface waters and serious human health implications related to the consumption of untreated water, especially in rural areas (Nogueira *et al.*, 2012; Brando *et al.*, 2013).

2.5.2 Assessment of uncertainty: How good is the data availability for water and soil resources?

Basic information and studies on soil properties of the dominating soil type of the Cerrado are readily available for the upper soil layers (upper 50 cm) but are less common for deeper soil horizons (Oliveira *et al.*, 2005). One major problem identified in the review is the wide range of chemical analysis methods, e.g., Mehlich1, Mehlich3, and resin are used for P extraction. McGrath *et al.,* (2001) expressed the strong need to standardise P extraction methods to enable more accurate comparisons across studies; however, progress has not been made.

Published water monitoring data that contain continuous samplings with a high resolution (i.e., more than once per month) over long time periods (i.e., exceeding one year) are very limited for Cerrado headwater catchments. ANA maintains a Federal database on water resources, which mainly combines the results of water quality monitoring of state environmental agencies; these data are available through webportals (Hidroweb, SNIRH) and a desktop application (Hidro). Within the Cerrado biome, 893 stations are registered; with datasets until 2012 or later. More than 95 % of these stations, however, have sampling frequencies of less than three times per year, on average; the sparse data severely limit the temporal representativeness of the analytical results. Furthermore, stations with higher sampling frequencies have catchment areas of at least 5,000 km^2 but generally more than 15,000 km^2. In a recent report on the state of water resources in Brazil, ANA (2012) concluded that the primary water quality problems, including those in the Cerrado region, are caused by untreated urban effluents, especially in areas downstream from urban centres, such as Brasília (DF), Belo Horizonte (MG), Goiania (GO) and major cities in the central and western regions of the state of SP. However, no specific evaluation of non-point source pollution from agricultural activities has been conducted.

Existing water samplings are conducted at very few research stations, e.g., clustered in the IBGE Reserve of the Federal District (Markewitz *et al.*, 2006; Parron *et al.*, 2010). Although more data are available from local and regional studies by local water managers or environmental protection agencies, they are not published in scientific journals. To our knowledge, no trans-regional study has compiled information in a consistent way or has related monitored water quality data to land use change.

2.5.3 Projection of future change: How is the Cerrado likely to change under future land use and climate change?

Future land use

The trend towards intensive agricultural use is likely to continue across the entire biome (Coe *et al.*, 2009; Ferreira *et al.*, 2013). To a smaller extent than other uses, the recent expansions of *Eucalyptus* and *Pinus* plantations (Figure 2-11) during the afforestation process were recognised (Zinn *et al.*, 2002; Sano *et al.*, 2008).

Figure 2-11: *Eucalyptus* plantation in Mato Grosso

Specifically, triple cropping will presumably result in an increase in maize and cotton crops that need N-fertilisers, which will increase the risk of nitrogen leaching (see the Review section in Brando *et al.*, 2013). The existing cash crop production dominates on Ferralsols because their higher clay content better protects against nutrient losses. However, there are serious concerns regarding the expansion of cash crop production on soils that are not adequate for agricultural use. In addition to the state of Mato Grosso, further expansion will primarily affect the northern part of the Cerrado biome (states of Maranhão, Piauí, Tocantins, and Bahia), i.e., areas dominated by sandy soils (Figure 2-2), and regions of the biome that are likely to require extensive irrigation. The fertilisation of sandy, poor soils (Arenosols) or the cultivation of soils close to wetlands, as well as the use of slopes and 'hilltops', is facilitated by the revision of the Forest Code (Wantzen *et al.*, 2012); with the reduction in the riparian vegetation, the leaching risk of P and water-soluble pesticides may increase. Sandy soils with low organic matter are also more prone to erosion (Nascimento *et al.*, 2012), so soil degradation is likely to become a more important problem.

Climate Change

The possible effects of climate change in Brazil are very uncertain (Chapter 2.2.2). The study of Carvalho *et al.*, (2013) documented an intensification of the irregularity in the rainfall distribution, with an increased dry spell length in the growing season for the Cerrado region in recent decades. Based on the rapid change in the occurrence of dry spells, the study predicted that agricultural productivity in the midwestern region may decline. Central Brazil was identified by Teixeira *et al.,* (2013) as a global hotspot of soybean heat stress under the A1B scenario for 2071–2100. In a modelling study, Assad *et al.,* (2013) found that increasing temperatures (according to the A2 scenario) cause a 15 % reduction in suitable areas for cotton cultivation through 2040, particularly in the northeast. In the west-central region, Mato Grosso do Sul is the only area that might be affected. Because of rising temperatures and projected long-lasting dry spells (Marengo *et al.*, 2009), irrigation will become more common to ensure stable yield levels, particularly for the water-demanding energy plantations (*Eucalyptus*) and cotton fields (Smith *et al.*, 1999). Bustamante *et al.,* (2006) concluded that for enhanced irrigation the currently low N_2O emissions might increase significantly. Although we could not give evidence that stream temperature is also enhanced by land use change, it is expected that stream warming occur for pasture and cropland streams as showed by Macedo *et al.,* (2013) for the lower Amazon. However, the projected longer periods of droughts in combination with irrigation may affect thus seriously water quality, as higher temperatures decrease the oxygen-carrying capacity of water; thus, the susceptibility to eutrophication via increased nutrient concentrations is enhanced. More frequent and intense fires may increase erosion by destroying vegetation cover (Section 5.1, Impact 2). Additionally, fires followed by heavy rainfall lead to nutrient leaching into deeper soil layers (Resende *et al.*, 2011). Because of faster nutrient losses, we expect a higher fertiliser demand. As more frequent extreme rainfall events are projected, resuspension of sediments and surface runoff are likely to increase due to agricultural field exports of higher nutrient, pesticide, and sediment loads to running water (Bustamante *et al.*, 2012; Roland *et al.*, 2012). The increased occurrence of high-intensity storms, overland flow, and reduced vegetation cover due to more frequent droughts may promote soil degradation and erosion processes, as well as the augmentation of existing gullies or the development of new gullies (2.5.1, Impact 1). The drier north-eastern part of the Cerrado is particularly at risk of soil degradation and desertification (Bustamante *et al.*, 2012).

The combined effects of land use intensification under climate change are likely to severely limit the Cerrado's future agricultural productivity and ecosystem stability. Large-scale eutrophication of surface waters and pesticide contamination are likely. The observed changes in the reviewed studies suggest that similar, undocumented environmental changes have occurred in many other catchments in the Cerrado. It is difficult to predict, however, whether and to what extent measures to mitigate and cope with (e.g., plant breeding, Ramalho *et al.*, 2009) adverse effects of climate change will be implemented. The review studies' compilation of water and soil characteristics may serve as a valuable database for further investigations, e.g., for parameterisation and testing of integrated modelling tools to investigate the impact of the described land use and climate change scenarios on water and soil resources in the Cerrado.

3 Quantification of soil and water degradation of different land uses in a heavily modified meso-scale catchment – A field study

Abstract:

This study aimed to (1) examine the effects of land use change on the soils of natural Cerrado transformed to common croplands (soybean/cotton/maize rotation and sugarcane) and pasture and (2) indicate how agricultural production affects water quality across a meso-scale catchment. Land conversion caused significant reduction in infiltration rates near the soil surface (0–40 cm depth) of pasture (–96 %) and croplands (–90 % to –93 %). Soil aggregate stability was significantly lower in croplands than in cerrado and pasture. Topsoil pH and nutrient concentrations were high in croplands and pasture. Soybean crops had extremely high extractable P concentrations (80 mg·kg^{-1}; 9 times greater than the natural background), whereas pasture N levels declined. Nutrient accumulation of N and P did not occur at deeper horizons for any land use type. Snapshot water sampling showed strong seasonality in water quality parameters. Higher temperature, oxi-reduction potential (ORP), NO_2^-, and very low oxygen concentrations (<5 mg·l^{-1}) and saturation (<60 %) were recorded during the rainy season. In contrast, remarkably high (up to 0.8 mg·l^{-1}) PO_4^{3-} concentrations were measured during summer. Water quality parameters were affected by agricultural activities at all sampled sub-catchments across the meso-scale catchment, regardless of stream characteristics (stream order, percentage of riparian vegetation, sub-catchment size); thus, no spatial trends were observed. Direct NO_3^- leaching appeared to play a minor role; however, water quality is affected by agricultural non-point sources, due to topsoil fertiliser inputs affecting the entire catchment, from small low order streams to the larger rivers of the modified catchment. In conclusion, land use conversion has degraded soil physical properties, leaving cropland soils more susceptible to surface erosion with potential lateral nutrient transport to the stream network.

3.1 Introduction

The acceleration of agricultural activities has generated economic wealth in the region, but has also generated environmental problems related to soil degradation and the contamination of water resources (Battle-Bayer *et al.*, 2010; Martinelli *et al.*, 2010; Schiesari and Grillitsch, 2011; Schiesari *et al.*, 2013). Cerrado soils are poor in nutrients because this area is dominated by dystrophic deeply weathered soils characterised by a pseudo-sand structure (Goedert, 1983; Lopes *et al.*, 2004). Thus, to produce high biomass yields, enormous lime application and fertilisation are needed (Carvalho *et al.*, 2009; Yamada, 2005). Several studies in the tropics have indicated that land use and vegetation cover influence the physical properties of soils (e.g. Hassler *et al.*, 2011; McGrath *et al.*, 2001; Scheffler *et al.*, 2011; Zimmermann *et al.*, 2006). Soil hydraulic properties, bulk density, compaction, and soil aggregate stability control water and nutrient flow; thus, these parameters represent sensitive parameters for quantifying the effect of deforestation and land use change. Soil aggregate stability is a key indicator of soil quality and rangeland health, indicating soil erosion processes and changes in water quality (Herrick *et al.*, 2001). Identifying changes in soil properties may help towards understanding the effects of land use change on stream water chemistry, which is mainly regulated by soil properties (Biggs *et al.*, 2004). The establishment of pastures in the Amazon has caused nutrient loss to the soils, due to increased overland water flow patterns in the last four decades (Biggs *et al.*, 2006). However, it remains unclear to what extent soils are influenced by the surplus of agrochemicals in the Cerrado and how water quality is affected by altered hydrologic flow paths in this originally nutrient-limited ecosystem. Due to a lack of data on soil properties, McGrath *et al.,*

(2001) recommended chronosequence studies of natural sites and adjoining sites derived from the same vegetation type but subject to land use, particularly annual cropping systems.

The increasing agricultural land extent tends to be related to declining water quality (reviewed by Allan, 2004); yet, only a few studies have assessed the impact of mechanised agriculture on water quality and how nutrient cycling has altered in the Cerrado (e.g. Fonseca *et al.*, 2014; Gücker *et al.*, 2009; Silva *et al.*, 2007, 2011). Numerous small streams connect the terrestrial environment to rivers and, subsequently, to the sensitive Pantanal wetlands; thus, it is essential to understand the biogeochemical processes in headwaters (Fonseca *et al.*, 2014). Most water quality data of the Agencia Nacional de Águas (ANA) are only available for the largest watersheds of Brazil, with a relatively low temporal resolution and irregular sampling intervals (ANA, 2009). Consequently, the scale effects of land use change on solute loads in streams across meso-scale catchments are unclear (Germer *et al.*, 2010).

This study aimed to (1) examine the effects of land use change on the soils of natural Cerrado transformed to common croplands (soybean/cotton/maize rotation and sugarcane) and pasture and (2) indicate how agricultural production affects water quality across a meso-scale catchment. We hypothesise that an increase in soil nutrient concentrations, due to the extensive fertilisation of agricultural land, is correlated with increased nutrient concentration in streams across altered meso-scale catchments, especially in the rainy season.

3.2 Description of the study region

The study area is located within the Cerrado biome in the Brazilian state of Mato Grosso. The Tenente Amaral Catchment is a typical meso-scale catchment that underwent significant land use change from natural Cerrado to pasture and cropland over the last 20–30 years. It is situated ca. 120 km southeast of the capital Cuiabá in Mato Grosso (Figure 3-1) on the southern edge of the Brazilian Planalto which is part of the Brazilian Shield (Marques *et al.,* 2004). The water of the catchment drains into the São Lourenço River which is a major feeder of the Pantanal floodplain.

The catchment covers ca. 865 km², with the elevation ranging from 225 to 800 m above sea level (a.s.l.). The climate type is classified as Aw according to the Köppen classification, with a distinct dry season between May and September. Mean annual precipitation is 1500 mm, of which about 80 % falls as heavy rain from October to April. Long term (1995–2007) mean annual runoff at the Tenente Amaral stream gauge (Figure 3-1) is about 8 $m^3 \cdot s^{-1}$, with a maximum and minimum of 17 $m^3 \cdot s^{-1}$ and 5.8 $m^3 \cdot s^{-1}$ in the rainy and dry seasons, respectively, indicating a large seasonal variability.

The catchment is characterised by tertiary laterites on the plateau of the upper part of the catchment and by Paleozoic quartz arenites (of the Furnas group) with rocky outcrops in the lower part. Characteristic topographical soil sequences determine the distribution of Latosols (after the Brazilian soil classification; Ferralsols, according to the FAO classification; or Red Oxisol according to USDA taxonomy). The plateaus of the central part of the catchment are more deeply weathered, and are dominated by heavier Red and/or Red-Yellow Latosols than the surrounding valley slopes (Vasconcelos, 1998). Due to erosion at the edge of the plateau, finer particles are partially transported to the rivers. This sorting process leaves sandier Yellow Latosols on the lower slopes and in the concave parts of the valley. The river bottom mostly consists of solid Paleozoic quartz sandstone bedrocks. The natural vegetation of the plateau is woody savannah (Cerrado *sensu stricto*), which has been almost entirely removed for agricultural production. In contrast, the lower hillslopes are seasonally waterlogged with high groundwater tables, leading to the formation of wetlands (called *vereda*). At the permanently waterlogged riverside, Gallery Forests (called *mata ciliar*) border the streams (but see Wantzen, 2003; Wantzen *et al.*, 2006, 2012).

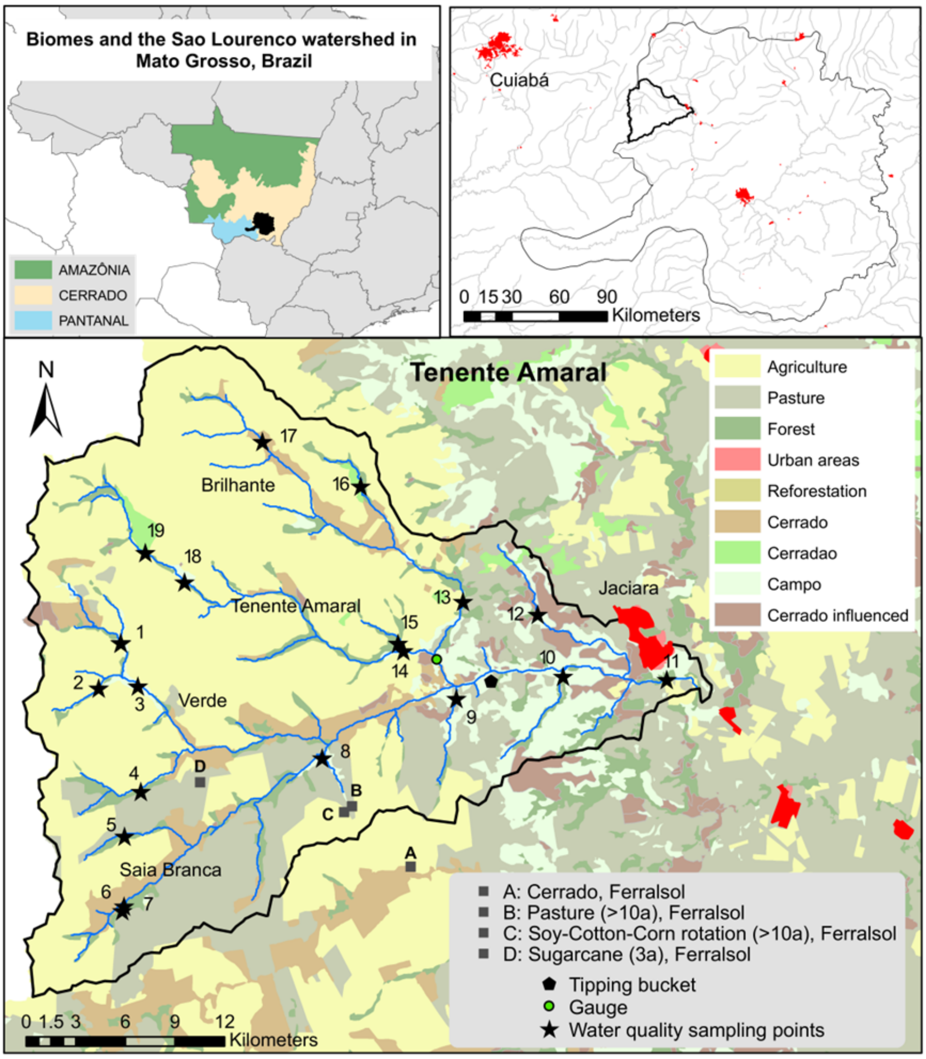


Figure 3-1: Location of the Tenente Amaral catchment within the São Lourenço watershed in the federal state Mato Grosso. Sampling sites (soil and water quality sampling) and land use of the Tenente Amaral catchment near the city Jaciará. (Data source for land use: WWF 2009)

Almost all of the Latosols of the high plains (about 70 % of the catchment) are subject to agricultural use for intensive cash crop production. Mainly sugarcane and soybean crops are grown in rotation with maize and cotton. Several sub-watersheds (covering about 18 % of the catchment) are used for cattle grazing (Rio Brilhante and parts of the Rio Verde tributaries; Figure 3-1). The small remaining part of the lower catchment is under nature conservancy. Several land management practices have been used to minimise soil erosion in the Tenente Amaral. For instance, double-cropping without irrigation is mainly used within the Tenente Amaral. Previously, no or minimal tillage was used, with soybean-maize rotation being directly planted for more than 15 years (Wantzen and Mol, 2013). Furthermore, cover crops were widely used during the dry season and small elevated contour banks were often installed on pastures and soybean fields. However, when cotton prices peaked in 2011, crop rotation practices shifted from soybean-maize to soybean-cotton, accompanied by the increased use of conventional tillage, which has resulted in the levelling of existing contour banks. At sugarcane sites, deep ploughing is conducted before the replanting every 4–5 years. The pastures are planted with *Brachiaria*, *Andropogon*, and *Panicum* sp., and are regularly fertilised. Farmers apply fertilisers, lime, and between 10 and 13 pesticides of about 2 kg·ha^{-1} depending on the crop (personal communication from the farmers, Table 3-1). Sugarcane is also fertilised with P and K rich filter cake residues and vinasse (*vinhaça,* a by-product of sugarcane distillation).

Table 3-1: Land management practices in the field study area selected for the sampling sites based on qualitative interviews with farmers of the Tenente Amaral Catchment. Percentage contribution of agricultural land-use types in 2010/2011.

Rotation system	Planting and percentage	Livestock and Tillage	Lime application	Fertiliser application (Macronutrients)	
Pasture *Brachiaria* sp.	30%	1 animal ha^{-1}	1.5–2 t·ha^{-1} (not every year)	200 kg NPK (34-10-10) or N as Urea (100 kg·ha^{-1}) during the rainy season (Jan.-Feb.)	
Soybean-corn	1. crop: planted in Nov, harvested in Feb	No tillage	3 t·ha^{-1} with planting and 1 t·ha^{-1} maintenance over the year	soybean: KCL: 120–150 kg·ha^{-1} P_2O_5 (00-21-00): 250–400 kg·ha^{-1}	corn: Urea: 200 kg·ha^{-1} or MAP*: 200 kg·ha^{-1} KCl: 80 kg·ha^{-1}
Soybean-cotton	2. crop: Mar to Sep 30%	Intensive tillage (disc harrow) after cotton harvest			cotton: Urea: 2 × 100 kg·ha^{-1} MAP*: 200 kg·ha^{-1} KCl: 150–250 kg·ha^{-1}
Sugarcane	harvest in Apr to Nov 20%	deep ploughing every 4–5 years before replanting	4 t·ha^{-1} from May to Oct (not every year)	~400–600 kg/ha NPK (20-00-20) in Sept. and P and K- rich by-products from distillation process (vinasse)	

* MAP = Monoammonium phosphate (11–52–00), MAP is sometimes used instead or combined with Urea for corn

3.3 Field samplings

3.3.1 Soil

Soil was sampled from January to March 2011, during the rainy season. To compare the impact of dominant land use types, four representative single hectare plots (100 m × 100 m) were selected: natural Cerrado, planted pasture (with a grazing intensity of one cattle per hectare), soybean-cotton rotation, and sugarcane represent different stages in a space for time approach. Five to 11 sampling points per plot were used (Figure 3-2).

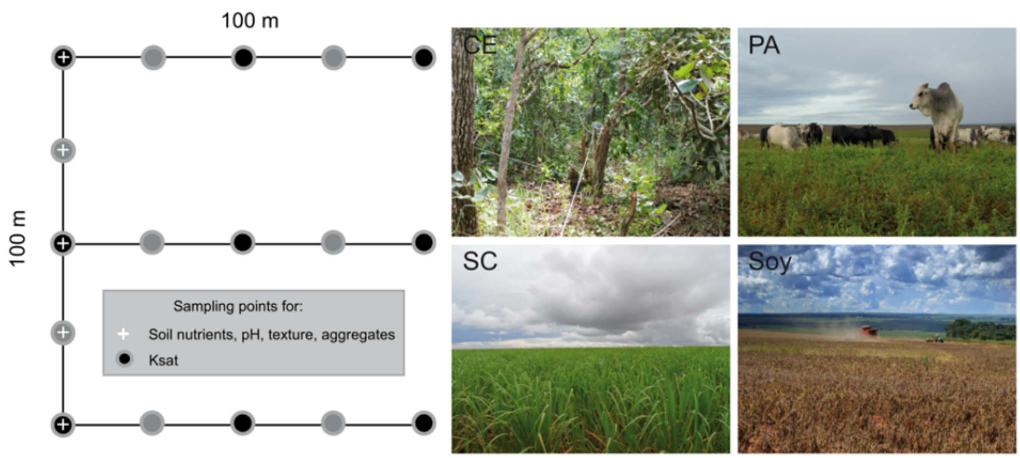


Figure 3-2: Soil sampling design on four single hectare plots (CE–Cerrado, PA–Pasture, SC–Sugar cane, Soy–Soybean)

All plots were located on soils that developed from sandy-clayey tertiary laterites on the wide plains with low slopes (of maximal 2–3 %). The parent materials are a saprolitic layer of Paleozoic quartz arenites. All plots had similar slopes so as to compare differences in soil physical and chemical properties as a function of land use only. The soils were homogenously weathered and showed little horizonation, with stonelines appearing at 1.5 m soil depth. The plot soils were classified as Dark Red dystrophic Latosols (*Latosolos vermelho escuro distrofíco)* according to the Brazilian soil classification (Rhodic Ferralsols according to the FAO classification), with low chroma colours for the Bw-horizon (Table 3-2).

Table 3-2: Soil properties at the four sampling sites. Average profiles of five 1 m auger cores per land use plot. The soil colour was determined according to the Munsell Company (1975).

	Geographic location (decimal °)	Horizon	Depth (cm)	Colour (moist)	Texture (0–75 cm)		
					Sand	Silt	Clay
Cerrado	55.100954 W	Ah	0–16	5 YR 3/2			
	16.086874 S	AB–BA	16–50	5 YR 3/6	72.5	5	22.5
	542 m	Bw	50–100+	2.5 YR 4/6			
Pasture	55.114300 W	Ap	0–17	5 YR 3/4			
	16.035925 S	AB–BA	17–62	5 YR 3/3	54.1	6.7	39.2
	574 m	Bw	62–100+	2.5 YR 4/6			
Soybean	55.117654 W	Ap	0–19	5 YR 3/4			
	16.039229 S	AB–BA	19–66	5 YR 3/4	60.1	8	31.2
	582 m	Bw	66–100+	2.5 YR 4/6			
Sugarcane	55.219188 W	Ap	0–17	2.5 YR 3/3			
	16.041406 S	AB–BA	17–64	2.5 YR 3/3	52.3	5.8	41.9
	646 m	Bw	64–100+	2.5 YR 3/5			

The following soil measurements were carried out on each land use type (Figure 3-2): ponded infiltration and Ksat measurements at 17 and 11 locations, respectively, with a minimum distance of 25 m between each location. Measurements were made at three depths (14, 20, 40 cm), because we expected land use change to have less effect at deeper layers (Hunke *et al.*, 2014). Soil was sampled using cores at five points every 25 m at three depths up to 1 m, to analyse soil nutrients (NPK), pH, and texture. At these five points, 45 soil aggregate stability tests were performed on the soil surface and at a depth of two centimetres. During the sampling period, gross precipitation was recorded continuously by a tipping-bucket rain gauge with a resolution of 0.2 mm (HOBO event logger) to determine rainfall intensity for comparison with the soil permeability of the different land uses.

Soil sampling methods

Direct field measurements of infiltrability, saturated hydraulic conductivity (Ksat), and aggregate stability were made.

Ponded infiltration rate [mm/h] was measured using a single-ring infiltrometer with a diameter of 15.0 cm (equivalent to a support of ca. 0.018 m^2), following the guidelines of Herrick *et al.,* (2005). The ring was filled with water and infiltration rates were determined until stationary flow condition was reached for several consecutive readings (Figure 3-3).

Saturated hydraulic conductivity [mm/h] (*Ksat*) was determined using a constant head permeameter (Amoozemeter; Amoozegar *et al.*, 1989, Figure 3-3). Within a cylindrical borehole, the stationary water flow was determined by keeping a constant head at three different depths until the final infiltration rate was monitored (Amoozegar, 1992). Hydraulic conductivity was calculated by the equation of Glover (Amoozegar, 1989, 1992).

Soil-aggregate stability [dimensionless] was estimated using a soil-aggregate stability kit developed according to Herrick *et al.,* (2001), with approximate support of 0.0005 m^2. The test kit is highly sensitive to differences in land management, and provides a repeatable and inexpensive direct estimation of soil aggregate stability of undisturbed samples in the field. The kit consists of a plastic box (21 × 10.5 × 3.5 cm^3) divided into 18 sections with 18 sieves that have a mesh size of 1.65 mm (Figure 3-3).

Figure 3-3. Ring infiltrometer, amoozemeter and the Herrick test kit for determining aggregate stability.

At each sampling point, we collected a surface sample and a sub-surface sample (of ~8 mm in diameter and ~3 mm thick) at a depth of 2–3 cm below the soil surface. The air-dried samples were placed on separate sieves and immersed in deionised water. After 5 min, the sieves were raised and lowered into the water by five dipping cycles. Based on the time of slaking, the samples are rated from zero (no stability) to six (high stability). During the first 5 min, the criteria used to assign the samples to the lower classes (0–3) include 50 % structural integrity loss and <10 % of the sample remains stable. Classes (3–6) are rated by the percentage of soil that remains on the sieve after the dipping cycles. Herrick *et al.,* (2001) showed a close correlation between the stability class and percent aggregate stability determined in the laboratory.

Soil pH was measured using 10 g oven dried soil in 1 M $CaCl_2$ (1:2.5) (WTW ph330i, EMBRAPA, 1997). Soil *particle size distribution* (clay-silt limit: 2 µm; silt-sand limit: 60 µm) was determined by the hydrometer (Incoterm densímetro) method (Bouyoucos, 1962) using 1 *N* sodium hydroxide and Na-hexametaphosphate solution to disperse the soil samples (EMBRAPA, 1997).

Available potassium and *phosphorus* were extracted from a 10 cm^3 oven dried soil sample with 100 ml of Mehlich-1 solution (soil:extractant ratio 1:10), and nutrient concentrations were determined using a flame photometer (Micronal B462, EMBRAPA, 1997). *Total soil nitrogen* concentration of 3 g dried soil samples was analysed by the Kjeldahl method (EMBRAPA, 1997), and measured with a spectrometer (CELM E-225D; EMBRAPA, 2006).

3.3.2 Water

To investigate the spatial and seasonal biogeochemical characteristics of the streams, we used the 'snapshot sampling' approach after Grayson *et al.,* (1997) at 19 sampling locations across the catchment at the beginning of the 2010 dry season (21–22 May) and during the 2011 rainy season

(21–22 February). Sampling locations were distributed randomly across the entire Tenente Amaral Catchment (Figure 3-1; some locations were slightly adjusted during the field campaign due to accessibility and restrictions by landowners). For each sampling location, the draining area/sub-watershed and land use distribution was calculated in ArcMap 9.3.1 Hydrotools extension (ESRI).

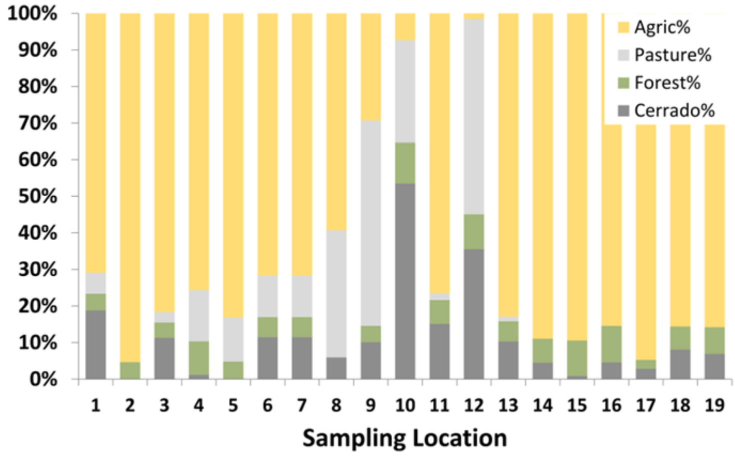


Figure 3-4: Percentage of land use in the sub-catchment of each sampling location. Location 12 represents the entire Tenente Amaral catchment.

Analysis of water samples

At each sampling point (Figure 3-4), three replicate samples were collected, and physical water parameters (temperature, dissolved and saturated O_2, pH, ORP and electric conductivity) were measured in situ with a HydroLab Quanta multiparameter probe. All samples were stored on ice in coolers immediately after collection. The samples were filtered (0.2 µm) and anion analyses (Cl^-, NO_3^-, SO_4^{2-}, NO_2^-, and PO_4^{3-}) were carried out 5–7 days after collection in the UFMT laboratory (Department Chemistry) with a Dionex ion chromatograph (model AS-40, ICS-90) system. Separated standard curves were prepared for ion analysis. Every sixth sample was pure water, as a control. The r^2 of the correlation between the standard and peak area was, in all cases, larger than 0.99 and all blank solutions were below the detection limits.

3.3.3 Statistical analyses

Due to non-normality of the soil and water quality data (normality was rejected after Kolmogorov Smirnov test), non-parametric statistical tests were performed. For the analysis of differences of soil physical and chemical properties as a function of altered land use, the Kruskal-Wallis test was employed ($\alpha = 0.05$) (Kruskal and Wallis, 1952) with post-hoc Bonferroni correction for multiple comparisons. Significant differences between soil aggregate stability classes per land use were tested with the Wilcoxon's rank sum test. To account for seasonality effects in the water quality snapshot sampling data, we performed a pairwise Mann-Whitney *U*-test. For comparisons of the water parameters across the sampling locations, we tested both seasons individually for significant effects between the different stream systems and stream orders by applying the Kruskal-Wallis test. Correlation analysis (Spearman) was conducted to assess the relationships of the percentage of land use per sampling location and distance to outlet with each water quality parameter.

All analyses were carried out with the open source software R version 2.15.3 (packages *agricolae* and *pgirmess*) using $\alpha < 0.05$ to report significant effects.

3.4 Assessment of soil characteristics in a heavily modified Cerrado catchment

3.4.1 Soil physical properties

Median infiltrability and Ksat decreased markedly with increasing depth after land use change from natural Cerrado to all investigated land use types (Table 3-3 and Figure 3-5). The Cerrado site had the highest infiltration rates, followed by extremely reduced rates for sugarcane (–90 %), soybean (-93 %), and pasture (–96 %). Cerrado and soybean showed wider ranges for surface infiltration within plots. This result may be due to macropores caused by termites and plant roots at the Cerrado site and plant residue from harvest at the soybean site. Infiltration was significantly different among all land use types, except for soybean and sugarcane, which were indistinguishable. At 40 cm depth, the land use signal markedly declined, although cerrado remained significantly different to the anthropogenic land use types. Compared to the anthropogenic land use types, cerrado had the highest sand content and the lowest clay content (Table 3-3).

Table 3-3: Physical soil properties of natural Cerrado vegetation, pasture, soybean, and sugarcane. Median (± mad) surface infiltrability, Ksat (at 14 cm, 20 cm, and 40 cm), and mean (± SD) soil stability classes after the Herrick kit (Herrick *et al.*, 2001; zero: no stability, six: high stability).

Location	Infiltrabilty (*n*=17)	Ksat (14 cm) (*n*=11)	Ksat (20 cm) (n=11)	Ksat(40 cm) (*n*=11)	Soil stability class (*n*=45)	
	mm/h				Surface	Subsurface
Cerrado	1200±177	95±45	14±9	12±4	5.53±0.81	5.82±0.39
Pasture	45±22	6±3	5±2	5±5	5.84±0.59	5.84±0.36
Soybean	240±177	9±6	5±2	3±2	3.51±1.03	4.13±1.27
Sugarcane	120±44	7±3	1±1	5±4	4.87±1.12	5.17±0.94

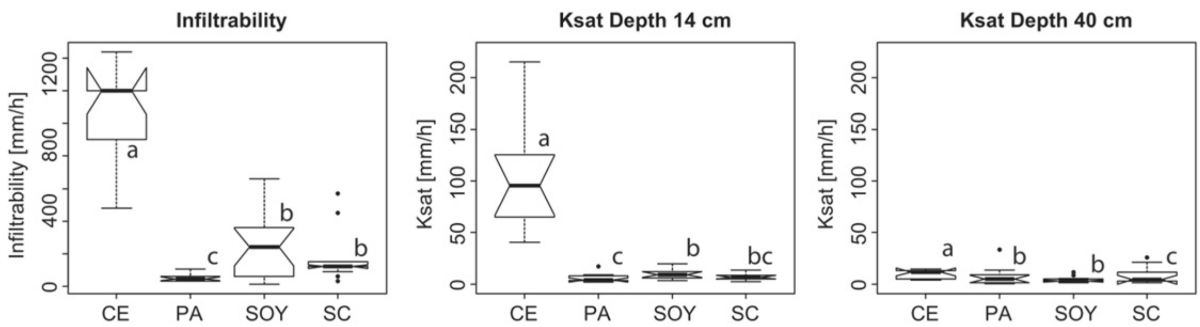


Figure 3-5: Surface infiltrability and Ksat at 14 cm and 40 cm soil depth as a function of land use type (CE–Cerrado, PA–Pasture, SOY–Soybean/cotton, and SC–Sugarcane) on Ferralsols. The width of the boxplot notches represents the 95 % confidence interval of the median value (notch= ±1.58 × interquartile range (IQR)/√n). Non-overlapping notches from two boxplots indicate significant differences between the medians. Lower-case letters denote significant differences ($p < 0.05$) after the Kruskal Wallis multicomparison procedure. n = 17 (infiltration) and n = 11 (Ksat) for each plot and depth, respectively.

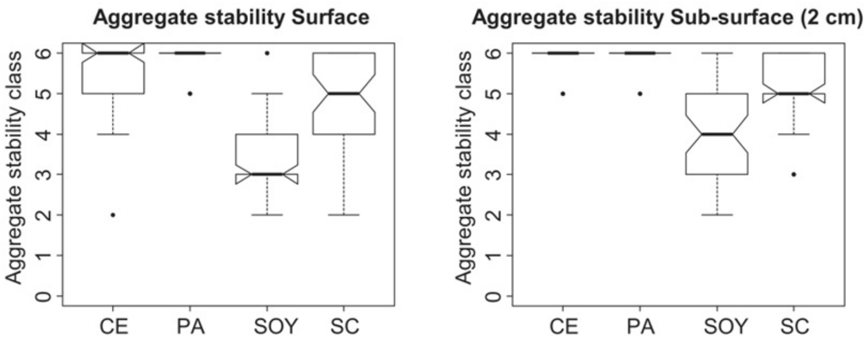


Figure 3-6: Boxplots of soil aggregate stability classes (after Herrick *et al.*, 2001) of land use type (CE– Cerrado, PA–Pasture, SOY–Soybean, SC–Sugarcane) on Ferralsols at the soil surface and at 2 cm depth (n = 45). The width of the boxplot notches represents the 95 % confidence interval of the median value (notch= ±1.58 × interquartile range (IQR)/√n). Non-overlapping notches from two boxplots indicate roughly significant differences between the medians.

Due to compaction, we observed very resistant *soil aggregate classes* for pasture at the surface and 2 cm depth (Table 3-3, Figure 3-6). Similarly high resistance at the Cerrado site might be caused by higher topsoil organic matter content stabilising soil particles. Significantly lower aggregate stability and greater variation within the dataset were detected for soybean plots (–50 %, many samples below class 3) and the sugarcane site. The Wilcoxon test showed the marked difference in soil aggregate stability for row crops with pasture and Cerrado, with the following ranking from stable to unstable ({} = no significant difference): PA>CE>SC>SOY at the soil surface and {CE,PA}>SC>SOY at 2 cm soil depth.

3.4.2 Soil chemical properties

Until a soil depth of 100 cm, the pasture, soybean, and sugarcane site soils were neutral, while those at the Cerrado site were moderately acid (pH values in Figure 3-7). Sugarcane had the highest soil pH values, followed by soybean and pasture.

Table 3-4: Chemical soil properties for natural Cerrado vegetation, pasture, soybean, and sugarcane with median values (± interquartile range– IQR) and standard deviation for pH (CaCl2) and soil nutrients at three depths differentiated by Munsell soil colour.

Plot	Location (geographical)	Soil Depth [cm]	pH [$CaCl_2$]	Potassium [mg kg^{-1}]	Phosphorus [mg kg^{-1}]	Nitrogen [g kg^{-1}]
Cerrado	55.100954 W	0 – 16	5.2±0.1	23.7±8.2	8.6±1.5	2.5±0.3
	16.086874 S	16 – 50	5.2±0.1	20.1±6.4	6.6±3.4	1.4±0.8
	542 m	50 – 100	5.6±0.3	6.4±1.8	2±2.1	1.7±0.3
Pasture	55.114300 W	0 – 17	6.2±0.2	42.9±11.9	13.2±5.3	1.7±0.6
	16.035925 S	17 – 62	6.3±0.2	30.1±21.9	7±10.1	1.9±0.6
	574 m	62 – 100	6.5±0.2	9.1±6.4	1.6±0.0	1.1±0.3
Soybean	55.117654 W	0 – 19	6.6±0.1	61.2±21	82.4±17.9	2.2±0.3
	16.039229 S	19 – 66	6.6±0.3	34.7±14.6	19.7±16.3	2.2±0.3
	582 m	66 – 100	6.8±0.1	25.6±7.3	1.7±2.6	1.7±0.3
Sugarcane	55.219188 W	0 – 17	6.9±0.0	17.3±1	8.7±9.5	2.0±0.3
	16.041406 S	17 – 64	7.0±0.8	15.5±8.2	3.4±1.0	2.0±0.6
	646 m	64 – 100	6.5±0.1	8.2±8.2	2.3±4.0	0.8±0.0

Compared to natural Cerrado, the pH values of the three land use types were significantly higher by 1–2 units in the topsoil. At 50–100 cm soil depth, pH tended to increase from Cerrado to pasture and soybean, whereas it significantly decreased for sugarcane ($p < 0.05$), showing only small differences between crop types. Cerrado and soybean had the highest soil nitrogen concentrations at all sampled soil depths down to 100 cm, with nitrogen concentration declining with increasing soil depth (Table 3-4). Among the anthropogenic land use types, pasture and sugarcane had the lowest soil nitrogen content. Artificial fertilisation had a pronounced effect on the topsoil concentrations of potassium and phosphorus for soybean, and to a lesser extent for sugarcane and pasture. With increasing soil depth, potassium and phosphorus content dropped markedly, showing only small differences among the plots (Table 3-4).

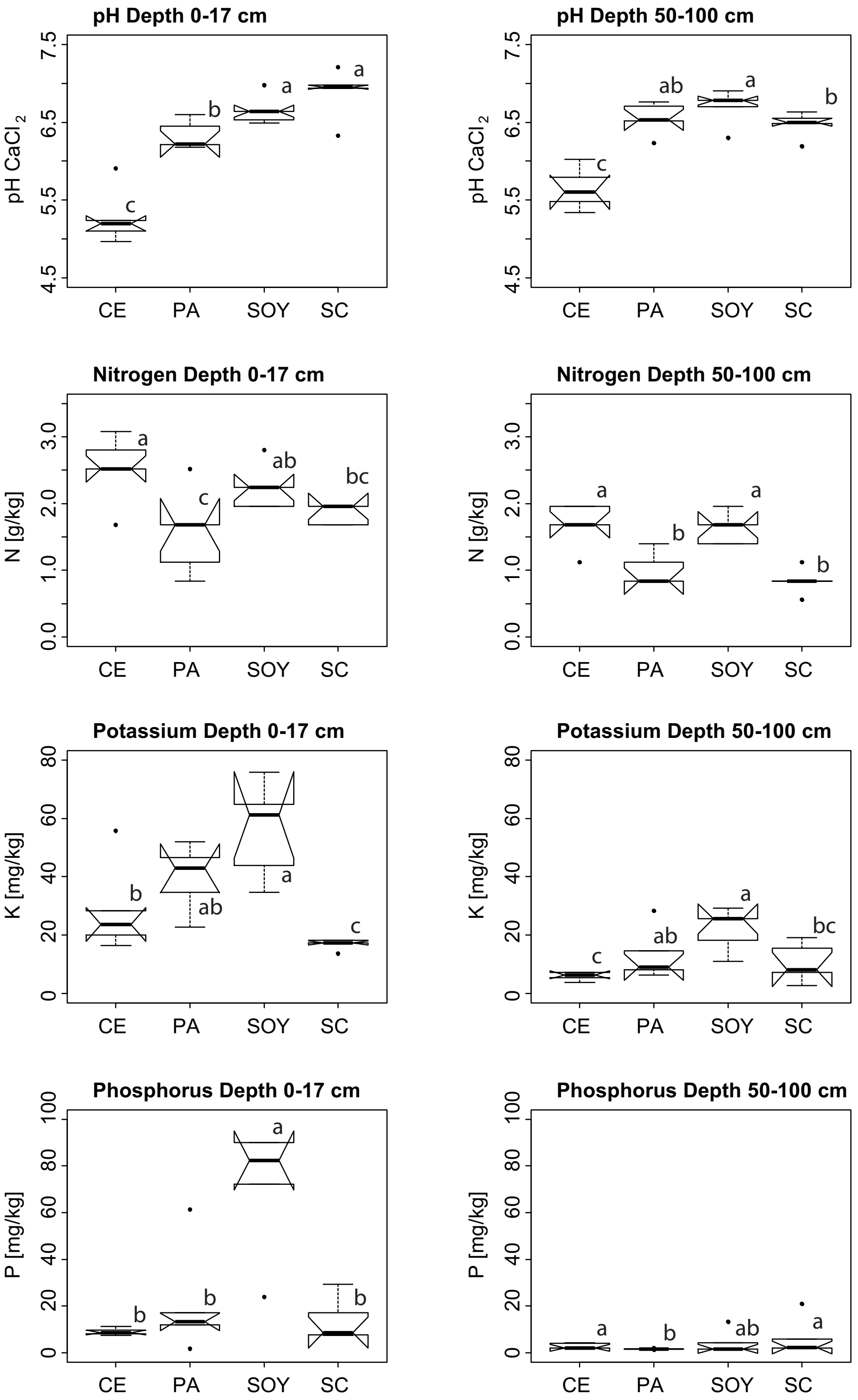


Figure 3-7: Boxplots for soil pH, total nitrogen, available potassium, and available phosphorus at two soil depths (0–17 cm and 50–100 cm) for different land use types (CE–Cerrado, PA–Pasture, SOY–Soybean and SC–Sugarcane) in the Tenente Amaral Catchment. The width of the boxplot notches represents the 95 % confidence interval of the median value (notch= ±1.58 × interquartile range (IQR)/√*n*). Non-overlapping notches from two boxplots indicate significant differences between the medians. Different letters indicate significant ($p < 0.05$) differences between the sites after Kruskal-Wallis multicomparison procedure (*n* = 5).

3.4.3 Discussion of the altered soil properties

Changes of infiltrability, Ksat, overland flow and implications of erosion processes after land conversion

Our field measurement results support those of previous studies, showing that deforestation for conversion to agriculture is a land use signal, resulting in decreased topsoil infiltration rates of almost one order of magnitude (Scheffler *et al.*, 2011; Zimmermann *et al.*, 2006, 2010). However, the recorded decline in infiltration rates for pastures (Zimmermann *et al.*, 2006) and soybeans (Scheffler *et al.*, 2011) was not as high as we monitored. The forest reference measurements in the study by Scheffler *et al.,* (2011) showed that sites characterised by similar clay content had similar infiltration rates to that recorded for the Cerrado in our study. The difference for the agricultural sites might be due to heavier land use practices or different land use history in the Cerrado compared to the Amazon. For instance, Zimmermann *et al.,* (2006) recorded reduced Ksat to 20 cm soil depth, whereas it was to 40 cm in our study. Therefore, natural Cerrado Ferralsols appear to have very high Ksat rates (Reatto *et al.*, 2007).

A reduction in soil hydraulic conductivity significantly affects the generation of runoff. The results indicate the occurrence of overland flow (OLF), as maximum 5 min rainfall intensities (I_5) frequently exceed superficial hydraulic conductivity for pasture, sugarcane, and soybean. One third of all I_5 events exceeded median infiltration at the soil surface of the pasture only. At 14 cm soil depth, I_5 exceeded Ksat in 83–96 % for all anthropogenic land use types, whereas it was just 7 % higher in the Cerrado (Figure 3-8). Therefore, an impermeable water table at 14 cm soil depth causes saturation at the soil surface, resulting in saturation and infiltration excess OLF during heavy rainfall events. This finding explained why we observed ponding and OLF at every rainfall event during the field campaigns.

(I) (II)

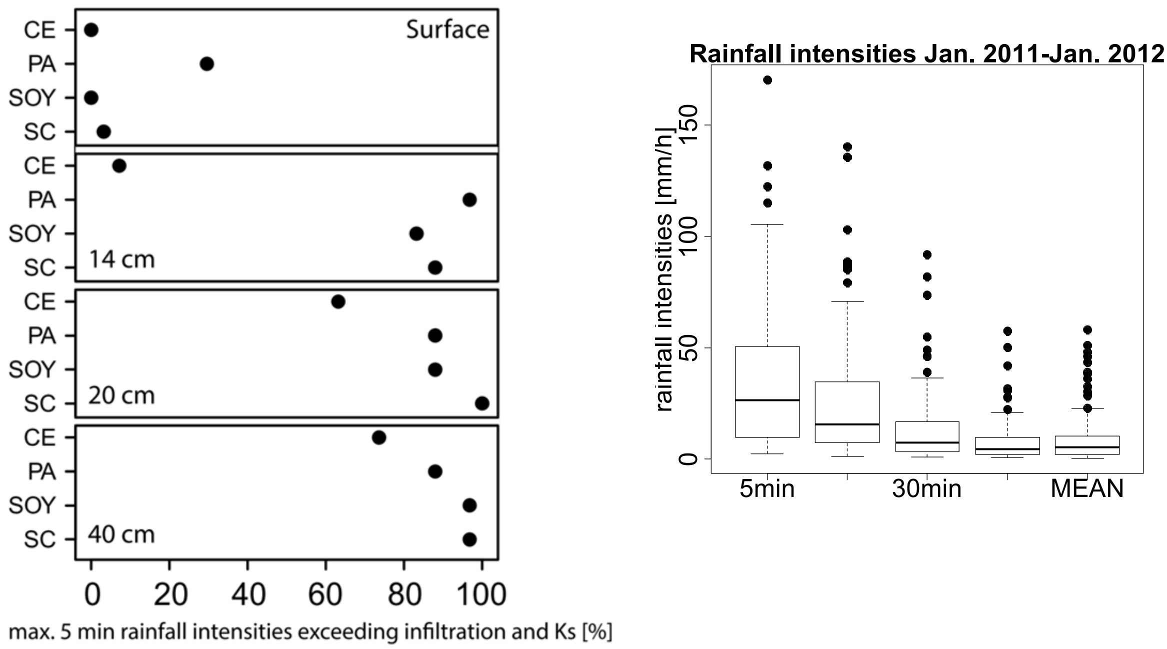


Figure 3-8: Percentage of max 5min rainfall intensity events exceeding surface infiltrability and Ksat (depth: 14, 20 and 40 cm) for different land uses (CE– Cerrado, PA–Pasture, SOY– Soybean, SC– Sugarcane) (I). Rainfall intensity statistics (5 min, 10 min, 30 min, 60 min and mean) from *n*=125 recorded rainfall events over a one year period (II).

Reduced infiltration is not only affected by mechanical compaction and increased bulk density (McGrath *et al.*, 2001; Trabaquini *et al.*, 2013) caused by cattle trampling and farm vehicles. For instance, Haynes and Naidu (1998) showed that lime application to Brazilian Ferralsol raised the pH_{KCL} to 6.5, which increased clay dispersion, destroyed soil aggregates, and reduced infiltration. The current study identified raised soil pH up to 100 cm soil depth, in addition to low soil aggregate stability and higher clay contents for soybean and sugarcane (Figure 3-6, Figure 3-7). Soil is likely to disperse during high-intensity rainstorm events, resulting in the transport of top soil material in more intensive land use types (Balbino *et al.*, 2002; Portella *et al.*, 2012). The low soil surface stability for soybean and sugarcane also indicates susceptibility to soil loss, even with reduced tillage. Biggs *et al.,* (2006) showed that the deforestation processes in the Amazonian region has increased solute and nutrient export that lasts for decades, due to altered infiltration processes and increased overland flow. Neill *et al.,* (2013) on the other hand stated that decreased soil hydraulic conductivity under soybean fields cause only rare occurrence of Hortonian overland flow. The authors concluded that the landscape is due to no-till practice resistant to rill erosion (but qualified their statement that long-term effects are not clear).

During the two field campaigns, water ponding was evident on the pasture after almost every rainfall event; even with lower maximum 5min rainfall intensities (Figure 3-9). We observed active erosion processes with the transport of suspended sediments through 38 gullies that were mainly located in soybean-maize-cotton areas of the catchment (de Jesuz *et al.*, 2013).

Figure 3-9: Erosion processes from degraded pastures. Water ponding can be observed even after smaller rainfall events on pastures across the Tenente Amaral catchment with the potential to develop 15 m deep and several hundred meter long gullies.

However, we do not know whether these gullies developed before the implementation of direct planting. Gullies tend to form close to cattle tracks, which seem to function as triggers (Wantzen, 2003; Wantzen *et al.*, 2006). Other studies attributed higher soil loss to soybean compared to sugarcane (Rossetto *et al.*, 2010).

Correction of pH and topsoil nutrient accumulation

Soil nutrient concentrations (K, P) are deliberately increased to raise biomass production on the Cerrado (Oliveira *et al.*, 2004; Pavinato *et al.*, 2009). Compared to Cerrado soils, soybean and, to a lesser extent, pasture soil nutrient concentrations were higher at shallower soil depths in the current study. To reduce Al toxicity and increase nutrient availability, the pH value in lower soil depth must be raised to >6, which is very high (EMBRAPA, 2003). The soybean site has been heavily modified by topsoil P, probably due to previously applied fertilisers. However, soil extractable P concentrations are notably higher (~6-fold) than the soil nutrient recommendations of EMBRAPA (2003) and Morais *et al.,* (2009). These values reach levels where no crop response resulting in higher yields are expected. Therefore, over-fertilised P is potentially available for displacement via surface erosion from soybean sites. Leaching from deeper soil depth (>66 cm) is unlikely, as there no soil P accumulation was observed. However, lateral subsurface flow paths in the rainy season may increase the risk of P loss (Delgado and Scalenghe, 2008) due to altered soil permeability (Figure 3-5). Pasture P and K concentrations were also altered to meet the requirements for increased biomass production (EMBRAPA, 2003; Oliveira *et al.*, 2000; Silva *et al.*, 2004). Unexpectedly, sugarcane had the lowest soil nutrient concentrations, which may be due to erosion and the entire loss of the organic topsoil layer. However, compared to the other land use types evaluated here, Ap horizons were not reduced in sugarcane soil core samples. As sugarcane was ready for the last harvest before replanting, less fertiliser may have been applied during the most recent fertiliser application (five months before).

Lower total N concentration was recorded in the pasture, possibly supporting Neill *et al.,* (1995, 1999) who observed a decline in soil N for older pastures after forest conversion, with higher net N mineralisation and nitrification rates in Amazonian forest topsoils. Roscoe *et al.,* (2001) also recorded higher N concentrations for Cerrado versus pasture. Compared to the Cerrado, N levels were also lower at the soybean-cotton rotation sites and sugarcane sites. These lower levels may have resulted because we sampled the soil shortly after the soybean harvest. Compared to sugarcane (Boddey *et al.*, 2003) soybeans, which are nitrogen fixers, were only fertilised with N if required (e.g. the leaves became brown) (Sousa and Rein, 2009).

During sampling in February 2011, the measured soil N content exhibited no risk of N leaching from the pasture, soybean, or sugar cane sites. However, this state might change after the soybean harvest in February, when N fertilisers (urea of in average 200 kg ha^{-1}) are applied to maize and cotton fields when the soil is bare and there is no direct plant uptake. Because Cerrado soils have low N concentrations, potential nutrient fluxes to the stream network are only related to fertilisers (Figueiredo *et al.*, 2010). In addition, NH_4^+ to NO_3^- may be quickly oxidised, contributing to eutrophication. Consequently, metastable intermediate NO_2^- is toxic, presenting a serious threat to aquatic organisms. Nitrate is highly mobile and mostly absent from the soil profile, due to fast leaching to groundwater or plant uptake. However, an N mineralisation flush is expected in September and October (Neufeldt *et al.*, 1999), when the soils are rewetted at the beginning of the rainy season.

3.5 Assessment of water quality in a heavily modified Cerrado catchment

3.5.1 Results of the water quality snapshot sampling field data

The snapshot sampling locations cover different stream systems and stream orders (2nd to 5th order, Figure 3-1). For 16 of the 19 sampling locations, upstream land use was dominated by agricultural use (Table 3-5). The electrical conductivity of the water quality samples was low (below 10 $\mu S \cdot cm^{-1}$, except for ID 12). Across the catchment, nitrate, chlorite, and ORP ranges were high. In particular, nitrite concentrations were high during the rainy season (>100 $\mu g \cdot l^{-1}$), with a ~4 fold increased median value compared to the dry season. High nitrite concentrations were correlated with very low oxygen concentrations (<5 $mg \cdot l^{-1}$) and critical low oxygen saturations between 50–65 %. Therefore, oxygen saturation was about 20 % lower in the rainy season compared to the dry season at all sampling locations. Phosphate concentrations were high (>200 $\mu g \cdot l^{-1}$) at most locations in the dry season and were absent during the rainy season, except at ID 19.

The percentage of agricultural land use in the sub-catchments and the riparian buffers was not correlated with nutrient concentrations at the sampling locations. We tested the significance between different stream systems (Table 3-5) and the relationship between each water parameter with stream order (2^{nd}–5^{th}). Significant differences between the sampled streams were only found for Cl^- ($p = 0.03$) with a 1.4–4.5-fold increase in the centrally located Tenente Amaral Stream (mean 508 $\mu g \cdot l^{-1}$) during the rainy season. DO saturation ($p = 0.03$) and DO concentration ($p = 0.03$) were below 6 $mg \cdot l^{-1}$ in the Saia Branca Stream during the dry season. No other water parameters showed significant differences or relationship with stream order, contributing area, or distance to outlet.

All water parameters showed strong seasonality, except water conductivity, and chlorite, nitrate and sulphate concentrations. Compared to the dry season, temperature ($p < 0.001$) and nitrite ($p < 0.001$) values were significantly raised, whereas DO ($p < 0.001$), oxygen saturation ($p < 0.001$), pH ($p < 0.001$) and phosphate ($p < 0.001$) were significantly lower, during the rainy season (Figure 3-10).

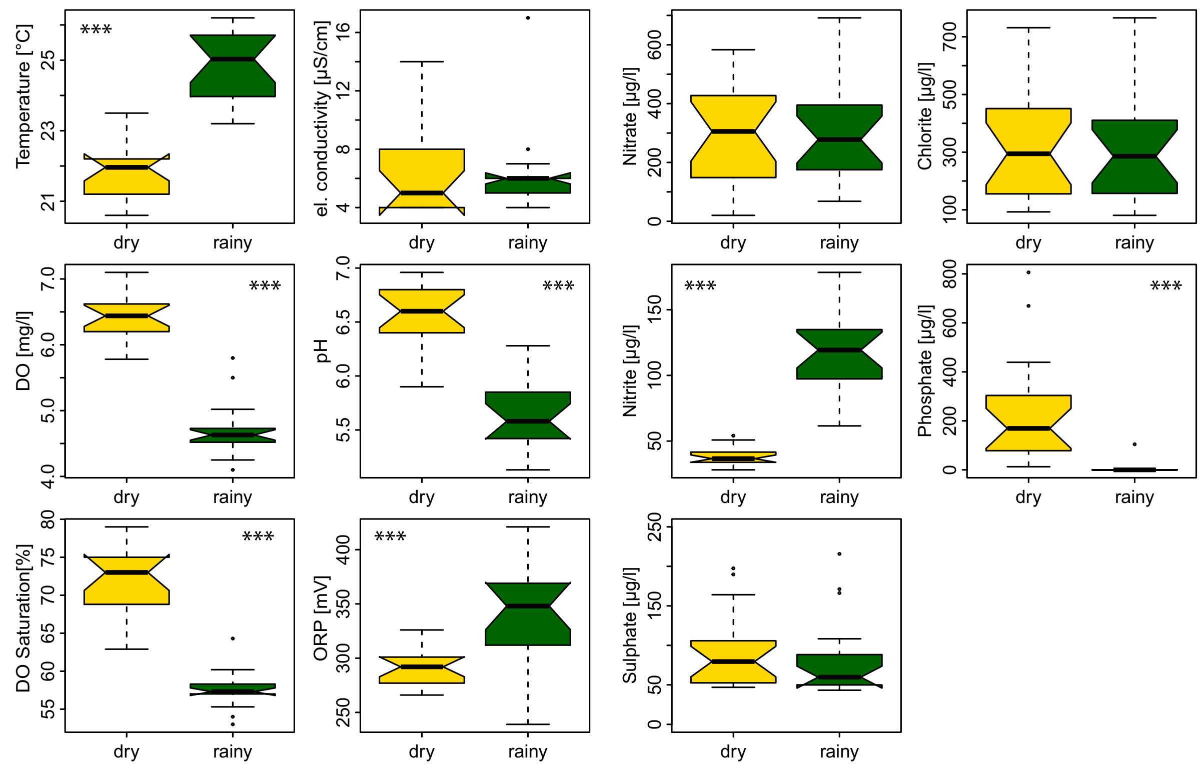


Figure 3-10: Boxplots of physical and chemical water parameters of the snapshot sampling locations in the dry and rainy season. Each sampling location (n = 19) is represented by the mean of three replicates. The width of the boxplot notches represents the 95 % confidence interval of the median value (notch= ±1.58 × interquartile range (IQR)/$\sqrt{n}$). Non-overlapping notches from two boxplots indicate significant differences between the medians. The three asterisks (***) indicate significant differences between the seasons (α = 0.05) after the Wilcoxon test.

Table 3-5: Sampling point (ID), stream system (V–Verde, SB–Saia Branca, LC–Lower catchment, B–Brilhante, TA–Tenente Amaral), distance to outlet (d), and water chemistry of the snapshot sampling locations in the dry and rainy season. Land cover (% contribution) is given for the sub-catchment area of each sampling location and for the 300 m wide riparian corridor. Reported water chemistry (NO_2^-, NO_3^-, PO_4^{3-}, SO_4^{2-}, Cl^-) values are means of three replicate samples and specific conductance (SC), water temperature (WT), dissolved oxygen (DO), pH, saturated DO, and oxi-reduction potential (ORP) means of three replicate measurements.

ID	Stream	Order	Area [km²]	Season	Agriculture [%]	Cerrado [%]	Pasture [%]	d [km]	NO_2^- [µg l^{-1}]	NO_3^- [µg l^{-1}]	PO_4^{3-} [µg l^{-1}]	SO_4^{2-} [µg l^{-1}]	Cl^- [µg l^{-1}]	SC [µS cm^{-1}]	WT [°C]	DO [mg l^{-1}]	pH	SDO [%]	ORP [mV]
1	V	3rd	33.42	dry	66.43 47.43	21.87 52.39	5.39 0.19	43.34	37.55	581.89	12.74	107.30	485.85	8.00	21.80	5.78	6.90	62.90	283.00
				wet					134.12	437.84	0.00	62.90	448.16	7.00	26.20	4.25	5.78	54.00	274.00
2	V	2nd	12.45	dry	95.34 73.32	4.66 26.68	0.00 0.00	42.99	28.67	460.69	62.59	83.27	526.36	8.00	21.02	6.24	6.94	68.80	284.00
				wet					119.76	382.54	0.00	54.93	407.70	6.00	23.20	4.63	5.58	57.30	321.00
3	V	3rd	65.51	dry	79.09 52.50	15.01 47.42	2.75 0.11	40.19	34.12	391.70	364.65	54.39	286.52	5.00	22.22	6.44	6.28	73.20	326.00
				wet					146.93	399.48	0.00	50.60	349.36	6.00	23.81	5.02	5.24	60.20	369.00
4	V	3rd	36.50	dry	75.64 18.82	10.36 69.68	14.00 11.50	39.51	29.60	308.77	169.18	52.07	310.06	4.00	21.72	6.28	6.70	72.00	301.00
				wet					104.25	278.00	0.00	47.74	163.92	4.00	23.50	5.00	5.57	60.20	353.00
5	SB	2nd	8.30	dry	83.13 34.58	4.82 53.34	12.05 12.08	42.00	35.65	477.98	105.56	52.55	452.59	6.00	21.96	5.80	5.90	66.30	319.00
				wet					82.30	424.27	0.00	56.55	150.35	5.00	25.03	4.49	5.26	55.30	385.00
6	SB	3rd	30.43	dry	71.67 31.53	16.96 66.58	11.37 1.90	43.19	54.08	20.13	182.44	82.03	148.53						
				wet					178.47	73.35	0.00	50.99	80.96						
7	SB	3rd	30.43	dry	71.67 30.70	16.96 67.09	11.37 2.21	43.52	28.07	44.26	89.62	79.46	449.77	5.00	22.72	5.96	6.40	68.30	276.00
				wet					73.77	67.96	0.00	59.76	90.77	7.00	26.07	4.60	5.85	57.00	240.00
8	SB	3rd	11.93	dry	59.26 63.86	5.95 2.11	34.79 34.08	27.21	37.45	91.90	169.15	52.47	137.48	4.00	22.11	6.01	6.33	68.20	319.00
				wet					61.56	118.16	0.00	64.17	128.85	4.00	24.42	4.35	5.13	53.00	421.00
9	LC	2nd	16.37	dry	28.83 17.47	14.36 92.92	55.28 31.12	17.88	32.21	317.56	669.40	46.89	145.13	4.00	22.20	6.60	6.80	75.00	300.00
				wet					79.48	317.39	0.00	47.91	178.96	4.00	25.73	4.10	5.68	58.30	350.00
10	LC	4th	17.14	dry	6.88 1.53	60.62 88.18	26.25 10.29	10.85	46.67	154.66	806.08	100.00	99.69	5.00	23.50	6.20	6.44	71.50	311.00
				wet					117.55	323.23	0.00	171.24	285.82	6.00	25.37	4.61	5.57	57.20	321.00
11	Outlet	5th	854.00	dry	74.25 25.88	20.97 65.32	1.74 10.97	3.59	38.78	305.40	396.69	197.53	323.29	5.00	21.20	7.10	6.96	79.00	296.00
				wet					129.92	391.08	0.00	215.79	357.10	6.00	25.40	5.50	5.94	64.30	303.00
12	LC	3rd	19.31	dry	1.19 24.89	35.47 50.67	42.05 28.33	14.47	44.27	583.31	17.21	901.18	294.55	14.00	22.17	6.33	6.60	71.00	270.00
				wet					127.83	691.56	0.00	1395.78	622.46	17.00	26.02	5.80	6.28	58.30	239.00
13	B	3rd	148.09	dry	82.94 33.27	15.80 64.33	1.26 2.40	23.31	50.10	278.23	67.06	47.98	209.43	4.00	20.71	6.80	6.48	75.30	292.00
				wet					119.31	239.19	0.00	48.25	254.25	5.00	25.71	4.72	5.42	58.40	348.00
14	TA	2nd	178.98	dry	88.92 41.61	11.07 58.52	0.00 0.00	21.72	50.83	494.06	165.07	164.15	731.67	8.00	21.98	7.00	6.76	78.00	273.00
				wet					96.11	443.40	0.00	166.25	765.65	8.00	24.80	4.63	5.95	57.20	317.00
15	TA	3rd	16.80	dry	89.40 53.10	10.60 46.90	0.00 0.00	22.45	36.62	153.68	242.71	54.35	278.20	5.00	21.16	6.75	6.80	75.60	277.00
				wet					135.66	238.63	0.00	65.70	413.81	5.00	25.00	4.65	5.86	57.30	361.00
16	B	2nd	15.02	dry	85.42 21.71	14.58 78.29	0.00 0.00	33.76	33.55	124.02	218.94	48.53	162.38	4.00	20.60	6.62	6.50	73.40	287.00
				wet					98.64	190.03	0.00	43.23	150.24	4.00	23.71	4.73	5.54	57.00	373.00
17	B	2nd	41.70	dry	94.72 47.93	5.28 52.07	0.00 0.00	40.47	36.59	143.72	26.74	56.20	93.09	5.00	23.36	6.44	6.00	73.00	299.00
				wet					140.66	128.07	0.00	49.30	179.37	5.00	25.60	4.61	5.29	57.70	374.00
18	TA	2nd	54.69	dry	85.34 39.31	14.39 60.70	0.00 0.00	38.10	34.87	394.41	439.10	189.80	605.47	8.00	21.90	6.50	6.69	74.40	266.00
				wet					118.08	237.03	0.00	108.32	563.05	6.00	23.97	4.52	5.77	55.80	312.00
19	TA	2nd	42.42	dry	85.55 40.68	14.14 59.32	0.00 0.00	41.16	38.91	237.52	228.66	104.31	362.06						
				wet					143.67	160.83	104.26	68.20	292.18						

3.5.2 Discussion of altered water quality

Effect of season on water quality

A seasonal pattern was observed for most measured water quality parameters (temperature, pH, DO, ORP, phosphate, and nitrite). However, water conductivity, nitrate, chlorite, and sulphate showed no seasonal response, which was also reported by Silva *et al.,* (2007) for natural and sugarcane catchments in the southern Cerrado. In contrast, Silva *et al.,* (2011) recorded higher solute concentrations with increasing discharge in rural and natural streams during the rainy season. At our study site, this pattern was only recorded for nitrite concentrations.

Stream temperature in the dry season has an average of four degrees lower (19–23.5 °C) than in the rainy season, which is directly linked to lower air temperature and higher groundwater recharge at baseflow conditions. Lower DO concentrations at all sampling locations in the rainy season support the findings of Silva *et al.,* (2011), and may be related to higher stream temperature and turbidity. DO saturation was also significantly lower, with small ranges in the rainy season data set across the catchment, which may indicate altered decomposition processes of organic material.

The absence of PO_4^{3-} in the rainy season was unexpected because (i) soil data showed high topsoil P concentration for row crops and (ii) active surface erosion processes were observed across the entire catchment. At the time of snapshot sampling, soybean and sugarcane were being harvested so there was no recent P fertilisation, in addition to samples being collected after 48 hours without rainfall. Probably, the first rainfall events of the rainy season had flushed out most deposited phosphate. Consequently, discharge (continuously) diluted PO_4^{3-} over time. Alternatively, higher plant uptake during the crop growth cycle may reduce soil P concentrations. Neill *et al.,* (2013) suggested that very high nutrient storage capacities of tropical soils results in P being not readily available for transport to the stream network. In contrast to Silva *et al.,* (2011) and Silva-Junior *et al.,* (2014), who found only very small quantities of P (16–35 $\mu g \cdot l^{-1}$ PO_4^{3-} and 10–15 $\mu g \cdot l^{-1}$ as SRP, respectively) in agricultural catchments in both the dry and rainy seasons, we detected high PO_4^{3-} concentrations (>100 $\mu g \cdot l^{-1}$) during the dry season. This finding is supported by Biggs *et al.,* (2004), who recorded higher P concentrations in pasture streams of the Amazon during the dry season. Such high PO_4^{3-} concentrations imply non-point agricultural influence from fertilisers applied to sugarcane and to the second crop after the soybean harvest (i.e. maize and cotton at our study site).

High nitrite concentrations (median >100 $\mu g \cdot l^{-1}$) across the catchment in the rainy season samples coincided with urea fertiliser application on maize and cotton about two weeks before sampling. Silva *et al.,* (2011) also documented higher nitrite concentrations in rural streams during the rainy season. Simultaneously higher ORP redox potentials indicated oxidising conditions, and supported the assumption of freshly converted ammonium oxidised to nitrite as an unstable intermediate compound in the nitrification process. However, urea seems to have faster nitrification rates than other nitrogen fertilisers (Mulvaney, 1994).

Impact of agriculture on water quality

The measured low water conductivity (<10 $\mu S \cdot cm^{-1}$) supported previous studies at deeply weathered, weakly buffered Cerrado sites (Markewitz *et al.*, 2006; Parron, 2004; Silva *et al.*, 2011; Wantzen, 2003). We expected electrical conductivity to increase due to inverse dilution effects (i.e. decreasing discharge) during the dry season (Biggs *et al.*, 2006). However, this trend was not detected in our water samples. In comparison to previous (20 year ago) measurements in the same catchment (Wantzen, 2003), water conductivity had slightly increased to be constantly >4 $\mu S \cdot cm^{-1}$. Silva *et al.,* (2011) detected higher water conductivity (of 7.3 $\mu S \cdot cm^{-1}$) in rural streams compared to natural low order catchments (4 $\mu S \cdot cm^{-1}$); thus, we conclude that agricultural land use has had a measurable impact on solute loads in the river system.

The Cerrado is a very nutrient-limited system (Bustamante *et al.*, 2012; Fonseca *et al.*, 2013; Parron *et al.*, 2010). Nutrient concentrations in stream water are generally much lower than in Europe (EU) or North America, due to the typical deeply weathered clays of the Cerrado region. This phenomenon was observed for most anions in the current study. However, phosphate content was high in the dry season, indicating pollution from fertilisers or animal waste. Even in comparison to agriculturally modified catchments in the US and EU (Gelbrecht *et al.*, 2005), our measured phosphorus concentrations (as phosphate) were high. Like other studies that compared natural reference sites with agricultural streams from the Cerrado (Fonseca *et al.*, 2013; Gücker *et al.*, 2009; Silva *et al.*, 2011), our water sampling results demonstrate the significant impact of agricultural use on water quality, especially for nitrate, nitrite, and phosphate (dry season) concentrations.

Due to biome-specific water quality thresholds lacking in Brazil, Fonseca *et al.,* (2013) suggested baselines for physical-chemical water parameters ranging from natural to very impacted conditions in the Cerrado area. Nutrient concentrations are very low in the Cerrado compared to other areas in Brazil (e.g. the Amazon), due to delayed and slower responses to anthropogenic impact. Yet nitrate and phosphate concentrations in some natural and soybean watershed areas of the Amazon are similar, due to P being fixed by iron and aluminium oxides, and anion exchange of nitrate in deep soils (Neill *et al.*, 2013). Yet, the N and P concentrations at our site exceeded the Cerrado baselines delineated by Fonseca *et al.,* (2013), indicating 'very impacted conditions' due to the influence of agriculture.

Water quality pattern across the catchment

Our assumption that water quality parameters are spatially correlated to stream order, contributing area, and upstream land use was generally not supported by the snapshot data, because no significant differences were detected. Only Cl^- increased in the centrally located Tenente Amaral Stream, indicating agricultural activity (Silva *et al.*, 2011). Likewise, Figueiredo *et al.,* (2013) incorrectly assumed that cation loads would increase downstream as the deforestation area increased in the eastern Amazon during the rainy season. Dilution effects with increasing sub-catchment size were also not observed (particularly for nitrite during the dry and rainy season: $p = 0.189$ and 0.099, respectively).

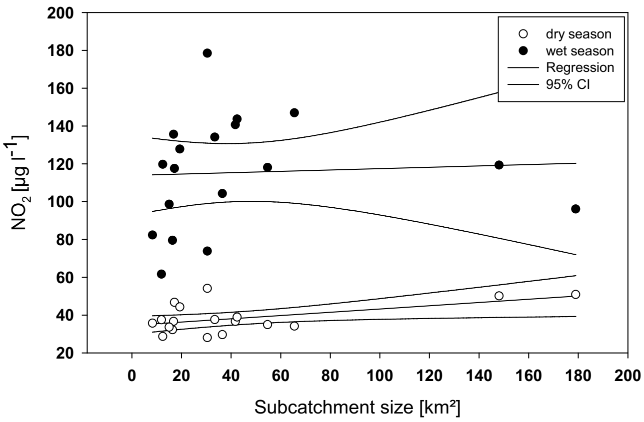


Figure 3-11: Exemplary the relationship between nitrite concentrations for the drainage area of each sampling location in the dry and the wet season.

The percentage of agricultural land use of the sampled sub-catchments was not correlated to the water quality measurements (Figure 3-11). Thus, differentiating sampling locations based on land use in a heavily modified catchment appears to inhibit the identification of reduced or undisturbed and closed riparian buffer strip. At each sampling location, land cover in a 300 m wide riparian buffer influenced Cerrado cover and the wider variability of agricultural land cover than in the sub-catchment area (Table 3-5). Riparian buffer strips and their structure (Fernandes *et al.*, 2014) are critical for maintaining water functions and minimising eutrophication (Boëchat *et al.*, 2013; Parron *et al.*, 2010). However, Allan (2004) observed that even modest catchment transformations of 3 % result in higher nutrient and sediment loads (Figure 3-12).

Figure 3-12: Even modest catchment tranformations and low disturbances in the riparian buffer zone cause sediment transport from agricultural fields to the streams (left and middle). Suspended sediment transport in an agricultural impacted stream compared to an effluent with crystal clear water from a forested sub-catchment of the Tenente Amaral area.

It remains unclear why the percentage of agricultural land cover at the sampling locations had no significant influence on the patterns of water quality across the catchment. In-stream nutrient alteration may occur across agricultural catchments, even though characteristics differ at sampling locations. Thus, comparison of land use types with an undisturbed natural site is required to resolve this issue.

3.6 Conclusion

Over a relatively short period of 20–30 years, land use change has significantly altered several soil physical and biogeochemical properties in the heavily modified Cerrado catchment. In the current study, the most pronounced effects have occurred in soybean plots, including (i) a significant decrease in infiltration rates, (ii) a significant decrease in soil aggregate stability, (iii) a significant increase in K at all sampled soil depths, and (iv) very high topsoil P concentration (but no accumulation of P in deeper horizons). Compared to natural Cerrado, pastures had a less pronounced effect on soil properties for pH, K, and P concentrations, but N declined significantly. We unexpectedly observed slightly lower soil nutrient (K and P) levels and decreased soil aggregate stability for sugarcane, indicating lower fertiliser inputs and/or topsoil degradation due to erosion processes.

Soil permeability (infiltration and Ksat) noticeably declined in all anthropogenic land use types, and is probably associated with frequent overland water flow events, decreased soil moisture in deeper horizons, accelerated erosion on agricultural fields accompanied by gully formation, nutrient depletion on fields, and nutrient export (dissolved and particular-bound) to streams.

Water snapshot sampling across the modified catchment showed strong seasonality in water quality parameters. The rainy season was associated with higher temperature, ORP, and NO_2^-, in addition to very low oxygen concentration and saturation. PO_4^{3-} concentrations were remarkably high in the dry season. No spatial pattering of water quality parameters was found in the river system (i.e. stream order, size of drainage area, percentage of land use in drainage area and a 300 m buffer, distance to outlet), signifying the relatively homogeneous distribution of water parameters. This distribution might be due to large riparian buffer strips of more than 50 m width, which are enforced by previous laws (No. 38/1995) and are in place throughout the catchment. Current plans with the revision of the Forest Code in 2012 (Government of Brazil, Law No 12.727) to dismantle the preservation of buffer stripes might have serious implications for water quality in the future.

Soil conservation and recommendations for farmers

In a recent review on environmental change in the Cerrado (Hunke *et al.*, 2014), we showed that agricultural land use intensification is likely to continue in the entire region. Consequently, the return of soil-conserving crop-pasture rotation systems (Reichenberger *et al.*, 2002) or the installation of agroforestry techniques (Atangana *et al.*, 2014) seems unlikely.

Figure 3-13: Freshly constructed contour banks on a pasture (left). No tillage with left crop residues after harvest on a maize field in the Tenente Amaral catchment.

The altered overland flow on agricultural sites recorded in this study emphasises the need to maintain permanent soil cover (Figure 3-13 right) and avoid over-fertilisation during the rainy season, by regularly (at least annually) monitoring soil macronutrient content. The combination of no-tillage and contour banks on the fields in conventional tillage systems seems to protect soils from nutrient losses in the region (Schindewolf *et al.*, 2014). Thus, levelled contours should be reconstructed at soybean-cotton and sugarcane sites (Figure 3-13). To prevent further gully formation, cattle should not have direct access to vegetation strips along the stream network (Wantzen *et al.*, 2012).

An intact riparian zone buffers the breakthrough of overland flow events from agricultural areas to streams. The use of non-native fodder plants on pastures should be avoided, as they are inadequate at preventing soil degradation (Wantzen and Mol, 2013). The restoration of degraded pastures with adequate plant species and soil correction measures (such as appropriate liming and fertilisation) is important because healthy pastures halt the spread of pests and ensure permanent soil cover.

4 Ecohydrological modelling with SWAT: Applicability and analysis of land use and climate change in the Cerrado

Abstract:

The watershed simulation model SWAT (soil water assessment tool) has been applied to the Upper São Lourenço catchment (~ 7000 km²) in the Brazilian Cerrado of Mato Grosso, which is characterised by decreasing discharges over the last 30 years, corresponding with a dramatic change in land use from natural cerrado cover to intensive agricultural use (planted pastures and cash crop production). Discharge simulations in the Brazilian Cerrado area are rare, therefore we conducted extensive model testing with different input data (satellite vs. measured precipitation inputs, different infiltration approaches) at daily and monthly time-steps. The model was calibrated and validated with SWAT-CUP using the SUFI-2 (Sequential Uncertainty Fitting) algorithm. Model testing with satellite-based rainfall data was unsatisfactory due to a strong underestimation of streamflow for some years. The testing of different infiltration methods (G+A–Green and Ampt vs. CN–Curve Number) resulted in a better model performance for the G+A approach, but also exhibited incorrect process representations for other primary water components. Therefore, the CN model was judged more reliable to simulate the water balance in the Cerrado. To model the impact of land use change and climate change, we created simple scenarios for the monthly model set-up. Therefore, complete cerrado, pasture and cropland cover were used to analyse the impact of land use on the primary water components and three climate change projections (for 2039–2058) of various conditions (temperature increase, adjusted precipitation pattern, increased atmospheric CO_2 level of 500 ppm) according to the projections of the RCP 8.5 high emission scenario. The comparison of primary water components of the pasture and crop parameterisation with a complete cerrado land cover showed that percolation, aquifer recharge and total water yield is reduced by 5 % for croplands and about 11 % for pastures. The ET for the crop scenario was increased (~100 mm a^{-1}) but the results also revealed that it is highly relevant how the Cerrado vegetation is parameterised. With a Cerrado adapted parameterisation the deforestation scenario confirmed the trend of the decreased discharges. However, there might also be other factors responsible for the observed decreases in streamflow. The climate change high emission scenarios showed a different impact on the primary water components. For drier conditions, decreasing discharge over the entire year was observed to exhibit potentially critical dry seasonal water availability when baseflow is the main contributing source. The evapotranspiration response (–7.5 % to –15 %) is mainly attributed to elevated CO_2 levels. Taking all high emission simulation scenarios into account, the most presumable effect is a prolongation of the dry season (by about one month), with higher peak flows in the rainy season. The combined effects of further land use intensification and climate change is uncertain, but both stressors imply higher peak flows in the rainy season. Consequently, potential threats for crop production at the beginning of the crop cycle with lower soil moisture (i.e. irrigation) and increased erosion and sediment transport during the rainy season are likely which should be considered in adaption plans.

4.1 Background

The conversion of natural vegetation disrupts the hydrological cycle (Bronstert *et al.,* 2002). Therefore, understanding the hydrological processes under land use as well as climate change is an important prerequisite for proper riverscape planning (DeFries and Eshleman 2004). The Cerrado region has faced a dramatic change in land use from natural savannah Cerrado to agricultural land use for the last 40 years. During the same period, the flow of the Rio São Lourenço and tributaries significantly decreased (Figure 4-1).

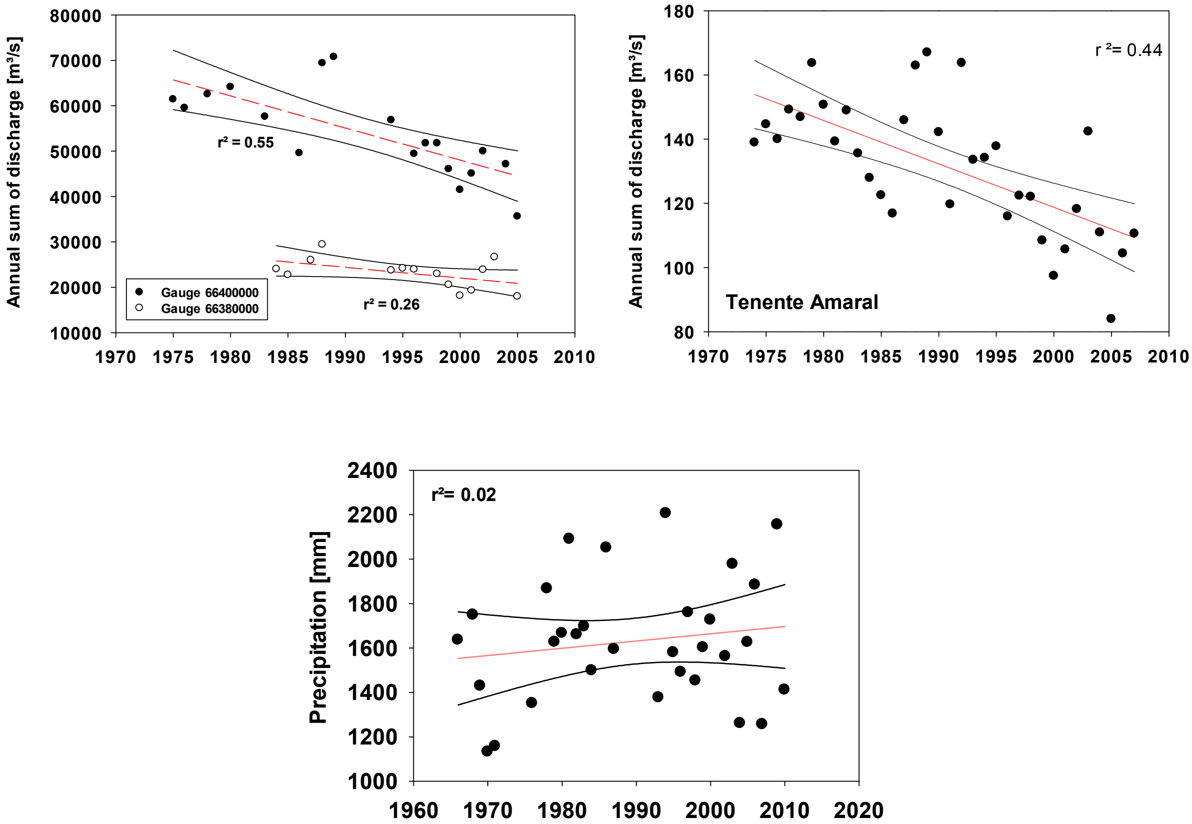


Figure 4-1: Annual sum of discharges from three gauging stations (ANA 66400000, 66380000 and PCH Tenente Amaral) of time-series containing complete daily records. Annual precipitation sums from the Jaciará station (ANA 1554006).

From the 1970s on, annual discharges decreased continuously in the study region. These decreases have been detected for all three available gauging stations (7000 km², 3400 km², 362 km² contributing area) served by different operators. More precisely, the average discharge for two selected periods at the São Lourenço (SL) outlet between 1975–1989 (from 8 years of complete daily records) was 169 m³/s. Between 1990 and 2005, ten complete years of daily records resulted in a mean discharge of 130 m³/s, thus the average decrease at the outlet of the SL is about 25 % (Figure 4-1). For the Tenente Amaral stream, we used monthly records for estimating the decrease in discharge. The mean annual discharge decreased from 1975–1990 compared to 1990–2005 from 12 to 10 m³/s, which is a decrease of 17 % while precipitation across the basin exhibits a slight positive trend (Figure 4-1). Guzha *et al.,* (2013) did not detect any significant trend in precipitation over the last 40 years in the region. So, the precipitation data are in contrast to decreasing discharges and it remains unclear which factors affect these flow alterations. We therefore hypothesise that land use change from natural Cerrado to intensive crop production implies the reduction in discharge. All observations of decreasing streamflow trends for the SL catchment are paired here with ongoing land use intensification over the last 30 years (Hunke *et al.,* 2014). It is unlikely that drivers other than land use are responsible for the decreasing discharges.

This hypothesis is in contradiction to findings from Amazonia. Several studies from the Amazon have shown that deforestation causes increased discharges by lowering the evapotranspiration (Coe *et al.,* 2011, Davidson *et al.,* 2012). However, at present, it is rather unclear to what degree and on what scale land use changes affect runoff generation and subsequently streamflow in the Cerrado area (Oliveira *et al.,* 2014). The hydrological responses to land use change are described to be rapid for small watersheds, whereas the effects in larger watersheds are often marginal (Rodriguez *et al.,* 2010, Oliveira *et al.,* 2014). On the continental scale, deforestation might have an influence on the precipitation pattern, therefore also resulting in lower discharges.

Also, the impact and alterations of the southern oscillation (SO) have to be taken into account for parts of the Cerrado. Foley *et al.,* (2002) stated that the average El Niño in the bordering Amazon causes drier and warmer periods than the long-term averages, whereas La Niña is wetter and cooler and results in large increases of river discharges and flooding in the northern and western tributaries of the Amazon.

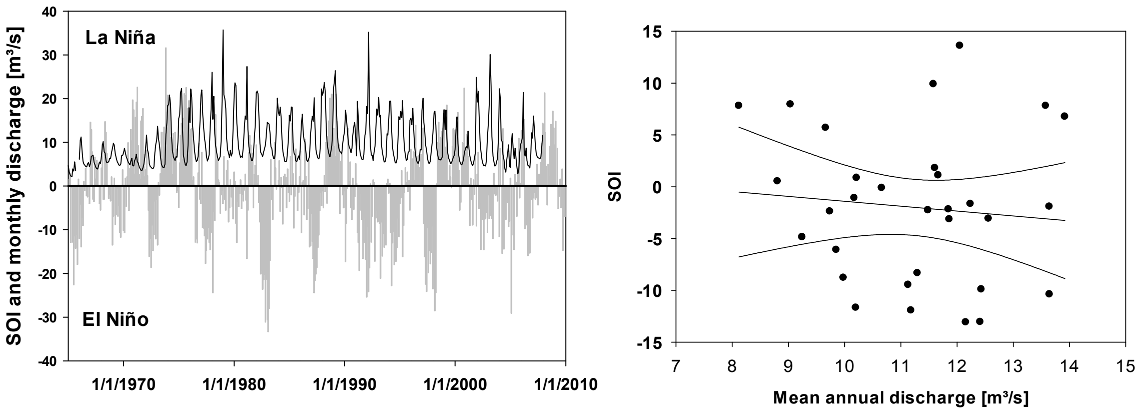


Figure 4-2. Southern Oscillation index (SOI) and mean annual discharge for the Tenente Amaral catchment (left). Scatterplot of annual discharge with the SOI (right).

For our study area, we assumed that the SO has little impact on stream discharge. However, we checked for the relationship between the Southern Oscillation Indices (SOIs) which represent the atmospheric pressure differences between stations in Tahiti and Darwin, Australia, which are negative during El Niño phases of ENSO, and positive for La Niña (Grimm *et al*., 2000). Also, for annual discharge with annual SOI, no relationship is evident to explain the decreasing discharge pattern (Figure 4-2). The weak relationship of wetter years in El Niño years contradicts the well-known impacts in the Amazon area of Brazil, where wetter conditions occur in La Niña years.

In order to obtain further information regarding the impact of land use change, hydrological models are important tools to understand the hydrological cycle. In ecohydrological modelling, a good performance in simulating the water balance is an important precondition for analysing sediment transport and modelling of nutrient and pesticide dynamics in watersheds (Chapter 2.4.2). For the rapidly changing Cerrado, water components (evapotranspiration, surface runoff, groundwater and percolation, soil water storage) are not very well studied (Hunke *et al.,* 2015, Oliveira *et al.,* 2015,). The region sustains economic wealth from agricultural commodities. Therefore, simulations of climate change with expected rising temperatures and a prolongation of the dry season (Chapter 2.2.2) are of interest for management and risk assessment.

Ecohydrological modelling is important to improve our understanding of the water cycle, especially in regions which lack data. Ecohydrological models like the Soil Water Assessment Tool (SWAT, Arnold *et al.,* 1998) are valuable instruments in watershed management and in making predictions (of water flux, water quality, biomass yield) for current and future land use and climate change by using scenario simulations. There are multiple applications of SWAT/SWIM for analysing land use and climate change impacts (Krysanova *et al.,* 2015, Krysanova and Srinivasan 2015, Gassmann *et al.,* 2007).

Currently, SWAT is increasingly used in Brazil. Results of previous studies are promising that SWAT is, in principle, applicable for riverscape management issues under different climatic conditions in Brazil (Garbossa *et al.,* 2011). Bressiani *et al.,* (2015) review about 100 Brazilian SWAT studies. However, 85 % of the studies are in Portuguese, and only 34 % (19 recent studies for all of Brazil) are published in peer-reviewed journals. The majority of recently published SWAT studies are located outside the Cerrado (Bressiani *et al.,* 2015). For the Cerrado region, only three internationally published peer-reviewed studies by one author (Strauch *et al.,* 2013, Strauch and Volk 2013, Strauch *et al.,* 2012 ,) are available from the core Cerrado area.

4.1.1 Objective

The main goal of the modelling study is to test the ecohydrological process-based model SWAT in data-sparse areas of the Cerrado. For performance testing of SWAT, different input data (satellite precipitation data vs. measured) and infiltration approaches in the upper São Lourenço catchment are considered. Applying SWAT, this chapter will quantitatively determine the primary water balance components in order to investigate the observed decreasing discharges and provide insight into how land use change and climate change impact the water balance (disrupt the water cycle). The specific objectives are the following:

(1) to test the applicability of the SWAT model in a savannah watershed of Brazil,
(2) to test different weather input data and infiltration methods for SWAT modelling,

However, assuming a satisfactory working model, SWAT is applied for simple scenario simulations of land use change and climate change. It is intended to:

(3) explore the impacts of land use changes (LUC) on discharge, ET and soil water storage, and
(4) to simulate the impacts of climate change (CC) on components (Q, ET, SW) of the water balance.

4.2 Methods

4.2.1 SWAT Model approach

The Soil Water Assessment Tool (SWAT, Arnold *et al.,* 1998) is a river basin scale and process orientated ecohydrological model under public domain which allows a simulation of water balance and water quality (nutrient and pesticide transport as well as erosion). It is widely applied for meso-scale ecohydrological modelling on all continents and in different ecosystems (Gassman *et al.,* 2007, Tuppad *et al.,* 2011, Douglas-Mankin *et al.,* 2010). The major goal of SWAT's development was to quantify the effects of management practices and scenario analyses in complex watersheds. It is a continuous time-routing model which operates with a daily time step for 1–100 years and is able to integrate observed datasets. The model is coded in FORTRAN 90 and the updated version SWAT 2009 can be run in ArcGIS and MapWindow-GIS environments as well.

The water balance equation (Eq. 1) is the basis of the model.

$$SW_t = SW + \sum(P_{day} - Q_{surf} - Q_{lat} - ET - Q_{gw}) \quad \text{(Eq. 1)}$$

SW_t= final soil water content, P_{day}=daily precipitation, Q_{surf} = surface runoff, Q_{lat}=lateral flow; ET=evapotranspiration; Q_{gw}=groundwater flow; [all components in mm]

The SWAT model is designed in a modular format and includes components for hydrology, crop growth, nutrient and management practices. Therefore, it is able to model the water cycle, matter fluxes and the impact of land management options on these components. SWAT is divided into a land phase and a routing phase. The land phase calculates runoff, erosion, interception, evapotranspiration, infiltration, percolation through the soil profile as well as lateral and groundwater flow. Plant growth, yield, nutrient cycling and pesticide loadings that reach the channel of a subbasin are also simulated. Then, the routing phase calculates the water, sediment and other loadings to the outlet, thereby taking degradation processes and transmission losses into account. Specific information on climate, topography, soils and land use is required for a proper parameterisation of the model. Catchment discretisation from subbasins to hydrotopes called hydrological response units (HRUs) which are a unique combination of slope, soil and land cover is accomplished by the overlay action in GIS.

Curve Number and Green and Ampt infiltration

The runoff can be estimated in SWAT using the SCS Curve Number procedure (CN) or the Green and Ampt infiltration method. The CN method does not consider rainfall intensity and duration; it is only based on the total rainfall volume.

The SCS (Soil Conservation Service) Curve Number approach is a rainfall-runoff model for computing direct runoff by assuming an initial abstraction related to the individual Curve Number before ponding. The Curve Number itself is a function of soil group (Groups A–D from sandy soils to heavy clays), land use and management and antecendent soil moisture content. SWAT updates an appropriate CN for every simulation time step based on the soil moisture simulated by the model. In the CN approach, 20 % of the daily rainfall is abstracted to represent depression storage, interception and infiltration before the development of surface runoff (Neitsch 2005). The CN method is very simple, as the Curve Number itself is a function of precipitation, soil permeability, land use and antecedent soil moisture (Eq. 2).

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)}$$

$$S = 25.4\,(\frac{100}{CN} - 10)$$

Q_{surf}: accumulated runoff [mm]; S: retention parameter [mm]; R_{day}: daily rainfall: I_a: Initial abstractions
CN: Curve Number (obtained from tables, correlated with soil moisture, land cover and soil type)

The Green and Ampt (G+A) method is time-based and is able to simulate the impacts of rainfall intensity and duration if sub-daily (hourly) data are provided. The G+A infiltration is described by an equation which assumes a homogenous soil profile, soil moisture, and total saturation above the wetting front. SWAT implemented the G+A sub-daily routing step as an alternative method for determining excess rainfall. Therefore, the physically based method relates infiltration to soil hydraulic conductivity and soil moisture content of the different soils.

In this thesis, the SWAT version from 2009 (Rev.528) is used. As the Priestley and Taylor approach often underestimates evapotranspiration in areas with prolonged dry seasons (Berengena and Gavilán 2005); here: 5-month dry season), the potential ET is determined by the Penman-Monteith equation, also to account for elevated CO_2 levels in order to simulate climate change scenarios. The uncalibrated model runs were transferred to SWAT-CUP (Abbaspour *et al.,* 2007), and flow-sensitive parameters adjusted to meaningful ranges. In our case, we followed the recommendations of Arnold *et al.,* (2012) to parameterise, calibrate and validate SWAT. The original set-ups were varied by different infiltration methods (CN vs. G+A) and in the driver's data (satellite precipitation data vs. observed station data) for the daily and monthly time steps. The SWAT-model set-up, calibration procedure is described in detail in the Appendix (A).

4.2.2 Study area and model parameterisation data

The study was conducted in the upper Rio São Lourenço watershed located in the state of Mato Grosso, Brazil. The watershed covers an area of 7072 km² and is a major feeder of the Pantanal wetland draining parts of the Brazilian Plateau (Planalto) which belongs to the Cerrado biome (Figure 4-3).

The catchment is dominated by agricultural land use, with a strong relationship to the underlying soil types (Figure 4-4). The watershed is dominated by planted pastures (37 %) and cash crops (28 %). The remaining 25 % is classified as Cerrado, which are the vegetation sub-formations *campo cerrado* and *cerrado sensu stricto* (open shrublands) in this area. The Latolsols (in total 35 %) of the Tenente Amaral sub-watershed are used for cash crop production, whereas the lower central parts of the Rio São Lourenço characterised by podzolic soil orders (in total 30 %) are used for planted pastures.

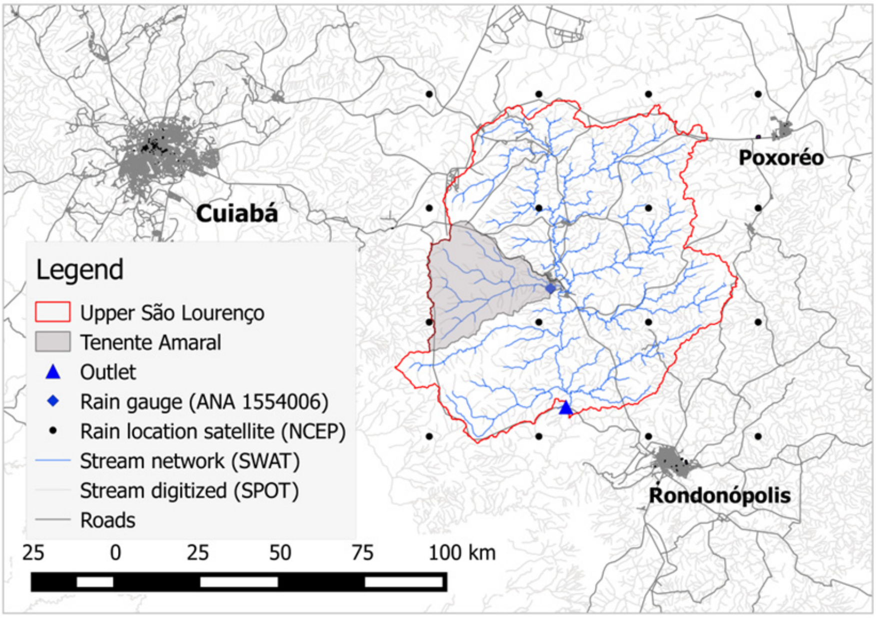


Figure 4-3: Upper São Lourenço watershed with three gauging stations; grid cells of satellite derived climate and rainfall data, and one precipitation station containing measured daily data.

Slope ranges between 2 % and 20 % and is steepest in the eastern parts of the catchment, where remaining natural areas with different Cerrado subforms still exist. The dominating slope classes range between 2–10 %, covering more than 72 % of the catchment (Figure 4-4).

Using a hydrologically corrected digital elevation model (90 m resolution SRTM version 5 DEM) for subdivision, 275 sub-watersheds and 1755 HRUs are calculated in SWAT. The HRUs do not interact with each other.

In the Cerrado region, often relevant soil data is lacking: especially soil hydraulic properties cannot be derived by the pedotransfer function due to the pseudosand structure of the occurring Latosols, which makes it essential to ensure in situ field measurements. Sediment retention basins (*Barraginhas*), typical phenomena in other regions of the Cerrado (but see Strauch *et al.,* 2013) are not constructed in the Upper São Lourenço watershed.

Daily time series of precipitation data observed from the city of Jaciará from 1965–2010 as well as nine series of satellite data from 1979–2010 are available (NCEP Climate Forecast System Reanalysis (CFSR)) containing data on humidity, wind speed, temperature, and solar radiation for the years 1979–2010.

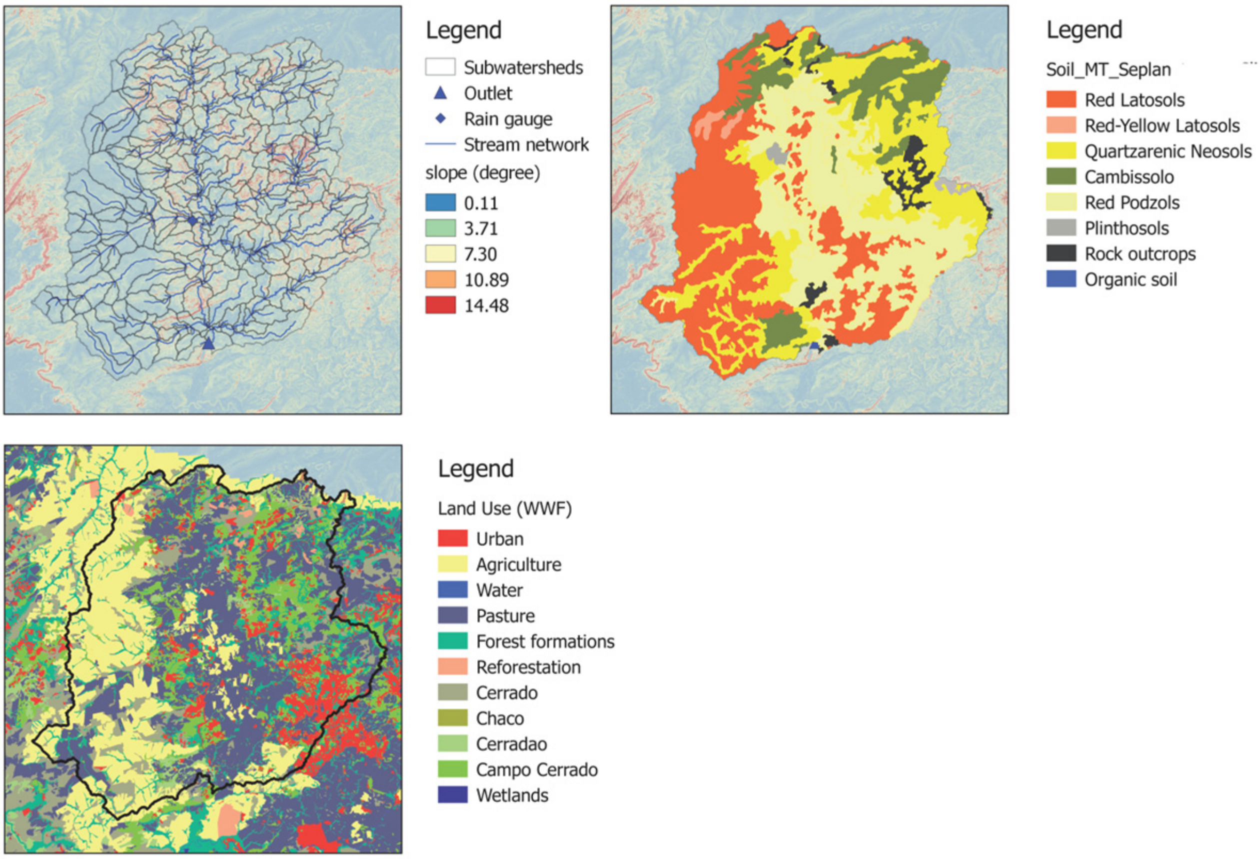


Figure 4-4: Hydrological and geophysical characteristics of the upper São Lourenço watershed.

Model validation data were available for different gauges across the catchment. The gauges contain gappy time series on a daily basis for the outlet (Station ANA 66400000 (outlet~7000 km²)) from 1965–2006. In the central part of the watershed, a very fragmented time series (Station ANA 66380000 draining 3500 km²) with daily data from 1984–2006 is available. On the monthly time step, data from 1970–2010 for the Tenente Amaral catchment are available (PCH-Embaúba) (Table 4-1).

Table 4-1: Input data for SWAT

Data type	Resolution/Scale	Data source
Digital elevation model	30m–90 m	SRTM data resampled and conditioned
Stream Network	3 m	Manually digitized from SPOT satellite images
Soil	1:250.000	Seplan Mato Grosso, 2003; RADAM Brasil- soil profiles (http://www.esalq.usp.br/gerd/); Field observation from different soil types for texture, Ks (Hunke *et al.,* 2015, Chapter 3)
Land use	1:200.000	WWF 2002, 2008, (WWF 2009), adjusted by manually digitized gaps and corrections on the basis of Spot statellite images from the year 2010
Precipitation	Daily, 38km grid	ANA (Hidroweb) Station 1554006 (1965–2010, with gaps) and satellite derived NCEP-CFSR data (1979–2010) from nine locations
Climate data	Daily, 38km	NCEP-CFSR data (1979–2010) from nine locations
Discharge	Daily (ANA), Monthly (SEMA)	ANA (Hidroweb) station 66380000 (1984–2006) and the outlet station 66400000 (1965–2006 with gaps); Station Tenente Amaral (1965–2007) from SEMA, Projeto Basico for PCH Embaúba
Management practices	8 Farms	Interviews with farmers (conducted by Suzy Klemp), Chapter 2

4.2.2.1 Cerrado specific inputs

Land use was classified using satellite images (SPOT) to correct and update the WWF (2009) land use map. Based on interviews with different farmers in the catchment as well as personal observations between 2010 and 2013, a representative crop rotation for the agricultural areas was implemented (see Chapter 3.2). For the agricultural areas, then, fixed growing dates were used to represent a crop rotation of soybean maize with a permanent cover crop to maintain vegetation cover for almost the whole year. A harvest and kill operation was used to stop plant growth at a specific month and day instead of the potential heat unit concept (SWAT theory). Although the model is parameterised with diverse crop rotations, in this study we focus mainly on the hydrological components of the outputs. Strauch and Volk (2013) conclude for the Cerrado region that streamflow prediction may be possible without further development of the plant growth module. However, Cerrado-specific vegetation parameters (such as LAI, which is lower than the default values of forests) were taken from the literature, especially from the recent study by Strauch *et al.,* (2013). Satellite-derived estimates such as MODIS-LAI products were found to be inappropiate in tropical regions (Biudes *et al.,* 2014) and also the MODIS-ET (evapotranspiration) are especially uncertain for agricultural areas (Loarie *et al.,* 2011).

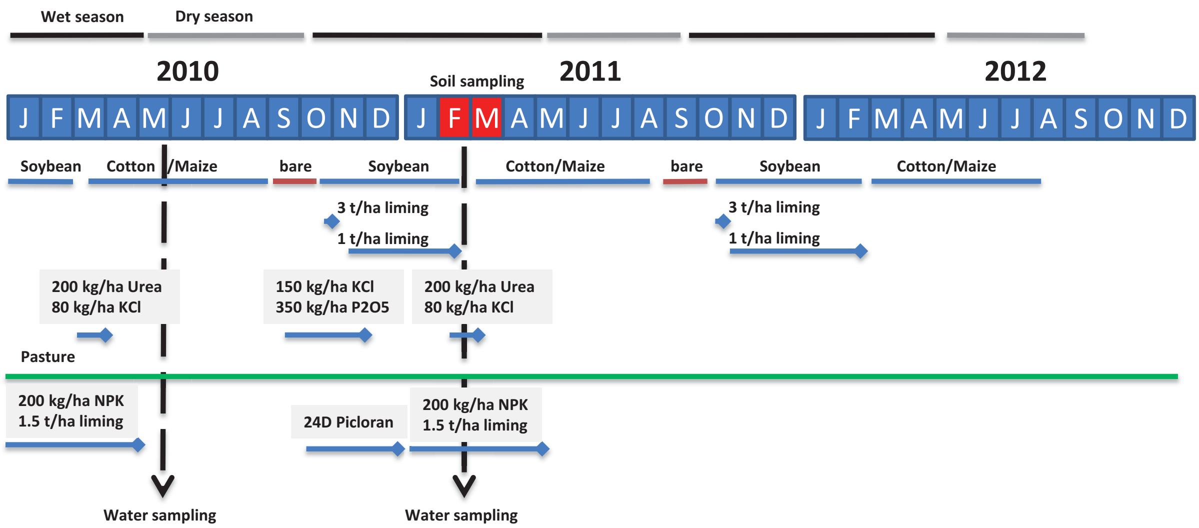


Figure 4-5: The SWAT-model is paramerised based on the field sampling data and the specific crop rotation scheme for the agricultural sites.

The soil database is user-defined and parameterised with field site-specific inputs to account for realistic soil types and properties (Figure 4-5). Especially the default values for the soil hydraulic conductivity (Ks), texture, bulk density were adjusted in the soil database for three soil depths by replacing them with site-specific inputs (Chapter 2.4.1 and 3.4.1). These data were derived from fieldwork (Chapter 3.4, Hunke *et al.,* 2015), but also from the Brazilian soil database (RADAM-Brasil profiles: http://www.esalq.usp.br/gerd/).

4.2.3 Scenario development

4.2.3.1 Effects of land use change (LUC)

In order to account for the overall effect of land use change, we run the calibrated SWAT model considering extreme scenarios from the default parameterisation based on the WWF land use (WWF 2009). As the low percentage (~1 %) of urban areas has not changed dramatically over the last 30 years, we performed model runs for the remaining parts of the areas which are covered by cerrado, pasture and cropland. To enable a sound comparison between the different land use inputs, the same input data and calibration procedure based on the best calibration parameters were used for all model runs with the CN-model on a monthly time-step. This approach allows us to represent the land use of the 1980s and gives an estimation on how water components might change with further land use intensification. We focussed on primary water components of water yield, evapotranspiration, groundwater recharge and soil water storage.

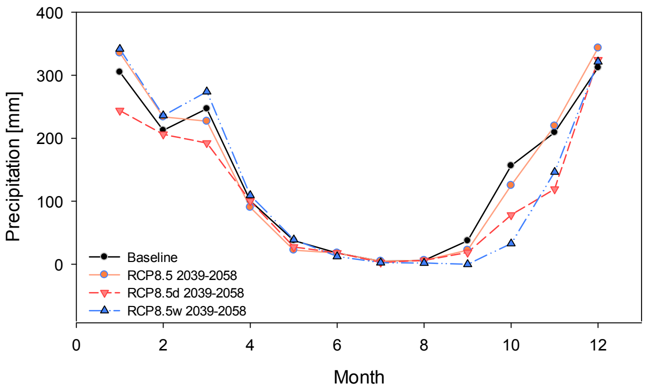
Although the scientific robustness of the modelling results require the consideration of uncertainties in the scenario analysis (Schuol *et al.,* 2007), we used the “best parameter-set” from the calibration procedure for all scenarios.

4.2.3.2 Effects of climate change (CC)

For climate change scenario analysis, the most recent climate change data according to model ensemble averages of the high emission Representative Concentration Pathways (RCPs) 8.5 for the period 2039–2058 were considered. The data were generated from a large dataset of climate simulations by the National Center for Atmospheric Research (NCAR 2012) Community Climate System Model (CCSM4). To calculate the monthly differences, reference time series of the closest grid cells covering the São Lourenço catchment, as well as two locations representing drier and wetter projections, were used (2039–2058). As the projections for Mato Grosso showed a wide range of possible trends from wetter to drier conditions and past observations from the catchment were rather erratic in both directions (IPCC 2013, Chapter 2.2.2), the trends were chosen for the São Lourenço catchment and two other locations in the semi-humid area with 4–5 drought months representing extremes of higher and lower annual precipitation (Table 4-2).

Table 4-2: Monthly averaged precipitation from daily records for the time period 1995–2005 and averaged monthly precipitation sums of the manipulated daily precipitation input based on the monthly differences of the RCP8.5 projections (2039–2058) for dry and wet extreme scenarios in the Cerrado region and for the projection of the closest grid cell in the watershed at 15.965°N 54.968°E (RCP8.5_SL), 10.088°N 42.037°E (RCP8.5_dry), and 5.241°N 47.015°E (RCP8.5_wet).

MON	Precipitation 1995–2005	RCP8.5_dry		RCP8.5_wet		RCP8.5_SL	
		Scenarios RCP 8.5 2039–2059					
	mm	mm	%	mm	%	mm	%
1	305.01	244.01	–20	341.61	12	335.51	10
2	212.78	206.4	–3	236.19	11	234.06	10
3	246.89	192.57	–22	274.05	11	227.14	–8
4	100.45	100.45	0	109.5	9	90.41	–10
5	37.63	27.47	–27	39.13	4	22.58	–40
6	17.91	17.91	0	12.54	–29	17.91	0
7	4.91	2.95	–40	2.45	–50	4.91	0
8	6.15	6.15	0	2.03	–66	6.15	0
9	37.42	18.71	–50	18.71	–50	22.45	–40
10	156.55	78.28	–50	32.88	–78	125.24	–20
11	209.26	119.28	–43	146.48	–30	219.73	5
12	312.17	324.66	4	321.54	3	343.39	10
Annual	1641	1333		1512		1643	



The percent differences between reference and projection were considered to manipulate the rainfall and temperature inputs of the SWAT model addressed by the parameters RFINC and TMPINC, both at the sub-basin level. The default CO_2 concentration was set to 330 ppm and adjusted in the climate change simulations to 500 ppm according to the IPCC (2013). The monthly temperature increased by 1.5–2.8 °C for the RCP8.5_SL projection with highest temperatures in September, October and November, whereas the RCP_wet and RCP_dry scenarios projected the highest increases of 2.2 °C for November–January. Particularly in the months of higher precipitation sums, relevant changes were expected, with rainy season ranges from –43 % to +10 % and –50 % – +50 % at the end of the dry season. The calculated changes between the years 2039–2058 and the reference period (1986–2005) for each grid-point were used to manipulate the precipitation input data of SWAT for a 10 year period of modelling. From the other locations in the Cerrado, derived and generated precipitation patterns were similar to those observed in the catchment area in the past (modelling time period) from drier and wetter years.

From the climate change scenarios, it can be stated that the beginning and end of the dry season seems to be most affected by lower precipitation, with the greatest decreases between 2039–2058 and the high emission scenario of the ensemble average.

4.3 Results and discussion

4.3.1 Model testing

4.3.1.1 Comparison of precipitation input data

Large problems are known to represent convective precipitation regimes in the tropics. Therefore, the precipitation input is most challenging in sub-tropical watershed modelling of the Cerrado. To better understand how input precipitation impacts model results, two types of precipitation data were used as drivers in the initial uncalibrated model versions. Recent studies showed that SWAT works satisfactorily well with satellite data, also in the Cerrado (Monteiro *et al.,* 2015, Guzha *et al.,* 2014). The increasingly used satellite data of the CSFR (Bressiani *et al.,* 2015, Fuka *et al.,* 2013) of nine grid cells were compared to one measured daily precipitation station in the central part of the watershed (Figure 4-6). The correlation between the different data sources were moderately correlated linearly (R^2= 0.67) on a monthly basis, which is similar to the findings of Monteiro *et al.,* (2015).

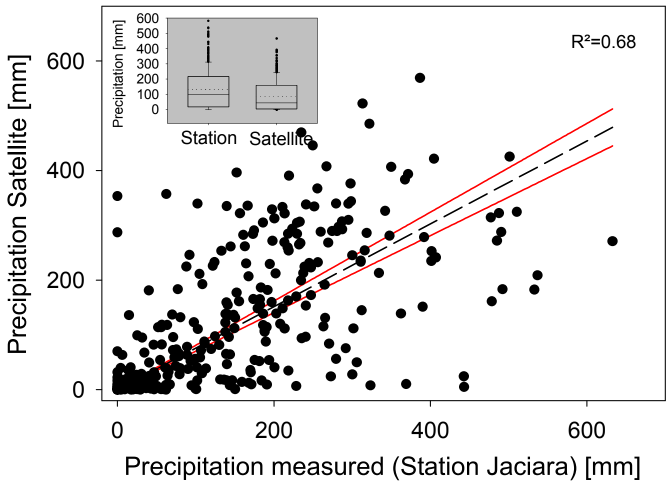


Figure 4-6: Monthly precipitation inputs for the Jaciará station (ANA) and respective CSFR closest grid cell.

The CSFR precipitation data often contain years where the data are obviously not satisfactory (especially the years 2001 and 2002 are not reliable, see Figure 4-7, Figure 4-8). In the data sets of all nine stations, many of the years significantly underestimate the annual sums; especially in the 1980s, the annual sums were often below 600 mm, which is not reliable. The testing in SWAT showed that the satellite data (regardless which of the nine grid cells were used) underestimated precipitation and therefore flow (see Figure 4-9, exemplarily based on monthly data).

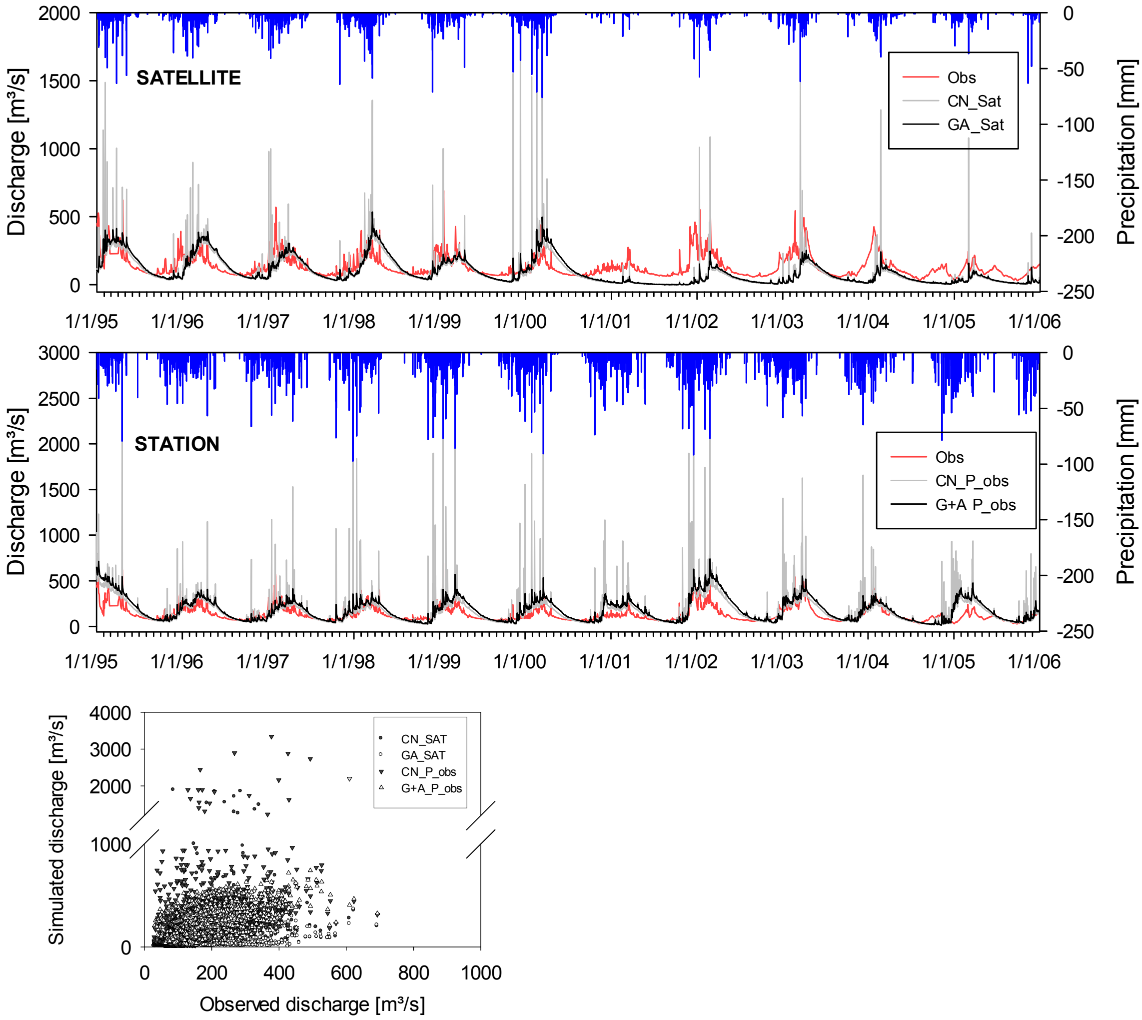


Figure 4-7: Modeled comparison of discharge with precipitation data from ANA (P_obs) and the CSFR data (_SAT) for ten years of simulation on the daily time-step for Green and Ampt (G+A) infiltration and Curve Number (CN).

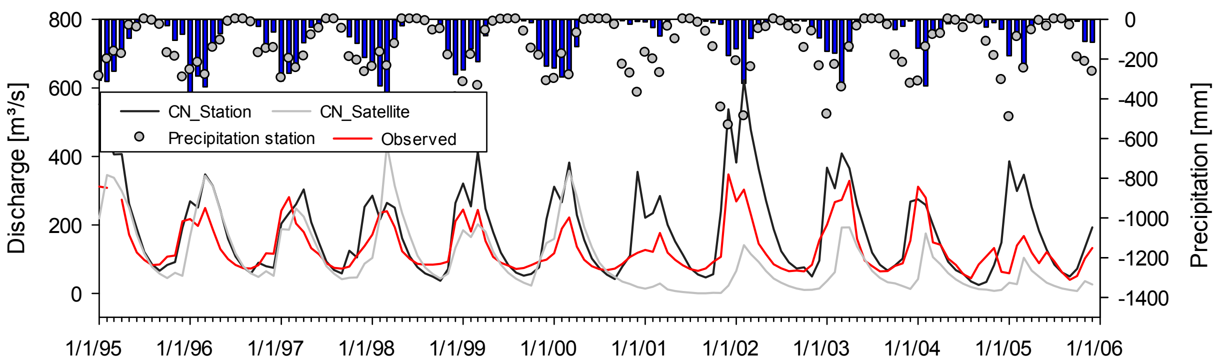


Figure 4-8: Modelled comparison of discharge with precipitation data from ANA (CN_=Curve Number Station) and the CSFR data (CN_Satellite) for ten years of simulation.

Nevertheless, for other years, the observed streamflow was captured well considering an uncalibrated model, but also the timing of the flow peaks is not matched satisfactorily for daily streamflow. The different parameterisations largely underestimate flow in the time period from 2001–2005 (Figure

4-8) which is clearly associated with the biased satellite-derived rainfall inputs. This pattern is evident for all time series of the CSFR data for the time-period provided for the region.

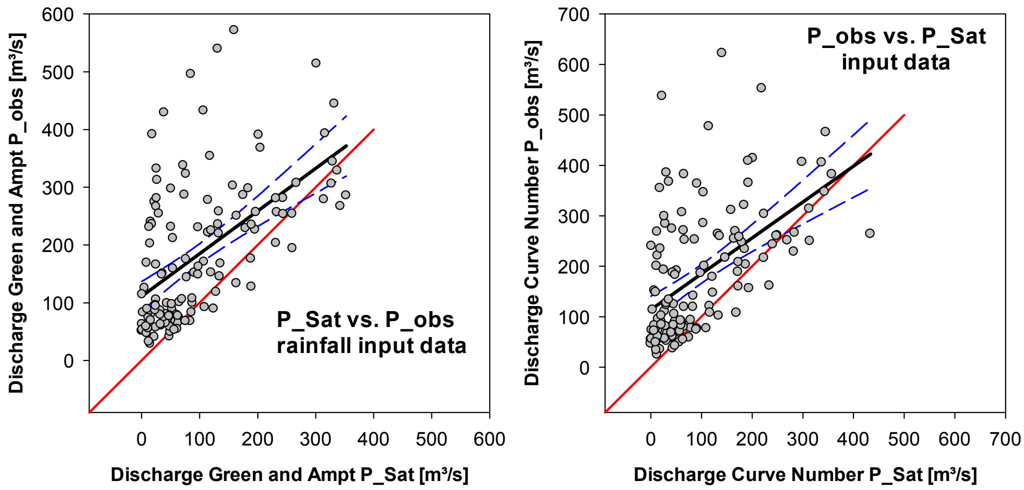


Figure 4-9. The impact of different rainfall input data (P_Sat= Satellite derived data from NCEP-CSFR, P_obs= measured precipitation data by ANA station Jaciará) on simulated flow at the outlet (~7000 km²) of two uncalibrated SWAT model (Soil Water Assessment Tool) set-ups (Green and Ampt and Curve Number). The results say nothing about the model performance of the simulated flow, but it can be stated that both rainfall inputs produce similar baseflow discharges, whereas higher simulated flows are associated with the measured precipitation data as the satellite data systematically underestimate flow.

The capture of the seasonality is an important precondition for further model testing. So, it is questionable whether the satellite CSFR data are accurate for our study area, as was shown for other regions of Brazil (Bressiani *et al.,* 2015, Guzha *et al.,* 2014).

The test model runs, therefore, showed that the satellite rainfall data of CFSR in the São Lourenço catchment should only be used with care. Our results are supported by Bressiani *et al.,* (2015a) who found, in a comparison with different rainfall input data, the smallest R^2 for the CSFR data with unsatisfactory results for all stream gauges studied. Therefore, inappropriate choice of drivers has a significant impact on model results by increasing uncertainty. It is expected that, in the near future, satellite-derived precipitation data at a daily resolution will be improved. Especially the very recent products of the WFDEI WATCH forcing data are promising for the Cerrado in comparison to the CFSR inputs (Monteiro *et al.,* 2015) to acquire proper rainfall data for setting up hydrological models in data-sparse areas.

4.3.1.2 Model calibration, performance and applicability

Model performance was first evaluated for streamflow prediction for the years 1990–2005 containing 5 years of warm-up, 5 years of calibration and the last five years for validation. Input parameters of the calibration procedure are given in the Appendix (A) for all model set-ups.

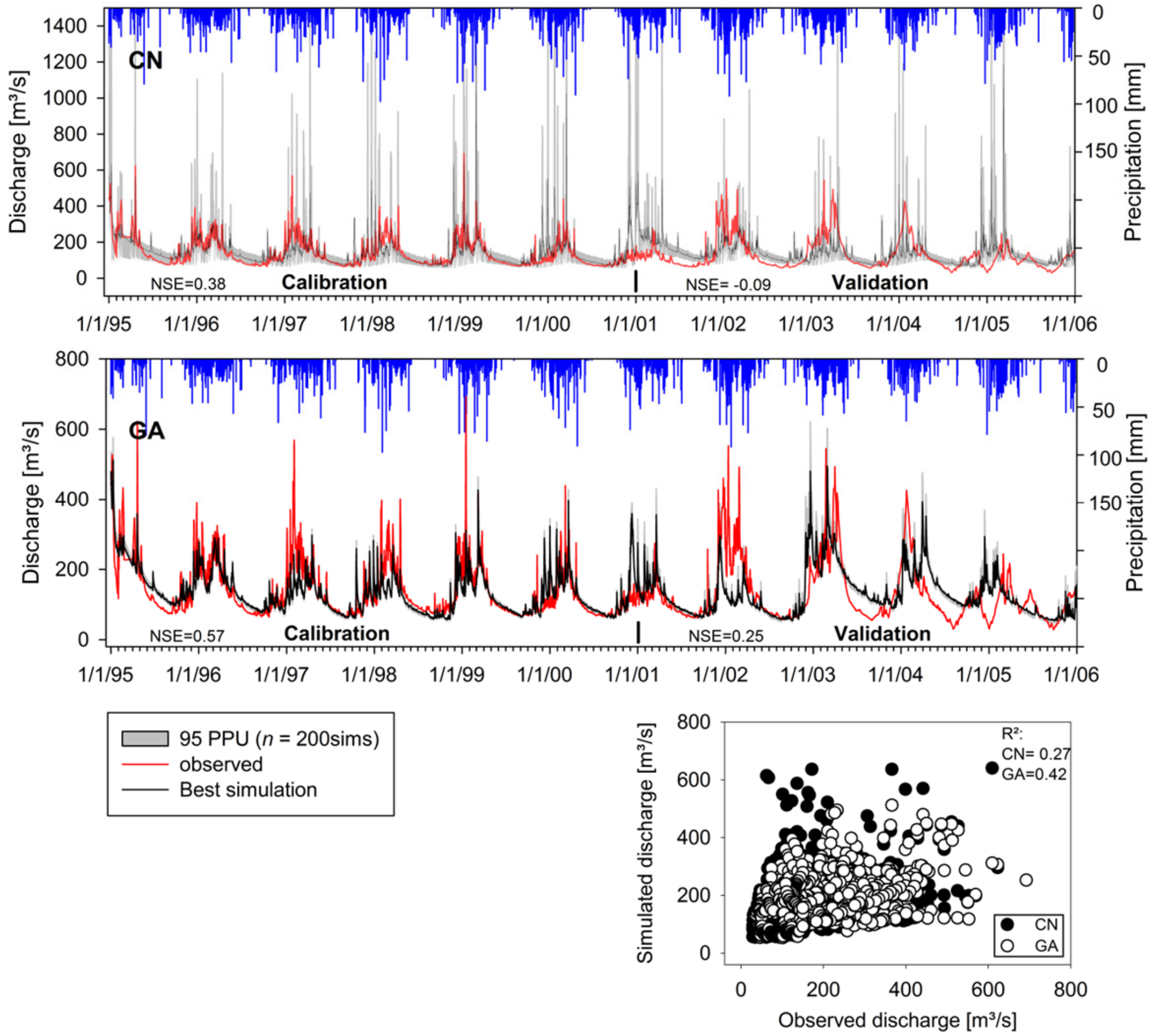


Figure 4-10. Results of the Soil and Water Assessment Tool (SWAT) calibration (1995–2000) and validation (2001–2005) for two model set-ups of simulating excess rainfall (CN– Curve Number, GA– Green and Ampt) for daily discharge at the outlet of the upper São Lourenço catchment (~7000 km²). Note the different scales for discharge. The overall uncertainty is quantified by the 95 % prediction uncertainty of minimum 200 simulations (of the last iteration) of final meaningful ranges of the calibration parameters. R^2 of observed versus simulated discharge is given for both, the calibration and validation period.

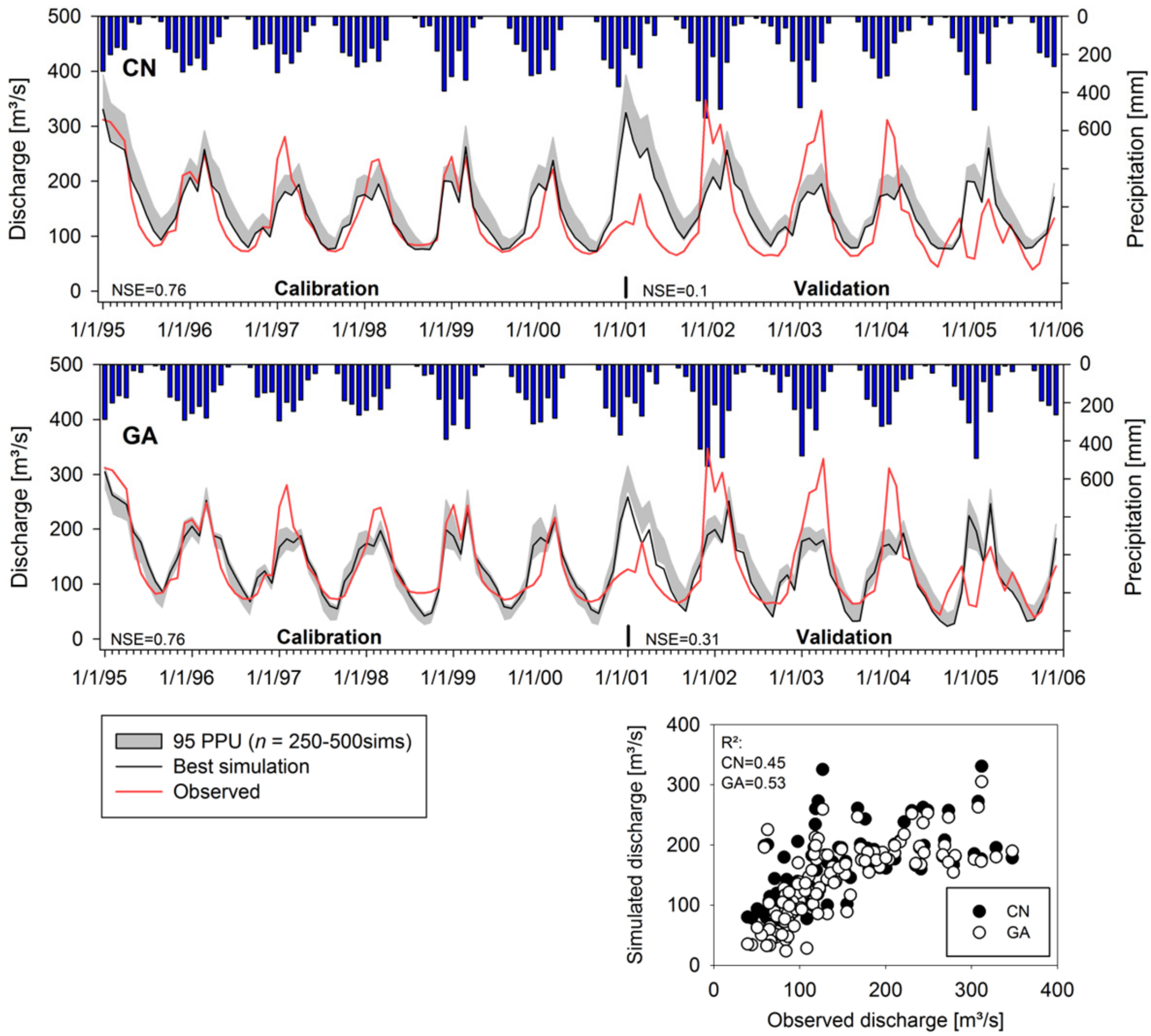


Figure 4-11. Results of Soil and Water Assessment Tool (SWAT) calibration (1995–2001) and validation (2001–2005) for two methods/model set-ups of simulating excess rainfall (CN– Curve Number, GA– Green and Ampt) for monthly discharge at the outlet of the upper São Lourenço catchment (~7000 km²). The overall uncertainty is quantified by the 95 % prediction uncertainty (95PPU) of 250 (CN) and 500 (GA) simulations of the final iteration with meaningful ranges of the calibration parameters. R^2 of observed versus simulated discharge is given for both, the calibration and validation period.

The model performance on the daily basis showed that the daily G+A model seems to work surprisingly well after applying calibration techniques (Appendix-A) in both the calibration and validation periods (even if the NSE is < 0.5 in the validation period) (Figure 4-10). The daily CN model set-up on the other hand was not satisfactory, with shortcomings in reproducing event recessions that are too slow (Figure 4-10). The CN model produces very high peaks with high uncertainty in the SWAT-CUP calibration and validation (R-factor of 0.91 and 0.82 by bracketing 75 % and 44 % of the measured data in the uncertainty bands), whereas the G+A reproduced the peaks quite well (with an R-factor of 0.26 and 0.28 on the cost of lower P-factors of 53 % and 43 %).

Table 4-3: Performance ratings (NSE– Nash Sutcliffe efficiency, PBIAS– percent bias and R²) for the different model set-ups (CN– Curve Number and G+A– Green and Ampt infiltration) for the calibration and validation period.

Period	Year	CN model			G+A model		
		NSE	R^2	PBIAS (%)	NSE	R^2	PBIAS (%)
Calibration period	1995–2000 (month)	0.75	0.76	4.6	0.76	0.76	0.1
	1995–2000 (day)	0.38	0.45	1	0.57	0.58	–3.4
Validation period	2001–2005 (month)	0.1	0.23	15.7	0.31	0.36	–4.9
	2001–2005 (day)	–0.09	0.11	6.8	0.25	0.3	–2.0

The calibration period of the monthly SWAT models showed excellent results (Moriasi *et al.,* 2007). SWAT can capture the amount and variability of annual and monthly streamflow well, with R^2 and NSE exceeding 0.75 in the calibration period (Table 4-3). However, three wetter years were not well reproduced by applying the parameters of the calibration period (Figure 4-11). Although the CN-model is rated as very good for the calibration from 1995–2000, the model failed to simulate the wetter years from 2002–2004 of the validation period. However, the incorrect reproduction of these years is likely due to imperfect flow validation data. The general agreement of the flow duration curve (fdc) for the monthly CN-model indicates an adequate simulation for a range of conditions (Moriasi *et al.,* 2007). The mid-range flow appears to be increased with an overestimation of the simulated flow (Figure 4-12).

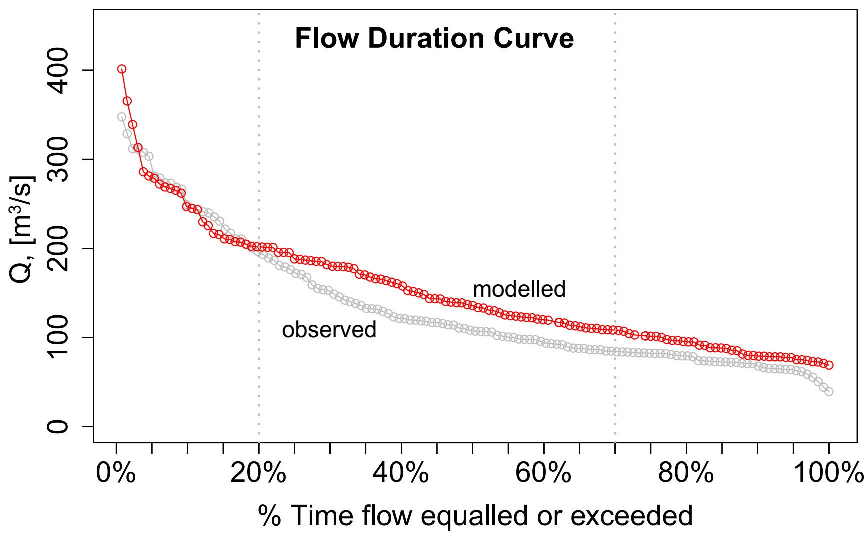


Figure 4-12: Flow duration curve for the monthly Curve Number model set-up compared to the observed flow.

Limitations and shortcomings seem to exist in other studies as well within the model validation period (Bonuma *et al.,* 2012), as only a small percentage of Brazilian SWAT studies report both calibration and validation results (Bressiani *et al.,* 2015). The lower NSEs for the validation period is in our case probably due to the fact that the validation time series of the observed data are biased, which seems likely after visual inspection of the hydrograph and the rainfall inputs. However, it is expected that multi-site calibration techniques could increase the model's performance (Cao *et al.,* 2006).

4.3.1.3 Green and Ampt vs. CN of the uncalibrated model

Two aspects are directly obvious. In the uncalibrated daily version, the CN model produces very high flow peaks in the rainy season and the timing of the recession is also not very well matched (too late). Through visual inspection of the hydrograph (Figure 4-13), on the other hand, the high flow period appears to be estimated well by the G+A model set-up. Likewise, the model efficiency of the G+A approach is much better than that of the CN set-up.

The tropics are characterised by heavy rainstorm events, and the G+A model seems to reproduce streamflow peaks better than the CN-simulations (Figure 4-13). The main problem of the Curve Number approach is that it does not account for rainfall intensity and duration. Daily rainfall of >70 mm d^{-1} is possible in the rainy season and surface runoff occurs across the catchment. So, the G+A is expected to be appropriate for simulating daily peak discharges, while the CN is empirical (King *et al.,* 1999).

However, higher subsurface flows (lateral soil and groundwater inflows) and unrealistically high soil water volumes for the G+A set-up model were simulated. Surface runoff was not produced for the G+A model, which implies an incorrect process representation (Figure 4-14). In the current version of SWAT (2012) the option of choosing G+A infiltration without providing sub-daily precipitation data is disabled indicating that our rainfall data inputs are not appropiate for the Green and Ampt approach.

The uncalibrated runs on the monthly time-step did not exhibit large differences of streamflow volumes between the two infiltration approaches (Figure 4-13).

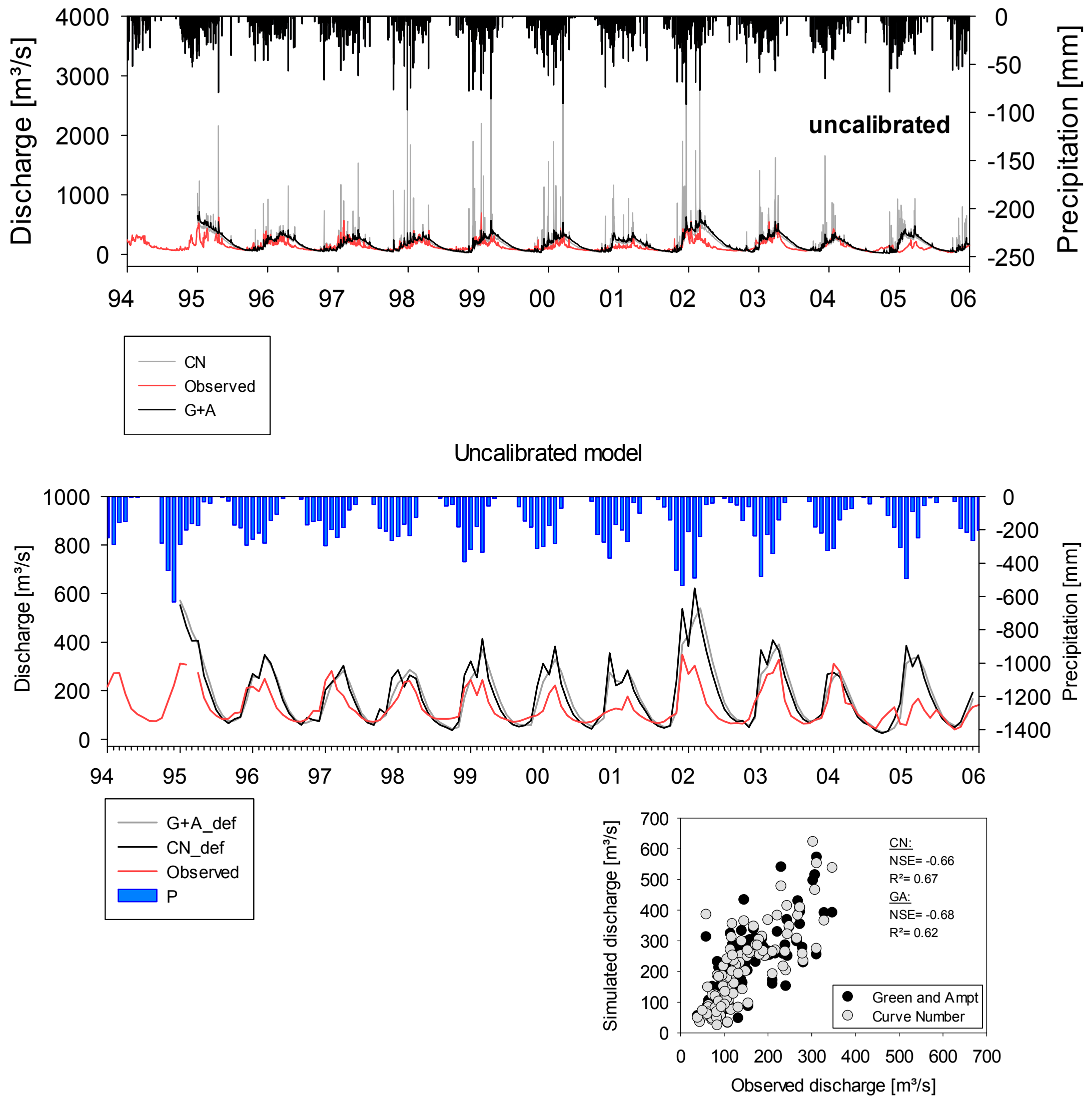


Figure 4-13: Daily and monthly discharge output for initial uncalibrated SWAT set-up with the Green and Ampt infiltration approch and the Curve Number simulating excess rainfall.

Other studies from Brazil also showed that SWAT failed to simulate sediments that depend on a proper simulation of overland flow (Bonuma *et al.,* 2012, Uzeika *et al.,* 2012). Bonuma *et al.,* (2012) demonstrated by modifying SWAT that for overland flow and sediment simulations model code adjustments would be necessary and might increase model performance at our study site. Furthermore, the G+A model testing showed that better NSE at the outlet masks the inadequate representation of other water balance components (e.g. inadequate soil water, surface runoff) compared to the CN set-up (Figure 4-14).

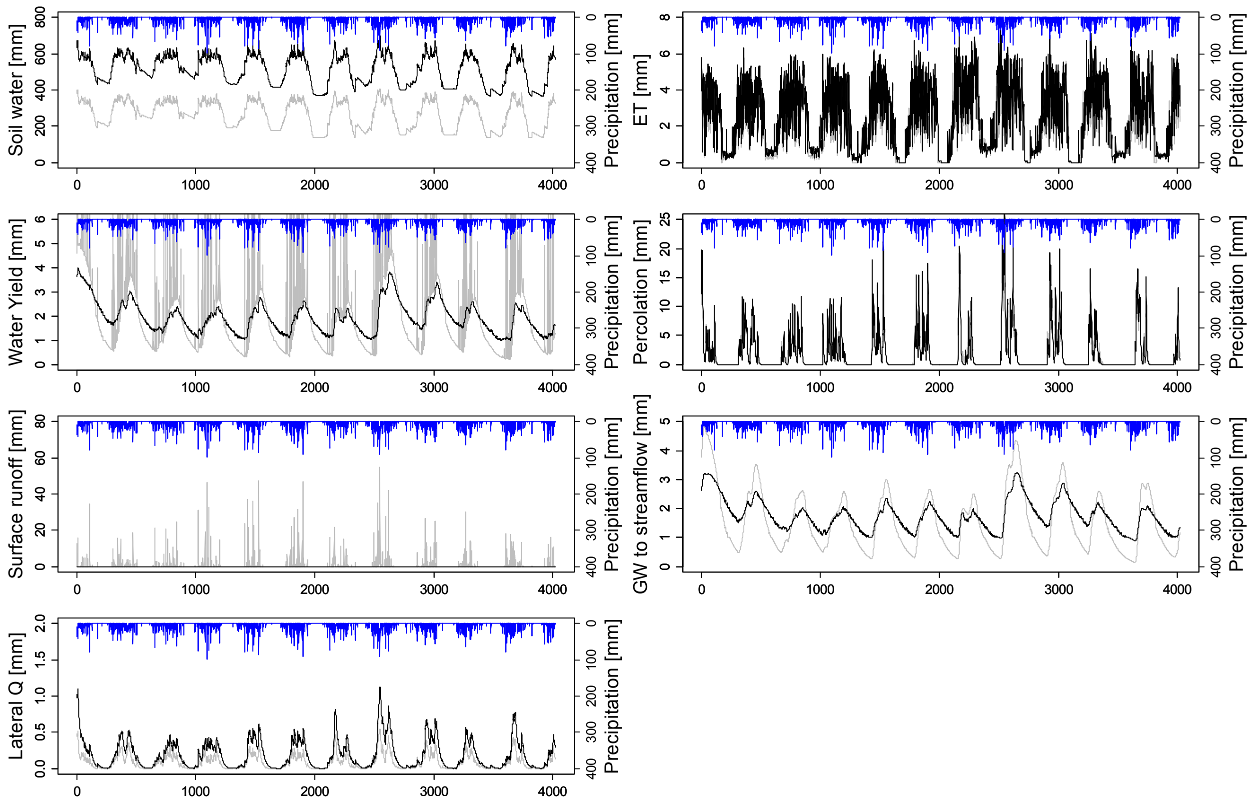


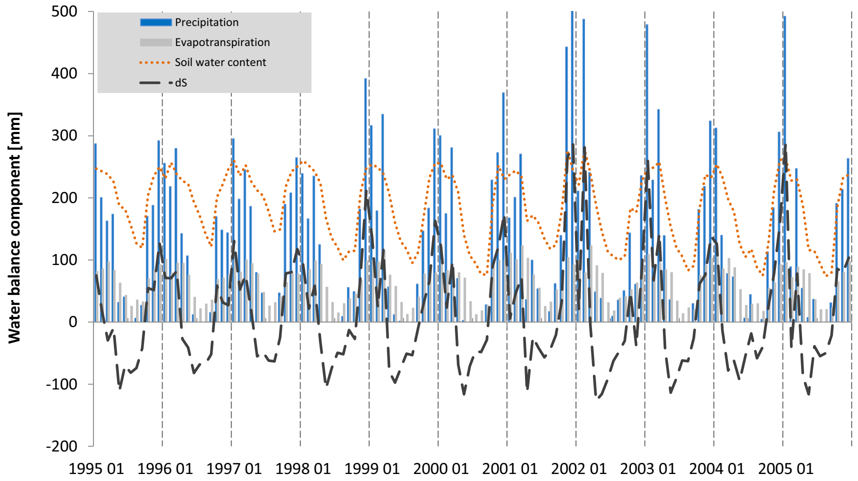
Figure 4-14: Exemplary water component outputs of the two model set-ups with Green and Ampt (black) and Curve Number (grey) infiltration methods of the subbasin 133 (113 km² on the Planalto 689m on Latosol) on the daily time-step.

To conclude from the results, the monthly G+A model performs best in simulating streamflow but is not able to predict surface runoff, as the precipitation input data are not on a sub-daily basis, which is a prerequisite. However, when focussing only on streamflow and not on other components of the water balance with aspects of sediment transport or erosion processes the G+A model could be useful.

The performance of SWAT on the daily time-step is not satisfactory. As we intend to focus not only on stream discharge at the outlet, and as the G+A-set-up did not capture surface runoff and soil water storage well, we decided to accept the CN-model on the monthly time-step for land use change and climate change scenario analysis because the dynamic and season of the system is represented in the initial uncalibrated model runs as well.

4.3.1.4 Plausibility of the modeled water balance with the monthly Curve Number model

Even though the validation results were not satisfactory for the CN model, the excellent calibration results encouraged us to consider the monthly CN model good enough to use for scenario analysis of how land use and climate change impact the water balance. Additionally, there are no obvious indications that the model represents any process incorrectly for the simulation of primary water components. Nevertheless, a more thorough look at the primary water components should provide insight if the model is able to reproduce the conditions of the Cerrado.



Water component	[mm a^{-1}]
Precipitation	1641.8
Surface runoff	36.52
Lateral runoff	150.57
Groundwater runoff	508.3
Total Water yield	695.26
Percolation out of soil	658.68
Evapotranspiration (ET)	800.2
Potential ET	1927.8

Figure 4-15: Water balance components at the mothly time scale (CN-model) of 10 years of simulation.

The monthly model thereby showed reasonable results in simulating the components of the water balance in the upper São Lourenço catchment (Figure 4-15). As expected, highest groundwater recharge with the lowest surface runoff were obtained for Cerrado vegetation, whereas croplands exhibit higher surface runoff and reduced percolation (Table 4-4).

Table 4-4: Primary water compontents per land use averaged over a ten-year simaltion period

Land use	Surface Q [mm]	Groundwater Q [mm]	ET [mm]	Available soil water capacity [mm]
Cerrado sensu strictu	6	690	808	206
Cerrado campo sujo/limpo	4	808	711	179
Planted pasture	8	640	830	224
Croplands	20	655	783	248

In comparison to other results from the Cerrado, the water balance is represented in a realistic manner (Figure 4-15, Christoffersen *et al.,* 2014). For instance, the runoff coefficient in our catchment was about 1.2 %, which is very similar to findings by Oliveira *et al.,* (2015) under similar conditions. As changes in the ET rates are causing differences in the streamwater response (Davidson *et al.,* 2012), a proper simulation of current ET rates is important. However, there are only a few flux towers in the Cerrado to determine ET (Oliveira *et al.,* 2015). Most studies reported ET values between 800 and 1000 mm a year for the Cerrado vegetation, which is in the range of what SWAT simulated. The Cerrado adapted vegetation parameters (Chapter 4.2.2.1) have effect on the simulated ET rates. The comparison of the SWAT default forest values of the SWAT original database with the Cerrado parameterisation showed on average >100 mm a^{-1} higher ET (Table 4-5).

Table 4-5: Average annual precipitation and evapotranspiration of different studies across the Cerrado compared to our simulated results for SWAT (10 year average of monthly outputs).

Land use	Precipitation [mm a^{-1}]	ET [mm a^{-1}]	Method	Location	Reference
Cerrado sensu strictu	1284	2.18 (mm d^{-1})	measured	São Paulo	Christoffersen *et al.*, 2014
Campo Cerrado		689	measured	Core Cerrado	Giambellucca *et al.*, 2009
Cerrado denso		823	measured	Core Cerrado	Giambellucca *et al.*, 2009
Cerrado	1139–1248	820–822	estimated	São Paulo	Oliveira et al. 2014
Original cerrado cover	1403	634	Simulated (SWAT)	Minas Gerais	Rodrigues *et al.*, 2015
Cerrado sensu strictu	725–1721	820–994	Measured Eddy tower	São Paulo	Bruno 2009
Campo Cerrado	1683	711	simulated	Mato Grosso	this study
Cerrado denso		1.8–3.8 (mm d^{-1})	estimated	DF, Central Brazil	Oliveira *et al.*, 2005
Cerrado	1121	576.5	Estimated	Minas Gerais	Lima *et al.*, 1990
Cerrado denso	1683	808	Simulated (SWAT)	Mato Grosso	this study
Default SWAT-Forest	1683	930	Simulated (SWAT)	Mato Grosso	this study
Soybean	1301	678.5	simulated	Central Brazil	Dias *et al.*, 2015
Cropland	1683	783	Simulated (SWAT)	MT, São Lourenço	this study
Pasture and croplands		1228	Simulated (SWAT)	MT, Rio das Mortes	Guzha *et al.*, 2014
Eucalyptus	1121	921.8	Estimated	Minas Gerais	Lima *et al.*, 1990

As SWAT performed excellently in the calibration period and no inconsistencies from calculating the water balance were obvious, the model performance is rated as acceptable to employ scenario analysis. Because the scenarios focus on longer (10 years) simulation periods and not on single events, the model outputs might be useful because all results are given as multi-year averages.

4.3.2 Scenario analysis: Impact of land use and climate change on water components

4.3.2.1 Impact of land use change on water components

To simulate the hydrological response of land use change on the water balance, three model simulations were conducted for ten years by replacing the current land use outside the urban areas by a.) cerrado, b.) pasture and c.) croplands.

The ten-year averaged annual water components range from increased water yield under cerrado (+8 %) and pasture (+2 %) conditions to decreases for the cropland scenario (–4 %). One main cause of the changed water yields is the decreased annual ET for the cerrado scenario, which is actually increased under cropland conditions. Percolation is increased for the scenario in which the entire catchment is covered by natural vegetation, whereas slight decreases are observed for the cropland scenario (Table 4-6).

Table 4-6: Differences of annual water components (10 years on average) of land use scenarios from the current conditions (Figure 4-15) to cerrado (cerrado denso and cerrado sensu strictu), planted pastures and croplands.

Primary water components	to cerrado	to pasture	to croplands
Precipitation	1641 mm	1641 mm	1641 mm
Monthly discharge	162 m^3/s (+10 %)	145 m^3/s (–4 %)	155 m^3/s (–2.5 %)
Water Yield	+7 % (+50 mm a^{-1})	+2 % (+17 mm a^{-1})	–4 % (–30 mm a^{-1})
ET	–9 % (–72 mm a^{-1})	–3 % (–27 mm a^{-1})	+4 % (+34 mm a^{-1})
Percolation	+12 % (+82 mm a^{-1})	+5 % (+37 mm a^{-1})	–3 % (–17 mm a^{-1})
Soil water	+13 % (+25 mm a^{-1})	–4 % (–7 mm a^{-1})	–4 % (–7 mm a^{-1})

The ten-year averaged monthly outputs of flow at the outlet showed the highest values for the scenario representing the full cerrado land cover. Also, the flow duration curve exhibits the highest flow for cerrado, followed by cropland and pasture for all flow conditions (Figure 4-16).

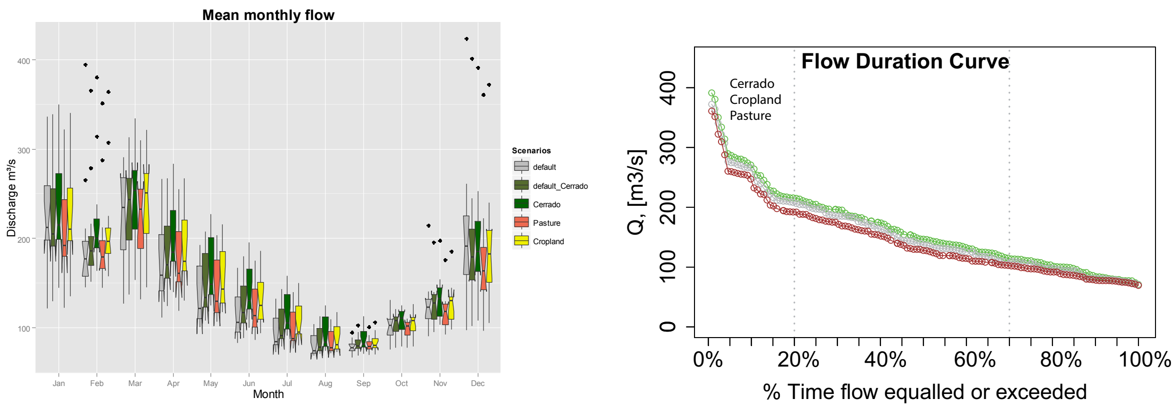


Figure 4-16: Monthly mean flow at the outlet for the different land use scenarios (def= current land use with SWAT Forest parameters; default_Cerrado= current land use with adjusted plant parameters for cerrado; cerrado; pasture;and croplands) and the corresponding ten-year averaged monthly flow duration curves of the land use scenarios.

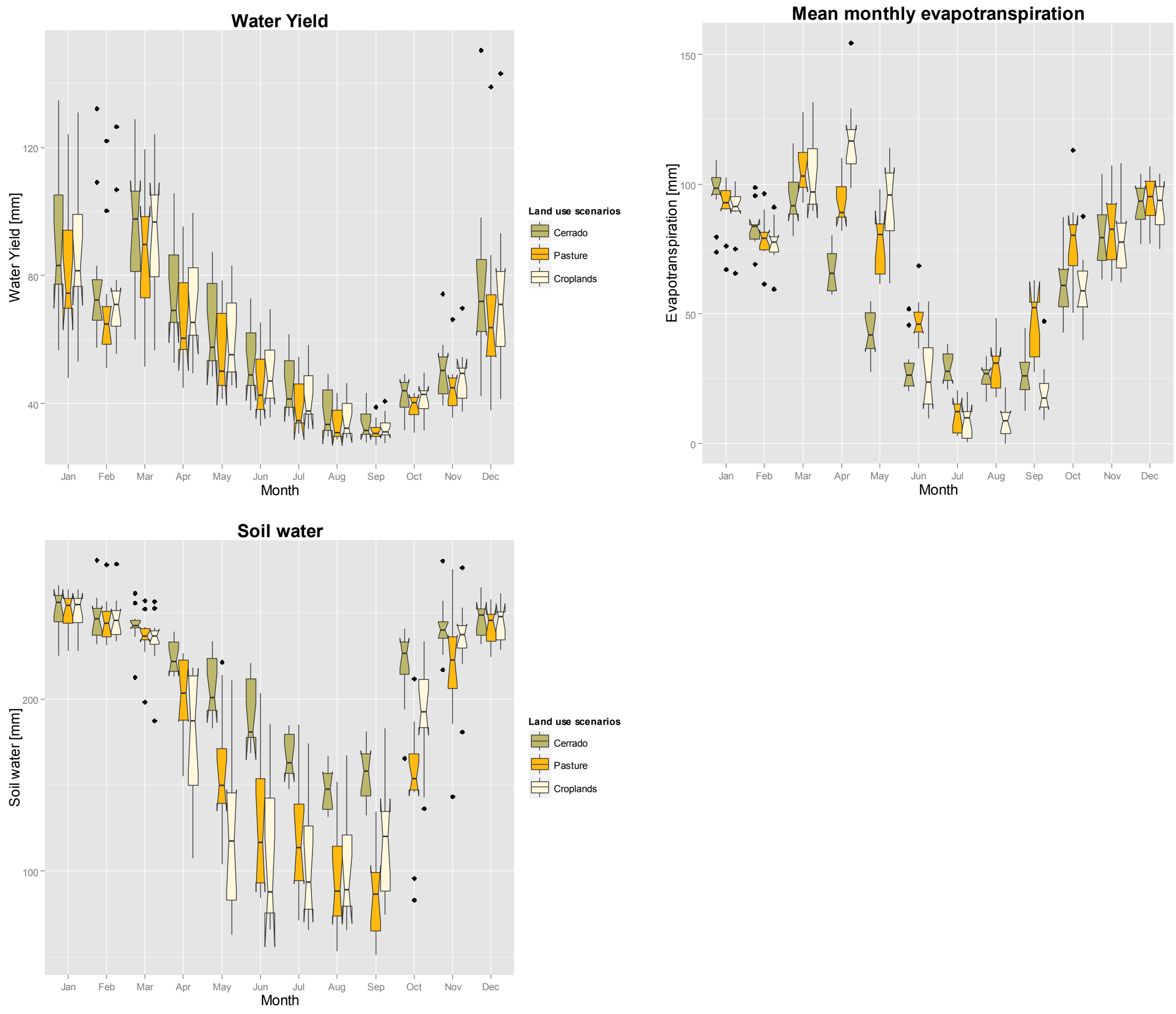


Figure 4-17: Primary water components (water yield, evapotranspiration, soil water) for ten years of simulation with SWAT for a cerrado, pasture and cropland scenario.

SWAT simulated a higher ET rates with increased agricultural land use (+60 mm a^{-1}) for the conversion of natural cerrado to the current land use with a crop rotation of two main crops and one cover crop to ensure permanent vegetation cover. At the same time, the averaged water yield decreased by 50 mm a^{-1}. The SWAT model scenarios for LUC resulted in a groundwater recharge decrease from cerrado (737 mm a^{-1}) to croplands (697 mm a^{-1}) to pastures (650 mm a^{-1}) resulting also in higher dry seasonal soil water storage under natural cerrado (Figure 4-17).

Impacts of deforestation on evapotranspiration and discharge

In the scientific literature, it is accepted knowledge that deforestation causes a change in the splitting of the net radiation into latent heat flux (which decreases) and sensible heat flux (which increases), as transpiration into the atmosphere is reduced due to less vegetation (Davidson *et al.,* 2012). Davidson *et al.,* (2012) argued that deforestation would reduce evapotranspiration (ET) and therefore cause increased discharges on the regional scale. In the same way, Panday *et al.,* (2015) found in model simulations for the southern Amazon that deforestation caused an increase of +6 % discharges due to –3 % ET and +1 % soil moisture. Costa *et al.,* (2003) found an increase of mean annual discharge (+24 %) in the Amazon due to increased high flows in the wet season. Neill *et al.,* (2013) stated that, after deforestation for soybean cultivation, water exports increased due to reduced ET up to fourfold in small streams. ET was then reduced by lower leaf areas, lower rooting depth and a shorter grow season. They estimated from MODIS data a 30 % reduction in mean annual ET for soybean compared to forest (Neill *et al.,* 2013, citing Coe *et al.,* 2013 unpublished data with about 1 mm/d reduction). The difference appeared in the dry season when soybeans were fallow (which is not the case in the Cerrado), whereas the wet season showed similar estimates (Coe *et al.*, unpublished in Neill *et al.,* 2013). In the same order of magnitude, Dias *et al.,* (2015) estimated for the transitional Amazon-Cerrado via modelling that agricultural sites showed 40 % lower ET than natural forest areas. Most authors stated that cropland expansion increases stream runoff. So, in the Amazon, decreasing ET is obviously a function of deforestation (Panday *et al.,* 2015) and increased surface runoff in small catchments (Oliveira *et al.,* 2015a). However, these findings may not be transferable to the core Cerrado area, as evidenced by our results from the SWAT model (Figure 4-16). Differences of the Cerrado and the Amazon may occur, because intra-annual ET dynamics are opposite in seasonal tropical systems compared to transitional or central Amazonian rainforests where ET peaks in the dry season with radiation maxima and lower rainfall (Biudes *et al.,* 2015, Christoffersen *et al.,* 2014). Hence, ET in the Amazon is not limited by water availability (da Rocha *et al.,* 2009). In contrast, in the Cerrado a significant decline of ET in the dry season between May and October has been recognised (Figure 4-17, Christoffersen *et al.,* 2014) which is associated to an inactive grass layer during that period (Giambelluca *et al.,* 2009).

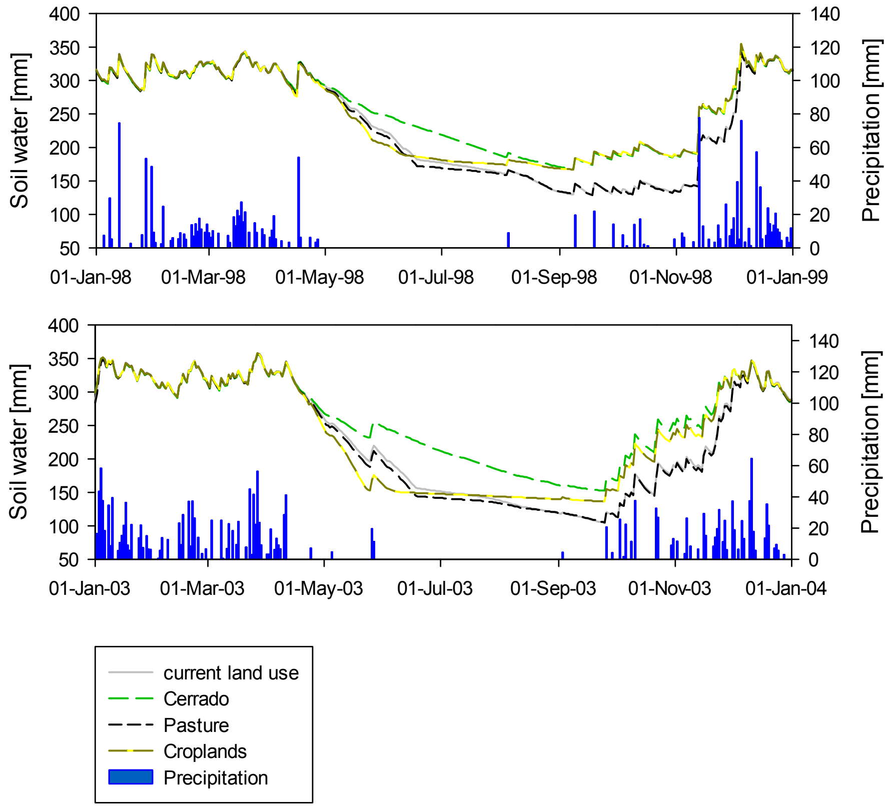


Figure 4-18. Daily soil moisture outputs for different land use scenarios for a year of lower (1998) and higher (2003) precipitation sums.

Thus, the ET rates of the Cerrado are a function of water availability and are significantly lower than those for transition forest and the Amazon rainforest. Cerrado vegetation stores more water in the soil than croplands (Figure 4-17). The differences of lower soil moisture for croplands are occurring in the dry seasonal months, whereas in the wet season the soil water storage is similar (Figure 4-18) among the land use change scenarios.

Impact of land use change for Brazilian SWAT studies

Results from a SWAT study of a Cerrado catchment (50 km north of our study area) presented by Guzha *et al.,* 2014 supported the findings from the Amazon (Coe *et al.,* 2011, D´Almeida *et al.,* 2007) that cropland expansion causes lower ET and higher streamflow. Similarly, Pereira *et al.,* (2014) found an increase of runoff in deforestation scenarios of +61 mm (+14 %) applying SWAT. The authors also attributed the percentage of woodland cover with higher ET values, which resulted in lower runoff. This was supported by Rodrigues *et al.,* (2015), who found that ET decreases (–8 %) and flow increases (+10 %) when the Cerrado savannah are replaced with pastures.

All these findings are in contradiction to the results of our SWAT study. It has to be mentioned that none of the SWAT studies give any information as to which vegetation parameters or default vegetation classes of the SWAT database were used. However, if SWAT were parameterised by the default forest parameters (which is the case in almost all SWAT studies in Brazil), the results of our catchment would be reversed and also end up in decreased ET rates after deforestation (as the default forest parameterisation produced >100 mm a^{-1} higher ET for the natural sites, Table 4-5), causing higher water yields. Then, the observed decreasing discharges would be contradictory. It has to be taken into account that only a small percentage of the natural vegetation is classified as dense woodland (*Cerradao* and *gallery forests*), which is similar to a forest. Most of the Cerrado in the São Lourenço catchment is characterised by Cerrado grasslands (*Campo limpo*) and both shrub and wooded Cerrado (*Cerrado sujo and Cerrado sensu stricto*) with a tree cover of < 50 % not taller than 6m. These more grass-dominated sites are characterized by lower plant available water compared to tree dominated (Oliveira *et al.,* 2005). Therefore, the model results showed lower ET rates for the natural sites with the consequence of decreasing flow at our study area. An increase of ET due to double or triple cropping with cash crops or for crops like sugarcane with a higher water demand is likely. There are also reports showing that the ET decrease comes only directly after conversion from native vegetation to croplands. After some years, the ET increases to levels which are comparable to the native vegetation (Oliveira *et al.,* 2014). It has to be taken into account that pastures have changed over the last 20 years from extensive cattle ranching to planted pastures (mainly *Brachiaria* ssp.) which are fertilized to enhance productivity, and in some cases water is also extracted for irrigation purposes. All this might increase evapotranspiration rates on agricultural sites.

Similarly, for 2003–2010, Oliveira *et al.,* (2014) showed water trends in the entire Cerrado indicating an increase in ET of 51 mm a^{-1} coinciding with decreased runoff of –72 mm a^{-1} in isolated watersheds of western Cerrado and the Tocatins River. Also in the central Cerrado, there are significant trends towards decreasing discharges evident in meso-scale catchments (Lorz *et al.,* 2012). As the catchment under study is located in western Mato Grosso, the observed decreasing gauges might be associated with land use change and therefore support our hypothesis by assuming an ongoing land use change (see Chapter 2.2.1). The SWAT model outputs provide evidence that the trend of decreasing flow could be partly explained by the conversion of natural Cerrado to agricultural land use (–8 % discharge, +9 % ET). However, the recorded decreases (~ 20 %) in discharge are far greater, which suggest that other factors may be responsible. Oliveira *et al.,* (2014) assumed for the western Cerrado three processes for higher ET rates after deforestation: 1.) increased crop production where the SWAT modelling gives evidence for such, 2.) water extraction for irrigation purposes, and 3.) the construction of reservoirs. Irrigation as well as reservoirs are both present in the São Lourenço catchment and might be responsible for the changes in streamflow. However, large damns play no role in the simulation period. Other authors (Lorz *et al.,* 2014) discuss whether the decreased discharges are already a signal of climate change.

In any case, it cannot be ruled out that other reasons such as changes in the discharge cross sections appeared without further adjustments over the last decades. Additionally, very high flow could often not be measured exactly with the stage-velocity relationship once the riverbed was overflown in the rainy season as is sometimes the case.

4.3.2.2 Impact of climate change on water components in the Cerrado

The IPCC (2013) reported that the Cerrado warms faster than other regions of Brazil and that the occurrence of more extreme conditions is likely over the mid-term. To address the impacts of climate change on primary water components, different model conditions of the RCP8.5 scenario were used to represent these conditions which the region was already facing.

Water yield and discharge under climate change

The simulated monthly water yield for the entire catchment showed for the SL scenario an increase of 5–17 % (up to 30mm per month) for all months within the projected years (2039–2058) – except for October, where a slight decrease of 5 % ~3mm was observed. The largest increases were recognised in the rainy season under high flow conditions (Figure 4-19).

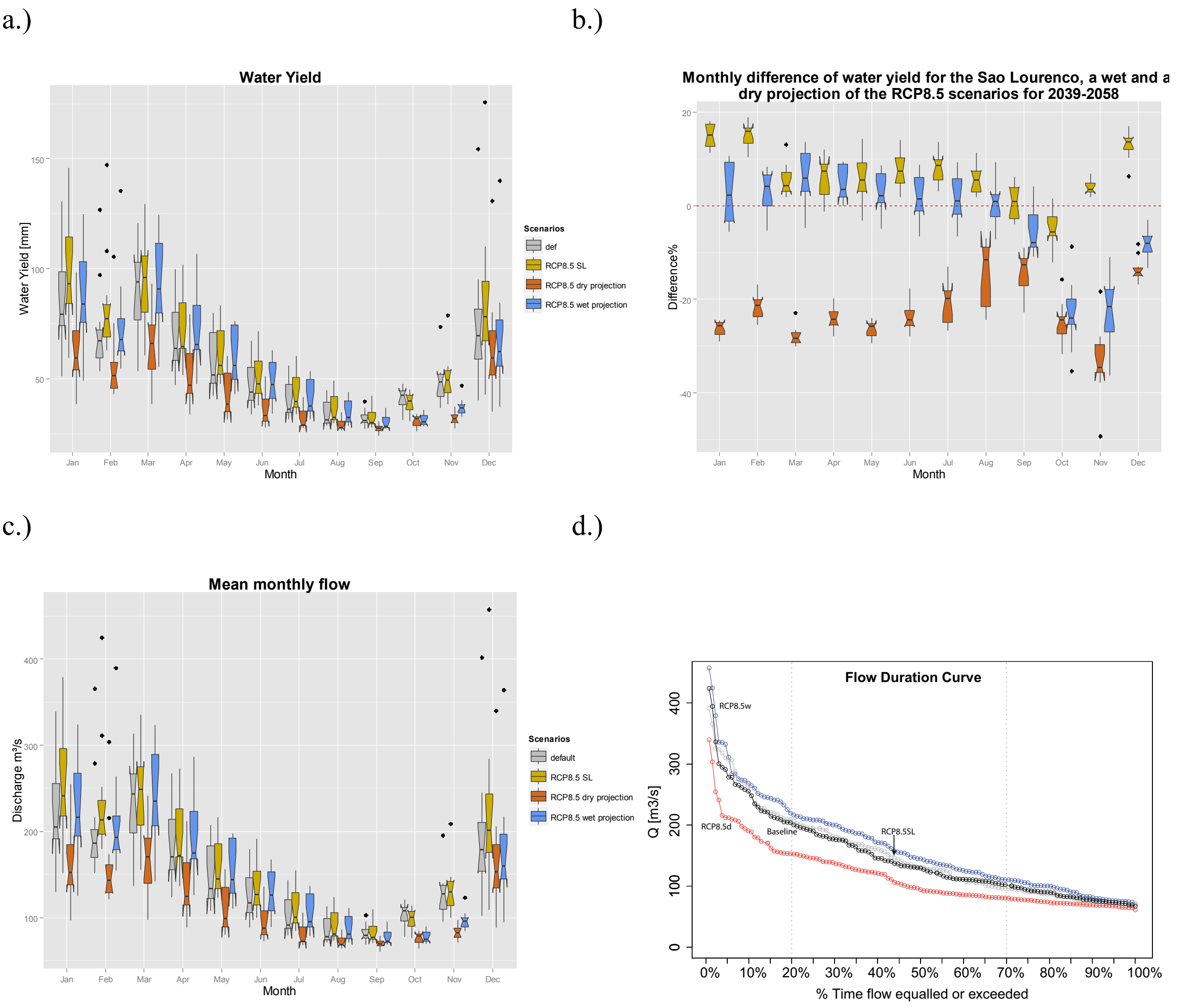


Figure 4-19: Boxplots of 10 years of monthly water yield outputs from the entire watershed for the baseline conditions (def/default) and the three climate change projections in a.) absolute numbers and b.) relative monthly differences from the present conditions. Boxplots of the monthly flow of 10 years of simulation at the outlet for the baseline (default) conditions and the three climate change projections (c.)) with the corresponding multi-year averaged flow duration curves (d.)).

Decreasing annual precipitation in the “dry” projection (which not necessarily means that rainfall intensities are lower, too) resulted in decreasing annual water yields over the year with minima in March (Table 4-7). Compared to the other two projections, the “wet projection” showed the lowest differences from the current conditions (Table 4-7 and Figure 4-19 with < 10 % relative monthly changes). The end of the dry season and the beginning of the wet season was characterised by lower flows.

Table 4-7: Changes in the primary water components for different RCP8.5 climate change scenarios for the years 2039–2058 compared to the present conditions. Details of the monthly distribution of precipitation are given in Table 4-2.

Primary water components	RCP8.5_SL	RCP8.5_dry	RCP8.5_wet
Precipitation	0	–19 % (–308 mm a^{-1})	–7 % (–129 mm a^{-1})
Monthly discharge	+8 % (+12m³/s)	–25 % (–36m³/s)	–1 % (–2 m³/s)
Water Yield	+8 % (+54 mm a^{-1})	–22 % (–161 mm a^{-1})	–1.8 % (–12 mm a^{-1})
ET	–7.5 % (–65 mm a^{-1})	–10 % (–94 mm a^{-1})	–15 % (–123 mm a^{-1})
Soil water	+4 % (+7 mm a^{-1})	0	0

From the monthly discharges for the modelling period of ten years, it can be stated that the climate change scenario for the São Lourenço (RCP8.5_SL) for the current land use mainly has an impact on the high peaks in the rainy season with an increase of discharge, whereas the baseflow in the dry season is only slightly increased. Average monthly discharges of 10 simulation years increased mean streamflow from 151 m³/s to 163 m³/s (CN) (+8 %), with CC (RCP 8.5_SL). Similar patterns are observed for the wet scenario, but with noticeable flow reductions at the end of the dry season. This water yield reduction is noteworthy for all three climate change projections in October. In the beginning of the rainy season (November and December), water yields differ between the SL projection and the two extreme scenarios of drier and wetter conditions, from increasing (SL 5–12 %) to decreasing water yields (–20 to –35 %). The finding of increased discharges in the São Lourenço projection is in line with Nóbrega *et al.,* (2011), who found increases between +5 and +10 % according to different emission scenario simulations (A1B, A2, B1, B2) based on HadCM3 for the Parana river.

On a daily basis, the precipitation regime of the RCP8.5_SL scenario causes higher discharge peaks in the rainy season (Figure 4-20), which has implications for erosion processes, nutrient losses and sediment transport because higher discharges are likely to cause higher transport capacities and soil erosion precisely at the time when fertilizers and other agrochemicals are applied (Chapter 2.5.1).

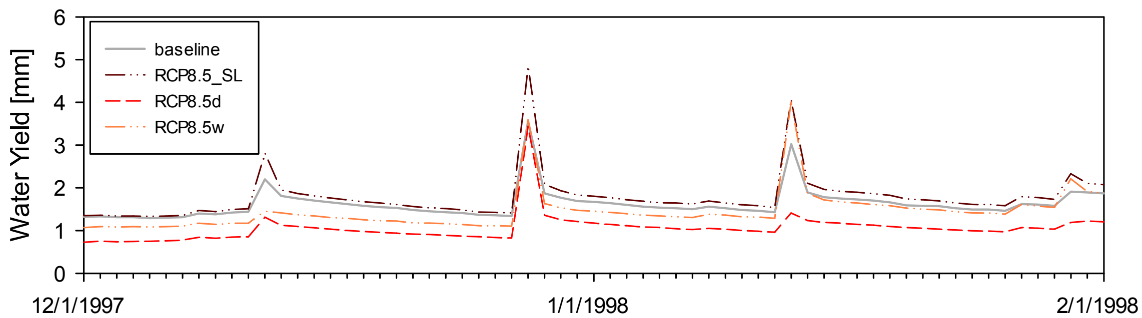


Figure 4-20: Exemplary daily water yield model output for two month in the rainy season of the sub-watershed 239 (111 km², agricultural land use) for the baselinie conditions and three climate change scenarios.

Climate-related crop failures through erosion events are also likely. On the other hand, lower water yields in the beginning of the growing season might imply yield losses due to water stress in the early phenological development stages.

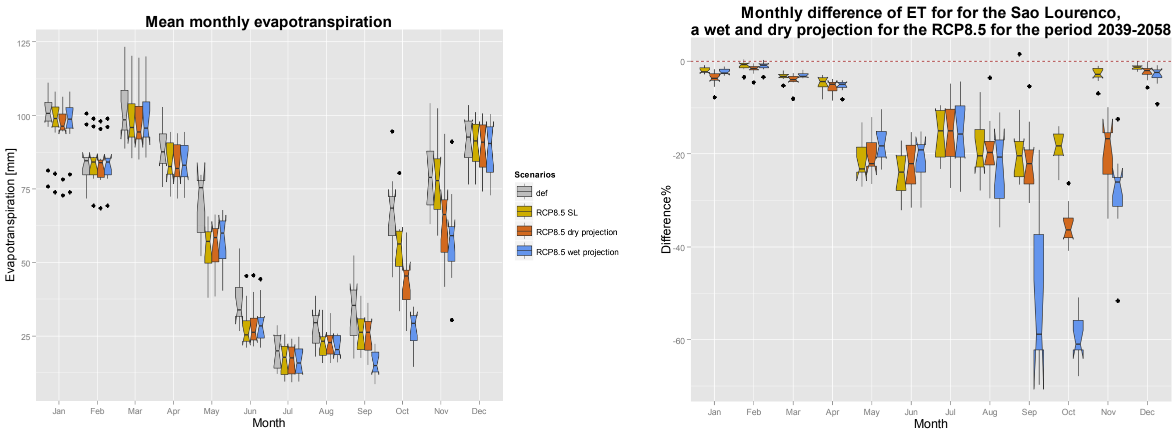


Figure 4-21. 10 years monthly evapotranspiration for the baseline simulation (def) and three RCP8.5 climate change projections as absolute values and b.) the percentual differences of the scenarios from the baseline.

ET under elevated CO_2

The analysis of the monthly ET rates showed decreases for all three projections of the multi-year averaged values with maxima of ~30 mm (minus ~20 %) in May. In September and October, ET decreases are lower in absolute terms, but range from –18 % (RCP8.5_SL) to a decrease of more than 60 % (RCP8.5_wet) (Figure 4-21).

Due to the lower projected ET rates in the dry season, the values for soil water content are higher in the dry season for all projections (from +14 mm to +25 mm between June and August, exceeding an average relative increase of +25 % in August). The decreased ET rates can be attributed to elevated CO_2 levels, as higher CO_2 concentrations cause a reduction in leaf conductance (Field *et al.,* 1995). SWAT accounts for this with a modification of the canopy resistence term (double CO_2 means a decrease of about 40 %, Morison 1987, Neitsch *et al.,* 2009) and consequently decreased transpiration. The assumption is considered appropriate for agricultural sites (Luo *et al.,* 2013), whereas an overestimation of the stomatal conductance response is reported for forests (Medlyn *et al.,* 2001). However, besides the changes in transpiration (stomata conductance effect), a competing effect of increased plant growth under the stimulation of CO_2 is known (Kergoat *et al.,* 2002, Drake *et al.,* 1997). In contrast, higher LAI causes increased transpiration (Bucci *et al.,* 2008). The plant growth effect is not included in the current SWAT version, but might have the opposite impact on evapotranspiration (Ficklin *et al.,* 2009). However, the "CO_2 fertilisation" effect is controversial for the tropics (Clark *et al.,* 2010). According to Piniewski (2012), the stomata conductance effect has a larger impact than an increased LAI. Because the São Lourenço catchment is dominated by agriculture, a decrease in the stomatal conductance amidst CO_2 enhances plant productivity with a lowering of the water requirements, which is therefore assumed to explain the higher soil water content in the dry season under conditions of climate change (Figure 4-22).

The remarkable decrease in soil water content at the end of the dry season (RCP8.5_dry and RCP8.5_wet, Figure 4-23) is caused by the projected precipitation decreases (Table 4-2).

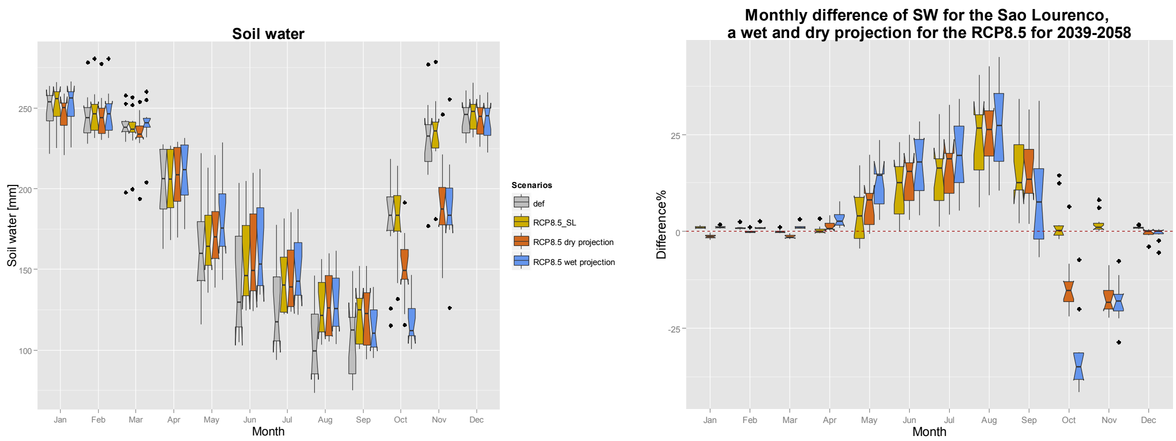


Figure 4-22. 10 years monthly soil water content for the baseline simulation (def) and three RCP8.5 climate change projections as absolute values and b.) the percentual differences of the scenarios from the baseline.

The effects of the prolongation of the dry season are demonstrated in the daily model outputs by changes in the soil water. At the beginning of the dry season, soil water content values differ, with higher soil water volumes for the climate change scenarios due to decreased evapotranspiration rates (Figure 4-23). However, at the end of the dry season, decreased precipitation causes lower soil water content for all climate change projections (lowest differences for the SL_projection) in a period in which the first crop (soybeans) is grown. Therefore, it is likely that the sowing might be later in some years.

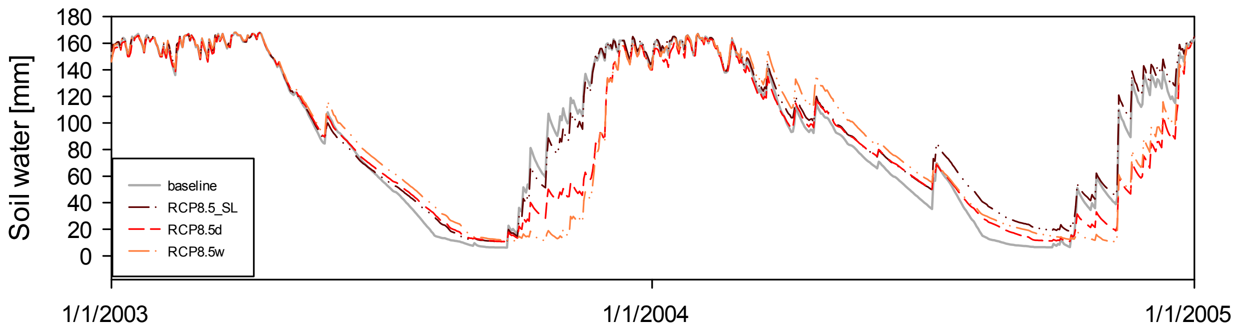


Figure 4-23. Example of daily soil water output for climate change scenarios (RCP8.5_SL= ensemble average projection for the São Lourenço catchment, RCP8.5d=ensemble average scenario representing drier conditions, RCP8.5w= ensemble average scenario representing wetter conditions in the rainy season).

The spatial distribution of the water components are mapped for the subbasin for years of drier and wetter conditions as different from current conditions. The water yield is likely to be dependent on groundwater contributions. Similar to findings from Cabral *et al.,* (2015) in wetter years, the percolation and groundwater recharge is increased (not shown), resulting in higher water yields on the well-drained Latosols in the western part of the catchment (Figure 4-24 for RCP8.5_SL). Therefore, the consistently observed decreased ET from elevated CO_2 inputs cannot be attributed to a decline in soil water content whose relative change is the opposite (+4 % for RCP8.5_SL) or no changes are observed (Table 4-7). Most important impacts of climate change scenarios will be the prolongation of the dry season under extreme conditions with huge impact on soil water, whereas annualized water content is supposed to change only little.

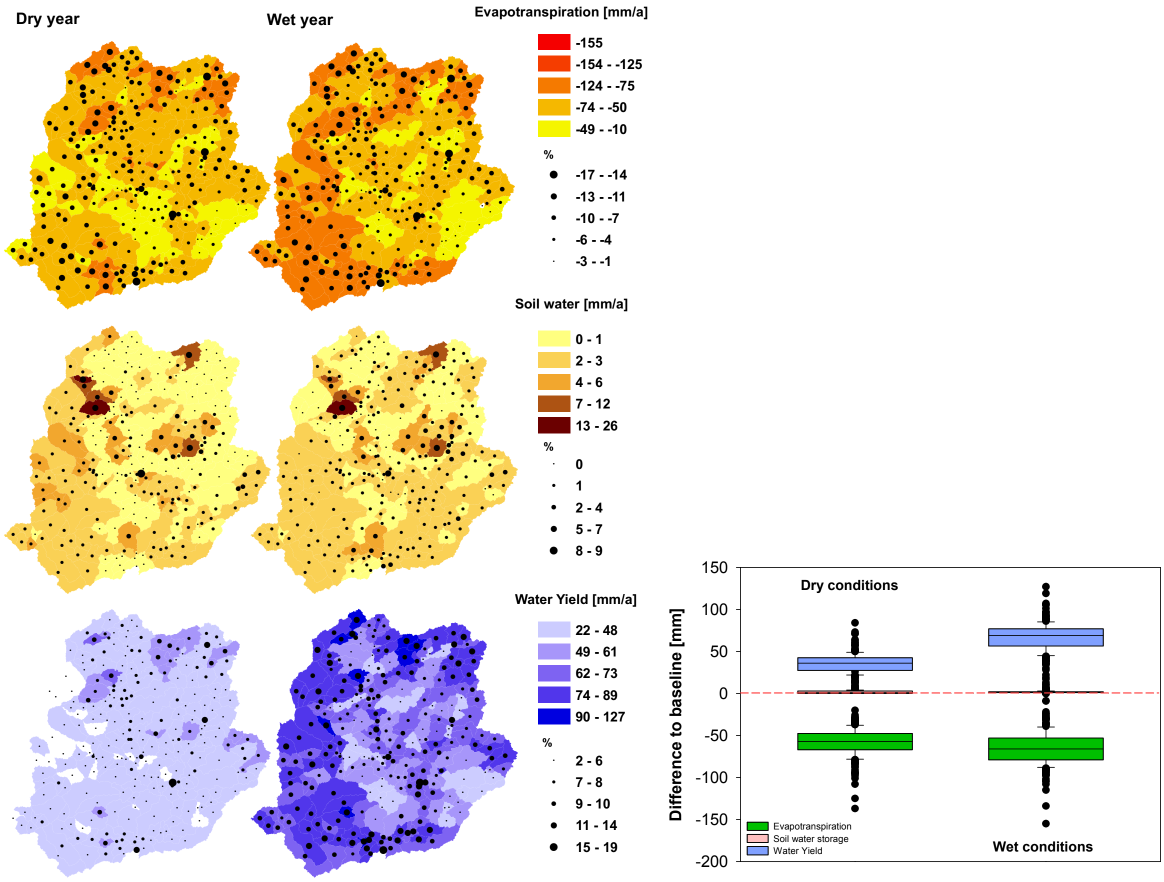


Figure 4-24: Effect of projected Climate Change (RCP8.5_SL, 2039–2058) on annual evapotranspiration, soil water content and water yield as absolute differences from baseline simulations on the subbasin level (n=257). The different boxplots represent years of drier and wetter conditions given as the absolute difference of the RCP8.5_SL from the current baseline simulation.

By applying SWAT, it becomes clear that the projected extreme dry conditions (IPCC 2013) result in decreasing discharge over the entire year, with potentially critical dry seasonal water availability when the baseflow is the main contributing source. However, more probable increases in streamflow in the rainy season are likely due to the extreme scenarios (RCP8.5_wet), but particularly for the watershed scenario (RCP8.5_SL). Taking all high emission simulation scenarios into account, the most presumable effect is a prolongation of the dry season by about one month and higher flows in the rainy season. Consequently, potential threats to crop production at the beginning of the crop cycle with lower soil moisture (i.e. irrigation) and increased erosion and sediment transport during the rainy season are likely. But these results are uncertain, although the CSM4 data (NCAR 2012) are based on ensemble averages.

4.4 Conclusion

The ecohydrological model SWAT was used to obtain information regarding the applicability and the impact of LUC and CC in the Brazilian Cerrado. The testing of SWAT showed that the type of precipitation data has a significant impact on modeled flow. The readily available estimated satellite rainfall data produced large uncertainties and should only be used with care. In terms of model efficiency, the G+A model set up is more suitable to simulate daily discharge in ungauged basins than the CN approach (yielding a higher average Nash-Sutcliffe coefficient of daily runoff simulation). But since other primary water components were not reliable (no surface runoff, overestimation of soil water content and evapotranspiration for all forms of land use), we accepted the CN-model on the monthly step to simulate the impact of LUC and CC on the primary water components.

The SWAT application provides new insights into the ecohydrological modelling of LUC and CC in data-sparse areas like the Brazilian Cerrado. The application of the calibrated CN model indicated that LUC and CC alter the hydrological cycle. Scenario analyses give insight into how the Cerrado is likely to develop. Extreme land use change scenarios from reforestation to total deforestation showed for both model set-ups (CN and G+A) that a higher Cerrado percentage caused an increase in streamflow, supporting the findings of the observed gauge data. Furthermore, the modelling was able to confirm the decreasing trend corresponding to higher crop cover in the region, but could not explain the findings as a single factor for these large decreases in flow. Another important finding is that ET rates and components of the water balance behave differently compared to the Amazon and show effects which are not in line with state of the art findings from the Amazon with regard to the impact of deforestation on the water balance. But also Cerrado-SWAT studies are in contraction to our finding which is most likely related to higher ET rates determined by the choice and the type of the natural vegetation classes. We showed that the parameterisation of the natural vegetation is a crucial point which may result in an overestimation of ET when using the default forest parameters instead of adjusting the vegetation database.

The combined effects of further land use intensification and climate change is uncertain, but both stressors imply higher peak flows in the rainy season. Consequently, potential threats for crop production at the beginning of the crop cycle with lower soil moisture and increased erosion and sediment transport during the rainy season are likely. Rainfall reduction at the end of the dry season may cause a decrease in soil moisture and extend the flow recession period and thus affect water availability, which might imply an increased need for irrigation after planting. Projected rainfall increases during the rainy season which caused an increase in streamflow that can modify the erosion dynamic of the rivers in the region.

5 Synthesis

The Cerrado is among the most important areas of cash crop production in the word. Large scale land conversion has been shown to alter the ecohydrological functioning of the Cerrado. The overall aim of the thesis was to analyse the impacts of land use change and partly climate change on water and soil resources. The thesis assembled different pieces on the functioning of the Cerrado to gain insight into relevant ecohydrological processes and thus giving quantitative evidence how the biome is already impacted and how it is likely to develop. The key findings of the previous chapters, their implications and limitations are discussed with reference to the three objectives (Chapter 1.2). Finally I point out suggestions for further research needs.

5.1 Main results and implications

5.1.1 Quantification of water and soil degradation in heavily modified catchments in the Cerrado

The thesis intended to answer the question to what degree land use change influenced the soil and water properties in the *entire* Cerrado and a meso-scale catchment in Mato Grosso. We aimed at composing a review study on the drivers, processes and interactions of water and land degradation on the status quo and the development regarding soil functioning and water quality to project how the Cerrado is likely to develop under future land use and climate change (Chapter 1.2, Chapter 2). To gain further insight into the dynamics of these processes on the plot and meso-scale, I carried out field studies in order to investigate soil changes under different land uses (cerrado, pasture, soybean/maize/cotton, sugarcane), and to link these impacts to seasonal and spatial patterns of water quality across a meso-scale heavily modified catchment (Chapter 3).

The main findings of Chapter 2 and 3 are discussed together, arranging the field study results of Chapter 3 in the overall context of the findings for the entire Cerrado (Chapter 2).

The results of both chapters showed several impacts from deforestation, pollution and overharvesting. The review in Chapter 2 pointed out that due to the new legislation in 2012 (Government of Brazil 2012, Law No. 12.727/2012) the deforestation of Brazil is mainly concentrated in the Cerrado and not in the Amazon. The literature analysis showed also that the trend towards intensive agricultural use is likely to continue for the entire Cerrado. Additionally, the review of the past and projected trends of the stressor climate change (Chapter 2.2.2) identified the Cerrado as a region which showed a general temperature increase of 0.08 to 0.2 °C, an increased occurrence of extreme rainfall events and an intensification of the dry spell length over the last 50–100 years. Future projections displayed inconsistencies between climate models (IPCC 2007, 2013). However, it is predicted that the Cerrado warms faster than the global average (Marengo *et al.,* 2011) with a prolongation of the dry season from 5–6 months but also the increase of heavy rainfall events of greater than 10 mm is very likely (Marengo *et al.,* 2009, 2010).

We compared soil and water quality parameters from different land uses (classified as cerrado, pasture, cropland and plantation) considering 80 soil and 18 water studies conducted in different regions across the Cerrado to provide quantitative evidence of soil and water alterations from land use change. In a qualitative assessment, the current impacts of these alterations were identified as follows:

Impact 1: Increased occurrence of overland flow, erosion and gully transformation

The thesis qualitatively identified in Chapter 2 an alteration of the soil-hydraulic behaviour as a function of land use. Infiltration rates are considerably lower at pasture and cropland sites which most authors attributed to the loss of macroporosity by soil compaction (Chapter 2). The findings of Chapter 2 are in accordance to our field data (Chapter 3) which allowed quantifying the changes of near surface infiltration of pasture (−96 %) and croplands (−90 % to −93 %) for a typical Latosol site. Chapter 2 could show that bulk densities are significantly higher for croplands and pastures than for cerrado. Beside machine traffic and cattle trampling, soil liming was discussed to destroy soil aggregates by clay dispersion and consequently cause a decrease of infiltration. This is likely as this thesis recorded substantial increases of soil pH values for croplands and pastures (Chapter 2 and 3). The field study (Chapter 3) could provide evidence that soil aggregate stability of soybean and sugarcane sites was significantly lower in accordance to higher clay contents.

A comparison of the measured infiltration rates rates with the maximum 5 min rainfall intensities indicated saturation and infiltration excess OLF on agricultural sites during almost all (83 to 96 %) rainfall events (Chapter 3). Therefore, hydrological flow paths of formerly well drained Latosols in the Cerrado are affected by decreased permeability and increased overland flow generation on the agricultural (in some cases over-fertilised) sites. These findings are expected to be transferable to other agricultural used catchments of the high plain Latosols and very likely to explain the increased susceptibility of the formation of gullies (Chapter 2)

Impact 2: Nutrient accumulations in land and water resources

A main finding of this thesis is that due to fertilisation at agricultural sites nutrients are accumulated in soil and water resources (Chapter 2 and 3). The literature study revealed significantly increased available P and K contents in the upper soil layer (up to ~ 40 cm) for croplands and pastures. Likewise in Chapter 2, we found notably high P concentrations in the topsoil of soybean sites (Chapter 3) which were manifold higher (~6-fold) than the soil nutrient recommendations of EMBRAPA (2003) and de Morais *et al.,* (2009), thus indicating over-fertilisation and a potential risk of P displacement via surface runoff and subsurface flow. However, regardless of the land use, P was not accumulated in deeper horizons (Chapter 2 and 3).

Surprisingly, P pollution was widely absent in surface waters of the reviewed water quality studies (Chapter 2), likewise in our own wet seasonal water quality sampling (Chapter 3). Especially for the rainy season, these unambiguous results were unexpected in an area which is characterised by active erosion processes and over-fertilised soils. We conclude from these results that very high-fixing capacities of deeply weathered soils as well as the filtering capacity of riparian vegetation (e.g. Boechat *et al.,* 2013) seems to play an important role in preventing surface waters from pollution. Contrarily, we recorded in dry seasonal increases of phosphate (Chapter 3) across the entire catchment which is likely to origin from animal waste and fertiliser application for the second crop. However, in the field study we could not give further evidence to explain these findings.

Soil total N did not differ between land uses because most of the cropland sites in the review study were nitrogen-fixing soybeans, which are not artificially fertilized with N. Likewise, we could not find altered concentrations of total N for the soybean sites (Chapter 3). However, the role that nitrogen leaching plays in agricultural Cerrado is inconclusive in this thesis. Chapter 2 and 3 in contrast show nitrogen enrichment in agricultural catchments, indicating fertilizer impacts and potential susceptibility to eutrophication from other crops (maize, cotton) after the soybean havest. Direct NO_3^- leaching appears to play a minor role; however, water quality is affected by agricultural non-point sources, due to topsoil fertiliser inputs affecting the entire catchment, from small low order streams to the larger rivers of the modified catchment (Chapter 3). Additionally, nitrate fertilizer is also applied directly to crops, and higher levels of inorganic nitrogen forms such as nitrate and nitrite we identified by own measurements (Chapter 3) in surface waters and in the review study (Chapter 2) may originate from granular fertilizer applications on bare soil between the seedling rows.

In absolute terms, nitrate concentrations in surface water were low compared with concentrations measured in European rivers; in relative terms, however, the nitrate values of the rivers in catchments under land use change are orders of magnitude greater than those found in natural Cerrado streams. Additionally, field sampling of Chapter 3 intended also to explore if there are any seasonal or spatial patterns of water quality evident. In the snapshot sampling, we could identify a strong seasonality with higher temperature, oxi-reduction potential (ORP), NO_2^-, and very low oxygen concentrations (<5 mg·l $^{-1}$) and saturation (<60 %) in the rainy season.

Our assumption that water quality parameters are spatially correlated to stream order, catchment size, up-stream land use, and the land use in a 300 m buffer was generally not supported by the snapshot data, because no significant differences were detected.

Impact 3: Pesticide contamination in the water cycle

This thesis reviewed all available studies on pesticide occurrence in the water cycle (Chapter 2). It turned out that agriculturally related pesticides were consistently detected throughout the entire aquatic system. However, Chapter 2 pointed out that pesticide pathways to surface and ground water are (1) wind drift from plane applications (Laabs *et al.,* 2002), (2) direct runoff from agricultural fields (Casara *et al.,* 2012) at sites with a non-intact riprian vegetation and (3) leaching through macropores (Dores *et al.,* 2009). In several case studies, extremely high-peak concentrations exceeded the considerably less strict Brazilian and EU water quality limits, which were potentially accompanied by serious health implications by the consumption of untreated water (Nogueira *et al.,* 2012, Brando *et al.,* 2013). Due to higher volatilisation rates in tropical areas, the wet and dry deposition rates of pesticides appears to be much more relevant and complex than in temperate regions (Laabs *et al.,* 2002), thus contributing to a much larger distribution of pesticidal effects across the region. Overall, we concluded that even with low-detection frequencies the reviewed studies found pesticide pollution in the water cycle which failed to comply with the stricter EU limits

The presented field data of soil and water degradation (Chapter 3) in the Brazilian Cerrado comprise novel and important information on how rapid land use change has altered soil physical and chemical properties of Ferralsols under different land uses in regard to its overland flow dynamics, erosion processes and water quality deterioration in a typical heavily modified catchment of the Cerrado area. To my knowledge there is almost no study which even tries to link changes of soil properties with water quality in a meso-scale catchment.

Chapter 2 and 3 of this thesis give for the first time quantitative evidence on how the water and soil resources across the Cerrado biome have been altered under modified land use. The compilation of a data base on soil properties and water quality parameters are valuable for multiple science disciplines and give a starting point for how the Brazilian Cerrado has changed over the last decades and how the region is likely to develop under future land use and climate change. Land use intensification is likely to continue, particularly in regions where less annual rainfall and severe droughts are projected in the northeastern and western Cerrado. Thus, the leaching risk and displacement of agrochemicals are expected to increase, particularly because the current legislation has caused a reduction in riparian vegetation.

Altogether it is concluded that the combined effects of land use intensification and climate change seriously limit the Cerrado's future productivity and ecosystem stability.

5.1.2 SWAT applicability and scenario analysis

There are currently no tools available which would allow for catchment-scale quantification of ecohydrological processes and water cycling in the Cerrado. To understand the dynamics of water cycling the main objective of Chapter 4 was to test the applicability of the process-based model SWAT in the Cerrado region. A set up based on field observations (Chapter 3) was used to test SWAT systematically on the daily and monthly time-step with different input data (satellite vs. measured precipitation data) and infiltration approaches (G+A–Green and Ampt and CN–Curve Number) in the upper São Lourenço catchment (7072 km^2).

Model performance testing

As a result, SWAT performance testing showed that the choice of precipitation input has significant impact on the modeled flow. The readily available estimated satellite rainfall data (CSFR) produced large uncertainties. We provided evidence that these data are inadequate for the region and should be only used with care. Streamflow calibration procedure resulted on the daily time step in the best performance for the G+A set-up (NSE 0.58) whereas the daily CN-model was judged unsatisfactory due to very high uncertainties to model peakflow. Furthermore, event recessions were too slow. On the monthly time step both models capture the amount and variability of annual and monthly streamflow well, with R^2 and NSE > 0.75 in the calibration period. Although the CN-model is rated as very good for the calibration (1995–2000), the models failed to simulate the years from 2002–2004 of the validation period. However, the incorrect reproduction of these years is likely due to imperfect flow validation data.

By analysing the output of the SWAT water components we could demonstrate that the G+A_monthly model set-up performed best (NSE 0.76) at the outlet, but thereby masks the inadequate representation of other water balance components (e.g. no surface runoff, overestimation of soil water storage and evapotranspiration). As we intended to not only focus on stream discharge and as the CN set-up did not indicate incorrect process representation or any inconsistencies (e.g. evapotranspiration rates) the model was used to simulate land use and climate change scenarios on the monthly time step.

Scenario analysis

At three gauges in the catchment a reduction of discharge (–17 % to –25 %) were observed in the last 40 years. At the same time the region was transformed from natural savannah vegetation to intensive agricultural land uses. Other factors causing decreased streamflow (e.g. decreased precipitation or the construction of reservoirs) were excluded which is why we assumed that increased ET due to cropland expansion caused decreasing water yields in the catchment. In order to account for the effect of land use change, we run the calibrated SWAT model considering simple land use scenarios

The comparison of primary water components of the pasture and crop parameterisation with a complete cerrado land cover showed that percolation, aquifer recharge and total water yield is reduced by 5 % for croplands and about 11 % for pastures. As we assumed, the ET for the crop scenario was increased (~100 mm a^{-1}) but the results also revealed that it is highly relevant how the Cerrado vegetation is parameterised and which vegetation type is dominant (e.g. open grassland-shrublands or a more dense Cerrado sub-type). We discussed that a SWAT parameterisation applying the default forest parameters would end up likewise as other SWAT studies (e.g. Guzha *et al.,* 2013) in decreased ET rates after deforestation, thus causing higher water yields. Chapter 4 added detail to the discussion how land use change alter ET and consequently streamflow. We could demonstrate with the application of SWAT that land conversion from a complete cerrado to the current land cover confirm the trend of the decreased discharges (–10 %). However, there might also be other unknown factors responsible for the discharge observations.

To gain further insight how the catchment`s future water cycling climate change high emission scenarios (increased temperature, altered precipitation and elevated CO_2 of the RCP8.5 high emission scenario) were applied. For drier conditions, decreasing discharges over the entire year were observed to exhibit potentially critical dry seasonal water availability when baseflow is the main contributing source. The ET response (–7.5 % to –15 %) was mainly attributed to elevated CO_2 levels. Taking all high emission simulation scenarios into account, the key findings of a prolongation of the dry season (by about one month) and higher peak flows in the rainy season supports what we figured out in the review chapter (Chapter 2).

The combined effects of further land use intensification and climate change is uncertain, but both stressors imply higher peak flows in the rainy season. Consequently, potential threats for crop production at the beginning of the crop cycle with lower soil moisture (i.e. water stress) and increased erosion (Chapter 2 and 3) and sediment transport during the rainy season are likely which should be considered in climate change adaption plans. Chapter 4 showed that ecohydrological modelling contributes to improve our understanding of the water cycle, especially in regions which lack data. On the other hand it could be shown that the knowledge of a catchment and the implementation of primary field data have a positive effect on model performance. The results from SWAT model testing are promising that the model become a valuable instrument in watershed management and in making predictions (of water flux, water quality, biomass yield) for current and future land use and climate change by using scenario simulations in the Cerrado.

All three chapters (2, 3 and 4) addressed the impacts of rapid land use change in the Brazilian Cerrado. It turned out that land use change and climate change altered the ecohydrological functioning of the Brazilian Cerrado.

5.2 Limitations

Limited soil and water data for the entire Cerrado

The main limitation to draw a complete "picture" of the degradation processes and complex ecohydrological functioning of the Cerrado biome is related to the fact that data availability is restricted. The considered field studies to assess water and soil degradation (Chapter 2) are clustered in different regions of the Cerrado. For instance, many of the few studies that investigate stream biogeochemistry are conducted in the central Cerrado whereas all the eight pesticide contamination studies are located in Mato Grosso (Chapter 2). With evidence-based mechanistic reasoning the identified impacts such as very high pesticide concentrations are likely to occur in the entire Cerrado (increased pesticide consumption in the states with agricultural production etc.) but restricted data availability did not allow for a more robust regional assessment, a meta-analysis and a deeper discussion of regional differences across the biome. Additionally, due to the availability of exclusively low-order stream water quality studies, scale dependence effects of land use on water quality could not be analysed. Other through webportals (ANA-Hidroweb, ANA-SNIRH) and a desktop application (Hidro) available data could not be included in the review study because we identified that more than 95 % of the 893 registered water quality stations in the Cerrado have sampling frequencies less than three times a year, on average; the sparse data severely limit the temporal representativeness of the analytical results.

Additionally, data availability of water and soil properties for energy plantations is considered too sparse to give a clear picture of change for the investigated parameter range. One major problem identified in the review is the wide range of soil chemical analysis methods, e.g., Mehlich1, Mehlich3, and resin are used for P extraction. McGrath *et al.,* (2001) expressed the strong need to standardise nutrient extraction methods to enable more accurate comparisons across studies; however, progress has not been made. Similarly a direct quantitative comparison of the sampled Ks values was not possible due to different sampling techniques (Amoozemeter, Guelph permeameter, or the constant head method. And finally, Chapter 2 and 3 mainly focus on the dominating soil type Latosol. Due to low data availability, other agricultural used soil types (Neosols, Cambisols) were neglected. It is not necessarily similar to findings from Latosols and it remains open if the identified impacts (Chapter 5.1) are transferable to these often close to the stream lying sites.

Limitations of the water sampling field campaigns

Our soil samplings gave evidence of the current degraded status of the sampled fields (Chapter 3), whereas the snapshot sampling of the river system revealed noticeable limitations and provided only a preliminary insight into the biogeochemical behaviour of the catchment. Due to the limited number of water samples, the short sampling period and low sampling frequencies (Chapter 3.3.2), high uncertainty remains about the spatial and temporal pattern of water quality and the observed high PO_4^{3-} nutrient concentrations during the dry season. The lack of water quality data directly after fertilisation and during or after heavy rainfall events prevented the complete understanding of process linkages between overland and erosion processes from the modified agricultural fields and the nutrient transport fluxes in the stream network. In the study (Chapter 3.5) no spatial pattern of water biogeochemistry in relation to the dominating surrounding land use of each sampling location (in the buffer vegetation and in the sub-catchment) was evident. However, I still assume that even in the heavily modified meso-scale catchment water quality samplings of higher accuracy (see below) would display a land use related pattern. Such findings would help to quantify whether e.g. the percentage of agricultural land use in the sub-catchments and/or the riparian vegetation is more important for preventing streams from pollution.

However, to my knowledge for the Cerrado there is no study which even tries to link changes of soil properties to water quality. Due to tensions between farmers and environmental agencies it is not easy to get access to private property to conduct field work. It is rather unrealistic in short project time horizons with limited budgets to conduct further field campaigns. Even with small sample sizes, the results of the field study showed significant changes of soil properties after land use change and support the findings of the review study (Chapter 2).

Ecohydrological modelling with SWAT

Several uncertainties arise in the modelling study (Chapter 4). Measurement errors and uncertainties are contained in the model input data (e.g. field measurements of Chapter 3, precipitation data of Chapter 4) as well as in the calibration and validation discharge data. These errors are hard to quantify as the Brazilian water agencies do not give any information on that. However, the visual inspection of the discharge data suggests that the years 2004–2005 are not well recorded.

Although the scientific robustness of the modelling results require the consideration of uncertainties also in the scenario analysis (Schuol *et al.,* 2007), we used the "best parameter-set" concept from the calibrated parameter ranges for the scenario analysis. The land use and climate change scenarios we applied in Chapter 4 had rather the intention to examine whether the model is able to simulate the water balance of a typical Cerrado catchment than to develop complex scenarios as input. Therefore the model results have to be interpreted with respect to model performance and can only give an insight how the region´s water balance is likely to develop under land use and climate change. However, the model application provided important insights on the key drivers of SWAT and should be followed by a more in-depth analysis.

All in all, time consuming modelling in combination with extensive field campaigns is in general limited within the time period of a Phd-thesis. Long-term research is needed to overcome these limitations by a proper consideration of the uncertainties. Additionally, the model calibration with only one gauging station at the outlet could be improved for large watersheds. It is expected that multi-site calibration improve model performance and reduce the error of predictions (Li *et al.*, 2010). Large uncertainties remain as the model is calibrated with a current land cover which is then applied to simulate land use change scenarios (Blume 2007).

Daily streamflow simulations were not satisfactory with large uncertainties for the CN-model (Chapter 4). Especially the peak flow events were not simulated satisfactory and it has to be assumed that heavy rainfall events of the subtropics (daily sums > 70 mm) could not be represented. These events are crucial for the proper simulation of overland flow and erosion. It is likely that code adaptions for SWAT are necessary to allow the simulation of erosion and nutrient dynamics in the future (Bonumá *et al,.* 2012). Although the G+A model set-up resulted in the best performance to simulate streamflow; the model reproduced surface runoff, the estimation of ET and soil water storage incorrectly. It is likely that processes are represented incorrectly due to rainfall inputs which were provided on a daily and not on a sub-daily basis.

5.3 Recommendations and further research

The main findings of this thesis displayed that there are still many knowledge gaps for a proper understanding of the ecohydrological functioning of the Brazilian Cerrado. From that starting point recommendations for further research activity and directions are given.

There are a lot of pressing topics in the Cerrado which are associated with soil erosion, water deterioration, and the role of the riparian buffer strips according to the new Forest Code (Chapter 2).The setting up of environmental guidelines to ensure a sustainable riverscape management would be fundamental for the Cerrado. For this step, more information about the dynamics of hydrological processes and nutrient cycling in intensively agriculturally used catchments of the Cerrado would greatly improve the knowledge to understand these impacted systems.

Process studies and the need for more soil-hydrological field data

Since there is insufficient monitoring and management in the Cerrado, an environmental monitoring requires at a minimum continuous data on indicators of land water and soil degradation (e.g. physical and chemical properties, nutrients, and pesticides). There is a need for pesticide risk management in the Cerrado as the review study clearly showed that overutilization of these substances increased.

In my opinion, the set-up of a robust and universal water quality indicator system with the definition of nutrient concentration baselines is required to assess whether a catchment is already negatively impacted or not. The thesis has discussed that the background concentrations are often much lower than in the bordering Amazon (Chapter 3). From the EU perspective and also from findings of the Amazon there appears to be no or only very low impact on water quality. But with regard to our measurements and reference measurements from the Cerrado (e.g. Fonseca *et al.,* 2013, 2014) many-fold increases of nutrient concentrations are evident. Therefore, the establishment of biome-specific baselines are needed as long as there are undisturbed catchments. Monitorings in these systems with e.g. inter-catchment comparison approaches would greatly improve the capability to assess the degree of change, as well as the understanding of biogeochemical similarity as a function of the landscape settings (e.g. geology, soils, and land cover).

Due to the large daily variation of rainfall volumes in the sub-tropics, high resolution (minutes, hours) monitorings allow to overcome the missing of critical peak events that are known to have huge impact on the ecohydrological functioning. Hence, I suggest sampling strategies which capture these peak flow events to close the gap between soil modification and impacts on water quality. Continuous sampling effort from the beginning of the rainy season, with peak concentrations being expected when soils are bare and freshly fertilised (Neufeldt *et al.*, 1999). For this, automatic water samplers should be installed on platforms as the riverbed is often overflown in the rainy season. Further sampling effort should also focus on direct measurements of overland flow generation and related nutrient displacement on the agricultural fields and within the observed gully system, with its role in connecting the terrestrial and aquatic system requiring clarification in the Cerrado.

Figure 5-1: Erosion and gully formation are very recent phenomena in the agricultural Cerrado.

Even though gullies have started to seriously reduce suitable farmland, very little research has been conducted to soil erosion. The changes in soil parameters (e.g. decreased aggregate stability and reduced infiltration Chapter 2 and 3) show an urgent need for a systematic study to figure out the extent and hotspots of erosion and its adverse effects on land and water resources. Climate scenarios predict that heavy rainfall events (>10 mm) that are also associated with the formation of gullies are very likely to increase in the Cerrado (Marengo *et al.,* 2010). Therefore, I suggest a study that combines field campaigns (laser scanning, determination of erosion rates per season and land use type, sampling of suspended sediment in the gully network, interviews with locals) with remote sensing. Such an approach would help to understand the spatial and temporal evolution of gully systems and allow quantification and risk assessment of gully erosion susceptibility in e.g. GIS-based and modelling approaches. Consequently, gullies should be included into the SWAT model (Chapter 4) as they serve as a quick transfer route for contaminants, such as pesticides, from the adjacent agricultural fields into the river system.

More studies are needed to quantify the biochemical cycling of nutrients (especially P and N) in the Cerrado. Despite of the high fixation of P in the soil profile, it needs to be clarified at which concentrations available P exceeds and then potentially begins to leach and if P pollution of streams plays a role and which factors have to be considered to prevent pollution (Chapter 3, Chapter 5.1.1). To resolve this issue, the set-up of transects from the agriculturally used high plains to the streams with varying buffer strip widths could characterise stocks and fluxes of P and N and contribute to a better understanding of the filter capacity and decomposition processes within the vegetation buffer strips.

All suggested plot-scale monitorings should use nested sampling approaches and include different land uses (e.g. data sparse plantations) to address scaling effects and to allow the data usage in meso-scale ecohydrological models.

Integrated modelling framework

Beside of collecting field data an integrated modelling framework is needed to test hypothesis such as management practices (optimisation/adjustment of agrochemical schemes, adjustment cash crop vs. cover crops, crop rotations) to e.g. control surface runoff and avoid the loss of soil material.

In my opion the thesis showed that SWAT might be a useful tool. However, in order to identify weaknesses of the model and then adjust the model code, SWAT needs to be further tested under Brazilian conditions in the Cerrado. Promising findings of significantly improved model performance are published by Strauch *et al.,* (2013), who for instance adjusted and replaced the LAI function curve by means of a logistic decline to user-defined minimum LAI at the end of the growing season. The results of the SWAT modelling (Chapter 4) showed that the establishment of a plant parameter database (for sub-formations of vegetation) would be an important step forward to use SWAT in the Cerrado. However, the implementation of gullies (Chapter 3.4.3) on the HRU level would be a challenge in accounting for erosion processes and sediment transport in the stream network, which also remains an unsolved problem on the field scale in the Cerrado and other tropical regions (Labriére *et al.,* 2015).

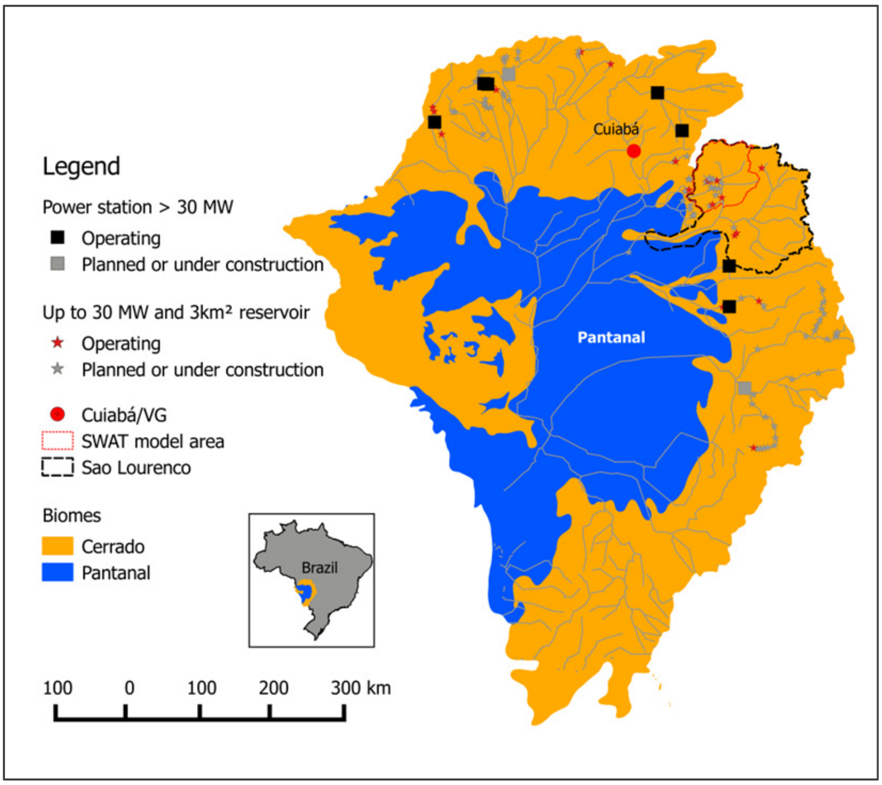


Figure 5-2: Planned and operating power stations in the upstream catchments of the Pantanal wetlands locating the São Lourenço catchment and the SWAT study area.

Another important process in the upper Pantanal region and also in the modelling area of the São Lourenço catchment is that a large number of reservoirs and hydro-power stations are planned (Figure 5-2) or already constructed (after the modelling period) for energy and irrigation purposes (three > 30 MW; 80 with up to 30 MW and four < 3MW). Their construction will have significant effects on the water and sediment fluxes in the Pantanal watershed. Process modelling with SWAT (which is able to implement reservoirs easily) can help to quantify these disturbances.

Still more modelling studies are needed on larger scales, to test hypothesis in riverscape management. Topics are water quality modelling, the role of the riparian buffer in regard to the Brazilian new Forest Code, land use change and climate change scenario analysis, and the production of bioenergy crops (see Bressiani *et al.,* 2015 for a review).

The impacts of agriculture on aquatic systems, i.e., pollution from nutrients and pesticides, their in-stream processes, and their effects on aquatic habitats, and on drinking water quality for human consumption are not well understood. In particular, the fate of pesticides in water, soil and air (see 5.1) requires more research because there seems to be only limited awareness of pesticides' adverse impacts on human health among local farmers and landowners (personal observations).

5.4 Final remarks

The aim of this thesis was to evaluate the impacts of land conversion for agricultural fields and partly climate change on the ecohydrological functioning and interactions causing water and soil degradation within meso-scale catchments in the Brazilian Cerrado.

The thesis showed that a multi-method approach is needed to monitor, analyse and model data scarce areas like the Brazilian Cerrado. Primary field data are required to understand those systems and to parameterise ecohydrological models for hypothesis testing. The approach of compiling a database from the literature and collecting field data on soil and water properties in combination with modelling delivered important and novel insights into the ecohydrological functioning of soil and water degradation of the Cerrado biome. With a critical discussion of the limitations, this thesis serves as a valuable starting point for further research activities and contributes to the challenges to set up an integrated sustainable land/riverscape management framework to stabilize the Cerrado.

List of Figures

List of Tables

Bibliography

Abbaspour KC, Yang J, Maximov I, Siber R, Bogner K, Mieleitner J, Zobrist J, Srinivasan R. 2007 Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT, Journal of Hydrology, 333, 413–430.

Agência Nacional de Águas–ANA (Brasil). Hidroweb. Sistema de informações Hidrólogicos. hidroweb.ana.gov.br (Accessed October 26, 2014)

Agência Nacional de Águas–ANA (Brasil). Sistema Nacional de Informações sobre Recursos Hidricos. www2.snirh.gov.br (Accessed October 26, 2014).

Agência Nacional de Águas (Brasil). 2012. Conjuntura dos recursos hídricos no Brasil: informe 2012. Ed. Especial. -- Brasília: ANA,2012.215 p. : Il. ISBN 978-85-89629-89-8

Agência Nacional de Águas (ANA), 2009. Implementação do enquadramento em bacias hidrográficas no Brasil. Sistema nacional de informações sobre recursos hídricos —SNIRH no Brasil: arquitetura computacional e sistêmica (Brasília: 145 pp.).

Agência Nacional de Vigilância Sanitária–ANVISA (Brasil). Seminário volta a discutir mercado de agrotóxicos em 2012. Brasília, DF, 2012.Disponível em: http://portal.anvisa.gov.br/wps/content/anvisa+portal/anvisa/sala+de+imprensa/menu++noticias+anos/2012+noticias/seminario+volta+a+discutir+mercado+de+agrotoxicos+em+2012.(Accessed December 12, 2013).

Ajayi AE, Dias Junior MS, Curi N, Okunola A, Souza TTT, Pires BS.2010. Assessment of vulnerability of oxisols to compaction in the Cerrado Region of Brazil. Pedosphere 20: 252–260.

Allan JD. 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. Annual Review of Ecology, Evolution, and Systematics 35: 257–284.

Amoozegar A. 1989. A compact constant-head permeameter for measuring saturated hydraulic conductivity of the vadose zone. Soil Science Society of America Journal. 53 (5), 1356–1361.

Amoozegar A. 1992. Compact constant head permeameter: a convenient device for measuring hydraulic conductivity. Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice, pp. 31–42.

Amorim PK, Batalha MA. 2008. Soil chemical factors and grasslandspecies density in Emas National Park (central Brazil). Revista Brasleira de Biologia 68: 279–85.

Arnold JG, Moriasi DN, Gassman PW, Abbaspour KC, White M J, Srinivasan R, Santhi C, Harmel RD, van Griensven A,Van Liew MW, Kannan N, Jha MK. 2012. SWAT: Model use, calibration, and validation. Transactions of the ASABE, 55(4), 1491–1508.

Arnold JG, Srinivasan R, Muttiah RS, Williams JR. 1998. Large-area hydrologic modeling and assessment. I: Model development. Journal of the American Water Resources Association, 34(1): 73–89.

Assad ED, Martins SC, Beltrão NEDM, Pinto HS. 2013. Impacts of climate change on the agricultural zoning of climate risk for cotton cultivation in Brazil. Pesquisa Agropecuária Brasileira 48(1): 1–8.

Assad ED, Sano EE, Masutomo R, de Castro LHR, da Silva FAM. 1993.Veranicos na região dos Cerrados brasileiros frequência e probabilidadede ocorrência. Pesquisa Agropecuária Brasileira 28(9): 993–1003.

Atangana A, Khasa D, Chang S, Degrande A., 2014. Agroforestry for soil conservation. Tropical Agroforestry. Springer, Netherlands, pp. 203–216.

Augustin CHRR, Aranha PRA. 2006. Piping em área de voçorocamento, noroeste de Minas Gerais. Revista Brasileira de Geomorfologia 7(1):9–18.

Ayarza M, Amézquita E, Rao I, Barrios E, Rondón M, Rubiano Y,Quintero M. 2007. Advances in improving agricultural profitability and overcoming land degradation in savanna and hillside agro ecosystems of tropical America. In Advances in Integrated Soil Fertility Management in sub-Saharan Africa: Challenges and Opportunities, Bationo A,Waswa B, Kihara J, Kimetu J (eds). Springer: Netherlands; 209–229.

Balbino L, Bruand A, Cousin I, Brossard M, Quétin P, Grimaldi M. 2004.Change in the hydraulic properties of a Brazilian clay Ferralsol on clearing for pasture. Geoderma 120: 297–307.

Balbino L, Bruand A, Brossard M, Grimaldi M, Hajnos M, Guimarães MF. 2002. Changes in porosity and microaggregation in clayey Ferralsols of the Brazilian Cerrado on clearing for pasture. European Journal of Soil Science 53: 219–230.

Barreto L, Schoorl JM, Kok K, Veldkamp T, Hass A. 2013. Modelling potential landscape sediment delivery due to projected soybean expansion: a scenario study of the Balsas sub-basin, Cerrado, Maranhão state, Brazil. Journal of Environmental Management 115: 270–7.

Batlle-Bayer L, Batjes NH, Bindraban PS. 2010. Changes in organic carbon stocks upon land use conversion in the Brazilian Cerrado: A review. Agriculture, Ecosystems & Environment 137: 47–58.

Bayer C, Martin-Neto L, Mielniczuk J, Pavinato A, Dieckow J. 2006.Carbon sequestration in two Brazilian Cerrado soils under no-till. Soiland Tillage Research 86: 237–245.

Berengena J, Gavilán P. 2005. Reference evapotranspiration estimation in a highly advective semiarid environment. Journal of irrigation and drainage Engineering, 131(2), 147–163.

Bernoux M, Cerri CC, Cerri CEP, Neto MS, Metay A, Perrin A-S, ScopelE, Raza fi mbelo T, Blavet D, Piccolo MdeC, Pavei M, Milne E. 2006.Cropping systems, carbon sequestration and erosion in Brazil, a review. Agronomy for Sustainable Development 26: 1–8.

Biggs TW, Dunne T, Martinelli LA. 2004. Natural controls and human impacts on stream nutrient concentrations in a deforested region of the Brazilian Amazon basin. Biogeochemistry 68 (2), 227–257.

Biggs TW, Dunne T, Muraoka T. 2006. Transport of water, solutes and nutrients from a pasture hillslope, southwestern Brazilian Amazon. Hydrological Processes 20 (12), 2527–2547.

Biudes MS, Machado NG, Danelichen VH, Souza MC, Vourlitis GL, Nogueira JdeS. 2014. Ground and remote sensing-based measurements of leaf area index in a transitional forest and seasonal flooded forest in Brazil. International Journal of Biometeorology; 58(6):1181–93.

Blume T. 2007. Hydrological processes in volcanic ash soils: measuring, modelling and understanding runoff generation in an undisturbed catchment. Doctoral dissertation, University of Potsdam.

Boddey RM, Urquiaga S, Alves BJ, Reis V. 2003. Endophytic nitrogen fixation in sugarcane: present knowledge and future applications. Plant Soil 252 (1), 139–149.

Bonumá NB, Rossi CG, Arnold JG, Reichert JM, Minella JP, Allen PM, Volk M. 2012. Simulating landscape sediment transport capacity by using a modified SWAT model. Journal of Environmental Quality,43(1), 55–66.

Bortolotto RP, Bruno IP, Dourado-Neto D, Timm LC, Silva AND, Reichardt K. 2013. Nitrate leaching through climatologic water balance in a fertigated coffee plantation. Revista Ceres 60(6): 785–792.

Bortolotto RP, Bruno IP, Reichardt K, Timm LC, Amado TJC, FerreiraADO. 2012. Nitrogen fertilizer (15 N) leaching in a central pivotfertigated coffee crop. Revista Ceres 59(4): 466–475.

Boëchat IG, Paiva ABDMD, Hille S, Gücker B. 2013. Land-use effects on river habitat quality and sediment granulometry along a 4th-order tropical river. Revista Ambiente & Água 8(3): 54–64.

Boëchat IG, Krüger A, Giani A, Figueredo CC, Gücker B. 2011.Agricultural land use affects the nutritional quality of stream microbial communities. FEMS Microbiology Ecology 77: 568–76.

Bonini CDSB, Alvez MC. 2011a. Aggregate stability of a degraded oxisol in recovery with green manure, lime and gypsum. Revista Brasileira de Ciência do Solo 35(4): 1263–1270.

Bonini CDSB, Alvez MC. 2011b. Recovery of soil physical properties by green manure, liming, gypsum and pasture and spontaneous native species. Revista Brasileira de Ciência do Solo 35(4): 1397–1406.

Bono JAM, Macedo MCM, Tormena CA, Nanni MR, Gomes EP, Müller MML. 2012. Water infiltration into an oxisol in the south-west Cerrado region under different use and management systems. Revista Brasileirade Ciência do Solo 36(6): 1845–1853.

Borges TA, Oliveira FA, Silva ED, Goedert WJ. 2009. Avaliação deparâmetros fi sico-hídricos de Latossolo Vermelho sob pastejo e sob Cerrado.Revista Brasileira de Engenharia Agrícola e Ambiental 13(1):18–25.

Bouyoucos GJ. 1962. Hydrometer method improved for making particle size analyses of soils. Agron. J. 54 (5), 464–465.

Bustamante M, Nardoto G, Pinto A, Resende JCF, Takahashi FSC, Viera L.2012. Potential impacts of climate change on biogeochemical functioning of Cerrado ecosystems. Brazilian Journal of Biology 72: 655–671.

Bustamante MMC, Medina E, Asner GP, Nardoto GB, Garcia-Montiel DC. 2006. Nitrogen cycling in tropical and temperate savannas. In Nitrogen Cycling in the Americas: Natural and Anthropogenic Influences and Controls. Springer: Netherlands; 209–237.

Brando PM, Coe MT, DeFries R, Azevedo AA. 2013. Ecology, economy and management of an agroindustrial frontier landscape in the southeast Amazon. Philosophical Transactions of the Royal Society, B: Biological Sciences 368:20120152.

Bressiani DDA, Gassman PW, Fernandes JG, Garbossa LHP, Srinivasan R, Bonumá NB, Mendiondo EM. 2015. Review of Soil and Water Assessment Tool (SWAT) applications in Brazil: Challenges and prospects. International Journal of Agricultural and Biological Engineering, 8(3), 9–35.

Bressiani D, Srinivasan R, Jones CA, Mendiondo EM. 2015a. Effects of different spatial and temporal weather data resolutions on the streamflow modeling of a semi-arid basin, Northeast Brazil. International Journal of Agricultural and Biological Engineering, 8(3).

Briedis C, Sá JCdeM, Caires EF, Navarro JdeF, Inagaki TM, Boer A, Neto CQ, Ferreira AdeO, Canalli LB, Santos JBdos. 2012. Soil organicmatter pools and carbon-protection mechanisms in aggregate classes influenced by surface liming in a no-till system. Geoderma 170: 80–88.

Broch DL, Pavinato PS, Possentti JC, Martin TN, Del Quiqui EM. 2011.Produtividade da soja no Cerrado influenciada pelas fontes de enxofre.Revista Ciência Agronômica 42: 791–796.

Bronstert A. 2004. Rainfall-runoff modelling for assessing impacts of climate and land-use change, Hydrological Processes, 18 (3): 567–570.

Bronstert A, Niehoff D, Bürger G. 2002. Effects of climate and land-use change on storm runoff generation: present knowledge and modelling capabilities. Hydrological Processes, 16(2), 509–529.

Bruno RD. 2009. Balanço de água em microbacias de cerrado restrito eucalipto: um estudo de caso com medidas observacionais, Ph.D. thesis, University of São Paulo, São Paulo, Brazil. (90pp.) http://livros01.livrosgratis.com.br/cp124363.pdf. Accessed 15th July 2015

Bucci SJ, Scholz FG, Goldstein G, Hoffmann WA, Meinzer WC, Franco AC, Giambelluca T, Miralles-Wilhelm F. 2008. Controls on stand transpiration and soil water utilization along a tree density gradient in a neotropical savanna. Agriculture Forest Meteorology, 148(6–7), 839–849, doi:10.1016/j.agrformet.2007.11.013.

Cabral OM, da Rocha HR, Gash JH, Freitas HC, Ligo MA. 2015. Water and energy fluxes from a woodland savanna (cerrado) in southeast Brazil. Journal of Hydrology: Regional Studies, 4, 22–40.

Campos Fde, Alvez M, Souza ZM De, Pereira G. 2011. Atributos físico-hídricos de um Latossolo após a aplicação de lodo de esgoto em área degradada do Cerrado. Ciência Rural 41(5): 796–803.

Cao W, Bowden WB, Davie T, Fenemor A. 2006. Multi-variable and multi-site calibration and validation of SWAT in a large mountainous catchment with high spatial variability. Hydrological Processes, 20(5), 1057–1073.

Carbo L, Souza V, Dores EFGC, Ribeiro ML. 2008. Determination of pesticides multiresidues in shallow groundwater in a cotton-growing region of Mato Grosso, Brazil. Journal of the Brazilian Chemical Society 19(6): 1111–1117.

Carmignotto AP, Bezerra AM, Rodrigues FH. 2014. Nonvolant small mammals from a southwestern area of Brazilian Cerrado: diversity, habitat use, seasonality, and biogeography. THERYA 5(2): 535–558.

Carneiro MAC, Souza ED, Reis ED, Pereira HS, Azevedo WD. 2009.Atributos físicos, químicos e biológicos de solo de Cerrado sobdiferentes sistemas de uso e manejo. Revista Brasileira de Ciência do Solo 33(1): 147–157.

Carvalho JR, Assad ED, Evangelista SRD, Pinto HS. 2013. Estimation of dry spells in three Brazilian regions — Analysis of extremes. Atmospheric Research 132: 12–21.

Carvalho J, Cerri CEP, Feigl BJ, Piccolo MDC, Herpin U, Cerri CC. 2009.Conversion of Cerrado into agricultural land in the south-western Amazon:carbon stocks and soil fertility. Scientia Agricola 66(2): 233–241.

Carvalho JLN, Cerri CEP, Cerri CC, Feigl BJ, Píccolo MC, Godinho VP,Herpin U. 2007. Changes of chemical properties in an oxisol after clearing of native Cerrado vegetation for agricultural use in Vilhena, Rondonia State, Brazil. Soil and Tillage Research 96: 95–102.

Casara KP, Vecchiato AB, Lourencetti C, Pinto AA, Dores EF. 2012. Environmental dynamics of pesticides in the drainage area of the São Lourenço River headwaters, Mato Grosso State, Brazil. Journal of the Brazilian Chemical Society 23(9): 1719–1731.

Castro SD. 2005. Erosão hídrica na Alta Bacia do Rio Araguaia:distribuição, condicionantes, origem e dinâmica atual. Revista do Departamento de Geografia 17: 38–60.

Chapuis Lardy L, Brossard M, Lopes Assad ML, Laurent JY. 2002. Carbon and phosphorus stocks of clayey Ferralsols in Cerrado nativeand agroecosystems, Brazil. Agriculture, Ecosystems & Environment 92(2): 147–158.

Christoffersen BO, Restrepo-Coupe N, Arain MA, Baker IT, Cestaro BP, Ciais P, Fisher JB, Galbraith D, Guan X, Gulden L, van den Hurk B, Ichii K, Imbuzeiro H, Jain A, Levine N, Miguez-Macho G, Poulter B, Roberti DR, Sakaguchi K, Sahoo A, Schaefer K, Shi M, Verbeeck H, Yang Z-L, Araújo AC, Kruijt B, Manzi AO,. da Rocha HR, von Randow C, Muza MN, Borak J, Costa MH, de Gonçalves LGG, Zeng X, Saleska SR. 2014. Mechanisms of water supply and vegetation demand govern the seasonality and magnitude of evapotranspiration in Amazonia and Cerrado. Agriculture Forest Meteorology, 191, pp. 33–50

Clark DB, Clark DA, Oberbauer SF. 2010. Annual wood production in a tropical rain forest in NE Costa Rica linked to climatic variation but not to increasing CO_2. Global Change Biology, 16(2), 747–759.

Cochrane TT, Jones PG. 1981. Savannas, forests and wet season potential evapotranspiration in tropical South America. Tropical Agriculture 58:185–190.

Coe MT, Latrubesse EM, Ferreira ME, Amsler ML. 2011. The effects of deforestation and climate variability on the streamflow of the Araguaia River, Brazil. Biogeochemistry, 105(1–3), 119–131.

Coe MT, Costa MH, Soares-Filho BS. 2009. The influence of historical and potential future deforestation on the stream flow of the Amazon River–Land surface processes and atmospheric feedbacks. Journal of Hydrology 369: 165–174.

Conab (Companhia Nacional de Abastecimento). 2015. Séries Históricas de Área Plantada, Produtividade e Produção, Relativas às Safras 1976/77 a 2014/15. http://www.conab.gov.br/conteudos.php?a=1252&t= (accesses August 3th, 2015)

Corbeels M, Scopel E, Cardoso A, Bernoux M, Douzet J-M, Neto MS.2006. Soil carbon storage potential of direct seeding mulch-based cropping systems in the Cerrados of Brazil. Global Change Biology 12:1773–1787.

Costa MH, Pires GF. 2010. Effects of Amazon and Central Brazil deforestation scenarios on the duration of the dry season in the arc ofdeforestation. International Journal of Climatology 30: 1970–1979.

Costa MH, Botta A, Cardille JA. 2003. Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. Journal of Hydrology, 283(1), 206–217.

Council Directive 98/83/EC of 3 November 1998 on the quality of water intended for human consumption 3. November 1998. Official Journal of the European Communities, L330, 32–54, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:1998:330:0032:0054:EN:PDF (accessed August 27, 2013)

Council Directive 91/414/EEC of 15 July 1991 concerning the placing ofplant protection products on the market, Annex I of 13 June 2007concerning the non-inclusion of carbofuran to Directive 91/414/EEC.Of fi cial Journal of the European Union. L156, 30–32. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:156:0030:0031:EN:PDF (accessed August 28, 2013)

Coutinho LM. 1990. Fire in the ecology of the Brazilian Cerrado. In fire in the tropical biota — ecosystem processes and global challenges. Ecological Studies 8: 82–105.

D'Almeida C, Vörösmarty CJ, Hurtt GC, Marengo JA, Dingman SL, Keim BD. 2007. The effects of deforestation on the hydrological cycle in Amazonia: a review on scale and resolution. International Journal of Climatology. 27 (5), 633–647.

da Rocha HR, Manzi AO, Cabral OM, Miller SD, Goulden ML, Saleska SR, Coupe NR, Wofsy SC, Borma LS, Artaxo P, Vourlitis G, Nogueira JS, Cardoso FL, Nobre AD, Kruijt B, Freitas HC, von Randow C, Aguiar RG, Maia JF. 2009. Patterns of water and heat flux across a biome gradient from tropical forest to savanna in Brazil. Journal of Geophysical Research. 114 (G00B12), 1–8.

da Silva MM, Alves MC, de Pádua Sousa A, Fernandes FCS. 2006.Impacto do manejo nos atributos físicohídricos de um LatossoloVermelho sob Cerrado, no município de Selvíria, Estado do MatoGrosso do Sul = The impact of management on the physical and hydrological attributes of a darkred latosol under Cerrado inSelviria, State of Mato Grosso do Sul. Acta Scientiarum: Agronomy 28 (1): 13–22.

Davidson EA, Araújo ACde, Artaxo P, Balch JK, Brown IF, Bustamante MM, Coe MT, DeFries RS, Keller M, Longo M, Munger JW, Schroeder W, Soares-Filho BS, Souza CM, Wofsy SC. 2012. The Amazon basin in transition. Nature, 481, 321–328

Davidson EA, Neill C, Krusche AV, Ballester VV, Markewitz D,Figueiredo R. 2004. Loss of nutrients from terrestrial ecosystems to streams and the atmosphere following land use change in Amazonia. Geophysical Monograph Series 153: 147–158.

De Alcântara FA, Buurman P, Furtini Neto AE, Curi N, Roscoe R. 2004.Conversion of grassy Cerrado into riparian forest and its impact on soilorganic matter dynamics in an Oxisol from southeast Brazil. Geoderma123: 305–317.

De Castro EA, Kauffman JB. 1998. Ecosystem structure in the BrazilianCerrado: a vegetation gradient of aboveground biomass, root mass and consumption by fire. Journal of Tropical Ecology 14: 263–283.

DeFries R, Eshleman KN. 2004. Land-use change and hydrologic processes: a major focus for the future. Hydrological processes, 18(11), 2183–2186.

de Jesuz CR, Ito JBB, Zeilhofer P. 2013. Erosões mecânicas da sub-bacia hidrográfica do rio Tenente Amaral, Jaciara–M, e suas determinantes socioambientais. Revista Mato-Grossense de Geografia. 16, 89–105.

De Moraes JM, Schuler AE, Dunne T, Figueiredo RDO, Victoria RL.2006. Water storage and runoff processes in plinthic soils under forestand pasture in Eastern Amazonia. Hydrological Processes 20(12):2509–2526.

De Moraes Sá JC, Cerri CC, Lal R, Dick WA, de Cassia Piccolo M, Feigl BE. 2009. Soil organic carbon and fertility interactions affected by atillage chronosequence in a Brazilian Oxisol. Soil and Tillage Research104: 56–64.

de Morais, N.R., Correchel, V., Leandro, W.M., Fernandes, E.P., de Godoy, S.G., 2009. Criteria of interpretation of soil quality of the cotton plant in Cerrado of the Goiás, Brazil. Bioscience Journal 25 (3), 129–140.

de Sousa DMG, Rein TA. 2011. Soil fertility evaluation and control for annual crops in the Cerrado. Better Crops 95 (3), 12–15.

Delgado A, Scalenghe R. 2008. Aspects of phosphorus transfer from soils in Europe. Journal of Plant Nutrition and Soil Science. 171 (4), 552–575.

Dias LCP, Macedo MN, Costa MH, Coe MT, Neill C. 2015. Effects of land cover change on evapotranspiration and streamflow of small catchments in the Upper Xingu River Basin, Central Brazil. Journal of Hydrology: Regional Studies, 4, 108–122.

Didoné EJ, Minella JPG, Reichert JM, Merten GH, Dalbianco L, de Barrros CAP, Ramon R. 2014. Impact of no-tillage agricultural systemson sediment yield in two large catchments in Southern Brazil. Journalof Soils and Sediments 14: 1287–1297.

Dores EF, De Souza L, Villa RD, Pinto AA. 2013. Assessment of metolachlor and diuron leaching in a tropical soil using undisturbed soil columns under laboratory conditions. Journal of Environmental Science and Health. Part. B 48(2): 114–121.

Dores EFGC, Spadotto CA, Weber OLS, Carbo L, Vecchiato AB, Pinto AA. 2009. Environmental behaviour of Metolachlor and Diuron in atropical soil in the central region of Brazil. Water, Air, and Soil Pollution 197: 175–183.

Dores EFGC, Carbo L, Ribeiro ML, De-Lamonica-Freire EM. 2008. Pesticide levels in ground and surface waters of Primavera do LesteRegion, Mato Grosso, Brazil. Journal of Chromatographic Science 46:585–90.

Douglas-Mankin KR, Srinivasan R, Arnold JG. 2010. Soil and Water Assessment Tool (SWAT) model: Current developments and applications. Transactions of the ASABE, 53(5), 1423–1431.

Drake BG, Gonzàlez-Meler MA, Long SP. 1997. More efficient plants: a consequence of rising atmospheric CO_2? Annual Review of Plant Biology, 48(1), 609–639.

Empresa Brasileira de Pesquisa Agropecária (EMBRAPA), 2006. Centro Nacional de Pesquisa de Solos. Sistema brasileiro de classificação de solos. 2 ed. (Rio de Janeiro).

Empresa Brasileira de Pesquisa Agropecária (EMBRAPA), de Oliviera RP, de dos Santos HG, Madari BE. 2003. Correção do solo e adubaçãono sistema de plantio direto nos Cerrados. Embrapa Solos.Documentos, 46. http://ainfo.cnptia.embrapa.br/digital/bitstream/CNPS/11219/1/doc_46_2003.pdf (accessed April 10, 2014)

Empresa Brasileira de Pesquisa Agropecária (EMBRAPA), 1997. Centro Nacional de Pesquisa de Solos. Manual de métodos de análise de solos 2 ed. (Rio de Janeiro. 212 pp.).

Eiten G. 1972. The Cerrado Vegetation of Brazil. Botanical Review 38:201–341.

FAO. 2009. Global forest resources assessment 2010. Brazil country report. United Nations, Food and Agriculture Organization (FAO),Rome, pp. 111

FAO. 2004. Fertilzer use by crop. Land and Plant Nutrition Management Service. Land and Water Development Decision. http://www.fao.org/docrep/007/y5376e/y5376e00.HTM (accessed September 20, 2014)

FAO. 2001. Zero tillage development in tropical Brazil. Agricultural Service Bulletin 147 http://www.fao.org/docrep/004/Y2638E/y2638e00.htm (accessed September 22, 2014)

FAS-USDA. 2003. Brazil: future agricultural expansion potential underrated http://www.fas.usda.gov/pecad2/highlights/2003/01/Ag_expansion/ (accessed July 15, 2013)

Favis-Mortlock D, Guerra A. 1999. The implications of general circulation model estimates of rainfall for future erosion: a case study from Brazil. Catena 37: 329–354.

Fearnside PM. 2007. Brazil's Cuiabá-Santarém (BR-163) Highway: the environmental cost of paving a soybean corridor through the Amazon. Environmental Management, 39(5), 601-614.

Ferreira ME, Ferreira Jr LG, Miziara F, Soares-Filho BS. 2013. Modeling landscape dynamics in the central Brazilian savanna biome: future scenarios and perspectives for conservation. Journal of Land Use Science 8(4): 403–421.

Ferreira J, Pardini R, Metzger JP, Fonseca CR, Pompeu PS, Sparovek G, Louzada J. 2012. Towards environmentally sustainable agriculture in Brazil: challenges and opportunities for applied ecological research. Journal of Applied Ecology 49(3): 535–541.

Ferreira LCG, de Deus JB. 2011. Características da produção sucro alcooleira na microrregião ceres–GO: uma abordagem sobre as políticas, a safra e obtenção de terras. Ateliê Geográfico 5(1): 196–218.

Ferreira LG, Huete AR. 2004. Assessing the seasonal dynamics of the Brazilian Cerrado vegetation through the use of spectral vegetation indices. International Journal of Remote Sensing 25(10): 1837–1860.

Ficklin DL, Luo Y, Luedeling E, Zhang M. 2009. Climate change sensitivity assessment of a highly agricultural watershed using SWAT. Journal of Hydrology, 374(1), 16–29.

Field CB, Jackson RB, Mooney HA. 1995. Stomatal responses to increased CO_2: implications from the plant to the global scale. Plant, Cell & Environment, 18(10), 1214–1225.

Foley JA, Botta A, Coe MT, Costa MH. 2002. El Nino–Southern oscillation and the climate, ecosystems and rivers of Amazonia. Global Biogeochemical Cycles, 16(4), 79–1.

Fonseca BM, de Mendonça-Galvão L. 2014. Pristine aquatic systems in a long term ecological research (LTER) site of the Brazilian Cerrado. Environmental Monitoring and Assessment 186(12): 8683–8695.

Fonseca BM, de Mendonça-Galvão L, Padovesi-Fonseca C, de Abreu LM,Fernandes ACM. 2013. Nutrient baselines of Cerrado low-order streams: comparing natural and impacted sites in Central Brazil. Environmental Monitoring and Assessment 186(1): 19–33.

Fontenele W, Salviano AAC, Mousinho FEP. 2009. Atributos físicos deum Latossolo Amarelo sob sistemas de manejo no Cerrado piauiense.Revista Ciência Agronômica 40(2): 194–202.

Fuka DR, Walter MT, MacAlister C, Degaetano AT, Steenhuis TS, Easton ZM. 2014. Using the Climate Forecast System Reanalysis as weather input data for watershed models. Hydrological Processes, 28(22), 5613–5623.

Furley P. 1999. The nature and diversity of neotropical savanna vegetation with particular reference to the Brazilian Cerrados. Global Ecology and Biogeography 8: 223–241.

Fageria NK, Moreira A, Moraes LAC, Moraes MF. 2014. Influence of lime and gypsum on yield and yield components of soybean and changes in soil chemical properties. Communications in Soil Science and Plant Analysis45 (3).

Fageria NK, Barbosa Filho MP. 2008. Influence of pH on productivity, nutrient use efficiency by dry bean, and soil phosphorus availability in ano tillage system. Communications in Soil Science and Plant Analysis 39: 1016–1025.

Faria A, Santos A, Filho FB. 2010. Influência do manejo do solo naspropriedades químicas e físicas em topossequência na bacia do rioAraguaia, Estado do Tocantins. Revista Brasileira de Ciência do Solo34(2): 517–524.

Fernandes JDF, de Souza AL, Tanaka MO. 2014. Can the structure of a riparian forest remnant influence stream water quality? A tropical case study. Hydrobiologia 724 (1), 175–185.

Figueiredo RO, Markewitz D, Davidson EA, Schuler AE, dos S Watrin O, de Souza Silva P. 2010. Land-use effects on the chemical attributes of low-order streams in the eastern Amazon. Journal of Geophysical Research: Biogeosciences. 115 (G4) (2005–2012).

Garbossa LHP, Vasconcelos LRC, Lapa KR, Blainski E, Pinheiro A. 2011. The use and results of the Soil and Water Assessment Tool in Brazil: A review from 1999 until 2010. In Proceedings of the 2011 International SWAT Conference & Workshops. Toledo, Spain.

Gassman PW, Reyes MR, Green CH, Arnold JG. 2007. The Soil and Water Assessment Tool: Historical Development, Applications, and Future Research Directions. American Society of Agricultural and Biological Engineers. 50(4): 1211–1250.

Gelbrecht J, Lengsfeld H, Pöthig R, Opitz D. 2005. Temporal and spatial variation of phosphorus input, retention and loss in a small catchment of NE Germany Journal of Hydrology 304 (1), 151–165.

Germer S, Neill C, Krusche AV, Elsenbeer H. 2010. Influence of land-use change on near-surface hydrological processes: undisturbed forest to pasture. Journal of Hydrology 380 (3), 473–480.

Giambelluca TW, Scholz FG, Bucci SJ, Meinzer FC, Goldstein G, Hoffmann WA, Franco AC, Buchert MP. 2009. Evapotranspiration and energy balance of Brazilian savannas with contrasting tree density. Agriculture Forest Meteorology. 149, 1365–1376.

Goedert WJ. 1983. Management of the Cerrado soils of Brazil: a review. Journal of Soil Science 34: 405–428.

Government of Brazil. 2012. Código Florestal, Federal Law N° 12.727 from the17th of October 2012. Brasilía, DF. http://www.planalto.gov.br/ccivil_03/_Ato2011-2014/2012/Lei/L12727.htm (accessed August 28, 2013)

Gonçalves JF, Graça MAS, Callisto M. 2007. Litter decomposition in a Cerrado savannah stream is retarded by leaf toughness, low dissolved nutrients and a low density of shredders. Freshwater Biology 52(8):1440–1451.

Grayson RB, Gippel CJ, Finlayson BL, Hart BT.1997. Catchment-wide impacts on water quality: the use of 'snapshot' sampling during stable flow. Journal of Hydrology 199 (1), 121–134.

Grecchi RC, Gwyn QHJ, Bénié GB, Formaggio AR. 2013. Assessing the spatio-temporal rates and patterns of land-use and land-cover changes in the Cerrados of southeastern Mato Grosso, Brazil. International Journal of Remote Sensing 34(15): 5369–5392.

Green CH, Van Griensven A. 2008. Autocalibration in hydrologic modeling: Using SWAT2005 in small-scale watersheds. Environmental Modelling & Software, 23(4), 422–434.

Green VS, Stott DE, Cruz JC, Curi N. 2007. Tillage impacts on soil biological activity and aggregation in a Brazilian Cerrado Oxisol. Soiland Tillage Research 92(1): 114–121.

Grimm AM, Barros VR, Doyle ME. 2000. Climate variability in southern South America associated with El Niño and La Niña events. Journal of Climate, 13(1), 35-58.

Gücker B, Boëchat IG. 2004. Stream morphology controls ammonium retention in tropical headwaters. Ecology 85(10): 2818–2827.

Gücker B, Boëchat IG, Giani A. 2009. Impacts of agricultural land use on ecosystem structure and whole-stream metabolism of tropical Cerrado streams. Freshwater Biology 54: 2069–2085.

Guzha AC, Nobrega R, Santos CA, Gerold G. 2013. Investigating discharge and rainfall variability in an Amazonian watershed: Do any trends exist?. IAHS-AISH publication, 346–351.

Guzha AC, Amorim RS, Nóbrega R, Lamparter G, Kovacs K, Bertão N, Gerold G. 2014. Impacts of Land Cover and Climate Change on Hydrology and Hydrochemistry in Selected Catchments in Southern Amazonia: Preliminary Analysis and Results. In: Hohnwald S, Gerold G. (Eds.), Carbon-Optimized Land Management Research for the Southern Amazon—Geographical and Organizational Settings of the Carbiocial-Carbioma Project Consortium. Interdisciplinary Analysis and Modeling of Carbon-Optimized Land Management Strategies for Southern Amazonia. pp 71–84.

Haridasan M. 2001. Nutrient cycling as a function of landscape and biotic characteristics in the Cerrado of central Brazil. In Biogeochemistry of the Amazon Basin and its Role in a Changing World. Oxford University Press: New York; 68–83.

Hassler SK, Zimmermann B, van Breugel M, Hall JS, Elsenbeer H. 2011. Recovery of saturated hydraulic conductivity under secondary succession on former pasture in the humid tropics. Forest Ecology and Management 261 (10), 1634–1642.

Haynes RJ, Naidu R. 1998. Influence of lime, fertilizer and manureapplications on soil organic matter content and soil physical conditions:a review. Nutrient Cycling in Agroecosystems 51(2): 123–137.

Herrick JE, Whitford WG, De Soyza AG, Van Zee JW, Havstad KM, Seybold CA, Walton M. 2001. Field soil aggregate stability kit for soil quality and rangeland health evaluations. Catena 44 (1), 27–35.

Hoffmann WA. 1996. The effects of fi re and cover on seedling establishmentin a neotropical Savanna. The Journal of Ecology 84: 383–393.

Hunke P, Roller R, Zeilhofer P, Schroeder B, Mueller EN. 2015. Soil changes under different land-uses in the Cerrado of Mato Grosso, Brazil, Geoderma Regional. 2015, 4, 31

Hunke P, Mueller EN, Schroeder B, Zeilhofer P. 2014. The Brazilian Cerrado: assessment of water and soil degradation in catchments under intensive agricultural use. Ecohydrology http://dx.doi.org/10.1002/eco.1573 (accepted for publication).

IPCC. 2013. Climate change 2013–the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the IPCC (Intergovernmental Panel on Climate Change) Cambridge University Press, Cambridge.

IPCC. 2007a. Climate change 2007 – the physical science basis: Working Group I Contribution to the Fourth Assessment Report of the IPCC (Intergovernmental Panel on Climate Change), Cambridge University Press.

IPCC. 2007b. Climate change 2007 – impacts, adaptation and vulnerability: Working Group II contribution to the Fourth Assessment Report of the IPCC (Intergovernmental Panel on Climate Change), Cambridge University Press.

Instituto Brasileiro de Geografia e Estatítisca (IBGE) (Brazilian Institute of Geography and Statistics). 2013. Censo Agropecuário 2006 (2006 Agricultural Census). http://seriesestatisticas.ibge.gov.br/series.aspx?vcodigo=AGRO34&t=producao-vegetal (accessed 22 August, 2013)

Janssen R, Rutz DD. 2011. Sustainability of biofuels in Latin America: risks and opportunities. Energy Policy 39: 5717–5725.

Jepson W, Brannstrom C, Filippi A. 2010. Access regimes and regional land change in the Brazilian Cerrado, 1972–2002. Annals of the Association of American Geographers 100(1): 87–111.

Jepson W. 2005. A disappearing biome? Reconsidering land-cover change in the Brazilian savanna. The Geographical Journal 171: 99–111.

Joris HAW, Caires EF, Bini AR, Scharr DA, Haliski A. 2012. Effects of soil acidity and water stress on corn and soybean performance under a no-till system. Plant and Soil 365: 409–424.

Kergoat L, Lafont S, Douville H, Berthelot B, Dedieu G, Planton S, Royer JF. 2002. Impact of doubled CO_2 on global-scale leaf area index and evapotranspiration: Conflicting stomatal conductance and LAI responses. Journal of Geophysical Research: Atmospheres (1984–2012), 107(D24), ACL–30.

King KW, Arnold JG, Bingner RL. 1999. Comparison of Green-Ampt and curve number methods on Goodwin Creek watershed using SWAT. Transactions of the ASAE, 42(4), 919–925.

Klink CA, Machado RB. 2005. Conservation of the Brazilian Cerrado. Conservation Biology 19: 707–713.

Kruskal, W.H., Wallis, W.A., 1952. Use of ranks in one-criterion variance analysis. J. Am. Stat. Assoc. 47 (260), 583–621.

Krysanova V, Srinivasan R. 2015. Assessment of climate and land use change impacts with SWAT. Regional Environmental Change, 15(3), 431–434.

Krysanova V, Hattermann F, Huang S, Hesse C, Vetter T, Liersch S, Koch H, Kundzewicz ZW. 2015. Modelling climate and land-use change impacts with SWIM: Lessons learnt from multiple applications. Hydrological Sciences Journal, 60(4), 606–635.

Labrière N, Locatelli B, Laumonier Y, Freycon V, Bernoux M. 2015. Soil erosion in the humid tropics: A systematic quantitative review. Agriculture, Ecosystems & Environment, 203, 127–139.

La Rovere EL, Pereira AS, Simões AF. 2011. Biofuels and sustainable energy development in Brazil. World Development 39(6): 1026–1036.DOI: 10.1016/j.worlddev.2010.01.004

Laabs V, Amelung W, Pinto A, Altstaedt A, Zech W. 2000. Leaching and degradation of corn and soybean pesticides in an Oxisol of the Brazilian Cerrados. Chemosphere 41: 1441–1449.

Laabs V, Amelung W, Pinto AA, Wantzen M, Silva CJ, Zech W. 2002. Pesticides in surface water, sediment, and rainfall of the northeasternPantanal basin, Brazil. Journal of Environmental Quality 31: 1636–1648.

Lambin EF, Gibbs HK, Ferreira L, Grau R, Mayaux P, Meyfroidt P,Morton DC, Rudel TK, Gasparri I, Munger J. 2013. Estimating the world's potentially available cropland using a bottom-up approach. Global Environmental Change 25(5): 892–901.

Lapola DM, Martinelli LA, Peres CA, Ometto JP, Ferreira ME, Nobre CA, Aguiar AP, Bustamante MMC, Cardoso MF, Costa MH, Joly CA, Leite CC, Moutinho P, Sampaio G, Strassburg BBN, Vieira IC. 2014. Pervasive transition of the Brazilian land-use system. Nature Climate Change. 4 (1), 27–35.

Li X, Weller DE, Jordan TE. 2010. Watershed model calibration using multi-objective optimization and multi-site averaging. Journal of Hydrology, 380(3), 277-288.

Liebmann B, Mechoso CR. 2011. The South American monsoon system. In The Global Monsoon System: Research and Forecast, Chang C-P,Ding Y, Lau N-C, Johnson RH, Wang B, Yasunari T (eds). World Scientific Publishing: New Jersey; 137–157.

Lilienfein J, Wilcke W. 2003. Element storage in native, agri-, and silvicultural ecosystems of the Brazilian savanna. Plant and Soil 254(2):425–442.

Lilienfein J, Wilcke W, Thomas R, Vilela L, Lima SdoC, Zech W. 2001.Effects of Pinus caribaea forests on the C, N, P, and S status ofBrazilian savanna Oxisols. Forest Ecology and Management 147:171–182.

Lilienfein J, Wilcke W, Vilela L, Ayarza MA, Lima SDC, Zech W. 2003.Soil fertility under native Cerrado and pasture in the Brazilian savanna. Soil Science Society of America Journal 67(4): 1195–1205.

Lilienfein J, Wilcke W, Ayarza MA. 2000. Soil acidification in Pinus caribaea forests on Brazilian savanna Oxisols. Forest Ecology and Management 128: 145–157.

Loarie SR, Lobell DB, Asner GP, Mu Q, Field CB. 2011. Direct impacts on local climate of sugar-cane expansion in Brazil. Nature Climate Change 1(2): 105–109.

Lopes A. 1996. Soils under Cerrado: A success story in soil management. Better Crops International 10: 9–15.

Lopes AS, Ayarza M, Thomas RJ. 2004. Managing and conserving acid savanna soils for agricultural development: Lessons from the Brazilian Cerrados. Centro Internacional de Agricultura Tropical (CIAT) International Center for Tropical Agriculture Apartado Aéreo 671370770, 11.

Lopes AS, Cox FR. 1977a. A survey of the fertility status of surface soils under "Cerrado" vegetation in Brazil. Soil Science Society of America Journal 41(4): 742–747.

Lopes AS, Cox FR. 1977b. Cerrado Vegetation in Brazil: An EdaphicGradient. Agronomy Journal 69: 828–831.

Lopes MA, Faleiro FG, Ferreira ME, Lopes DB, Vivian R, Boiteux LS.2012. Embrapa's contribution to the development of new plant varieties and their impact on Brazilian agriculture. Crop Breeding and Applied Biotechnology S2: 31–46.

Lorz C, Bakker F, Brandão C, Frimmel F, Günthert W, Koide S, Makeschin F, Neder K, Roig H, Uhl W, Walde D, Weiss H, Worch E. 2014. Chapter 1: Introduction and Overview–In: Lorz, C. *et al.* (Hrsg) Integrated Water Resource Management in Brazil, IWA Publications (ISBN 978–1–78040–489–9).

Lorz C, Abbt-Braun G, Bakker F, Borges P, Börnicke H, Frimmel F, Gaffron A, Höfer R, Makeschin F, Neder K, Roig LH, Steiniger B, Strauch M, Worch E, Weiss H. 2012. Challenges of an Integrated Water Resource Management for the Federal District of Brasília, Western Central Brazil–climate, land use and water resources.–Journal of Environmental Earth Sciences 65 (5), 1601–1611

Luo Y, Ficklin DL, Liu X, Zhang M. 2013. Assessment of climate change impacts on hydrology and water quality with a watershed modeling approach. Science of the total Environment, 450, 72–82.

Machado RB, Ramos Neto MB, Pereira P, Caldas EF, Gonçalves DA,Santos NS, Tabor K, Steininger M. 2004. Estimativas de Perda da Áreado Cerrado Brasileiro. Conservation International do Brasil, Brasília http://www.conservation.org.br/arquivos/RelatDesmatamCerrado.pdf (accessed August 21, 2013)

Maquere V, Laclau JP, Bernoux M, Saint-Andre L, Gonçalves JLM, Cerri CC, Piccolo MC, Ranger J. 2008. Influence of land use (savanna, pasture, Eucalyptus plantations) on soil carbon and nitrogen stocks in Brazil. European Journal of Soil Science 59: 863–877.

Marchão RL, Becquer T, Brunet D, Balbino LC, Vilela L, Brossard M.2009. Carbon and nitrogen stocks in a Brazilian clayey Oxisol: 13-year effects of integrated crop-livestock management systems. Soil and Tillage Research 103: 442–450.

Marengo JA. 2004. Interdecadal variability and trends of rainfall acrossthe Amazon basin. Theoretical and Applied Climatology 78: 79–96.

Marengo JA, Chou SC, Kay G, Alves LM, Pesquero JF, Soares WR,Santos DC, Lyra AA, Sueiro G, Betts R, Chagas DJ, Gomes JL,Bustamante JF, Tavares P. 2012. Development of regional future climate change scenarios in South America using the EtaCPTEC/HadCM3 climate change projections: climatology and regional analyses for the Amazon, São Francisco and the Paraná River basins. Climate Dynamics 38: 1829–1848.

Marengo JA, Ambrizzi T, Da Rocha RP, Alves LM, Cuadra SV, Valverde MC,Torres RR, Santos DC, Ferraz SE. 2010. Future change of climate in SouthAmerica in the late twenty- first century: intercomparison of scenarios from three regional climate models. Climate Dynamics 35(6): 1073–1097.

Marengo J, Betts RA, Nobre CA, Chou SC, Tomasella J, Sampaio G,Alves LM, Obregon G, Soares WR, Kay G. 2011. Dangerous climate change in Brazil – a Brazil-UK analysis of climate change and deforestation impacts in the Amazon. Centro de Ciência do SistemaTerrestre (CCST) of the Instituto Nacional de Pesquisas Espaciais(INPE), Brazil, and the Met Office Hadley Centre, UK.

Marengo JA, Jones R, Alves LM, Valverde MC. 2009. Future change of temperature and precipitation extremes in South America as derived from the PRECIS regional climate modeling system. International Journal of Climatology 29: 2241–2255.

Marinho CD, Martins FJO, Amaral Júnior AT, Gonçalves LSA, AmaralSCS, de Mello MP. 2012. Use of transgenic seeds in Brazilian agriculture and concentration of agricultural production to large agribusinesses. Genetics and Molecular Research 11: 1861–80.

Markewitz D, Resende JCF, Parron L, Bustamante M, Klink CA,Figueiredo RDO, Davidson EA. 2006. Dissolved rainfall inputs and streamwater outputs in an undisturbed watershed on highly weathered soils in the Brazilian Cerrado. Hydrological Processes 20: 2615–2639.

Marques JJ, Schulze DG, Curi N, Mertzman SA. 2004. Major element geochemistry and geomorphic relationships in Brazilian Cerrado soils. Geoderma 119(3): 179–195.

Marris E. 2005. The forgotten ecosystem. Nature 437: 944–945.

Martinelli LA, Naylor R, Vitousek PM, Moutinho P. 2010. Agriculture in Brazil: impacts, costs, and opportunities for a sustainable future. Current Opinion in Environmental Sustainability 2(5): 431–438.

Mattsson B, Cederberg C, Blix L. 2000. Agricultural land use in life cycle assessment (LCA): case studies of three vegetable oil crops. Journal of Cleaner Production 8: 283–292.

McGrath DA, Smith CK, Gholz HL, Oliveira FDA. 2001. Effects of land-use change on soil nutrient dynamics in Amazônia. Ecosystems 4(7):625–645.

Medlyn BE, Barton CVM, Broadmeadow MSJ, Ceulemans R, De Angelis P, Forstreuter M, Freeman M, Jackson SB, Kellomäki S, Laitat E, Rey A, Roberntz P, Sigurdsson BD, Strassemeyer J, Wang K, Curtis PS, Jarvis PG. 2001. Stomatal conductance of forest species after long-term exposure to elevated CO_2 concentration: a synthesis. New Phytolologist. 149(2):247–64.

Meinzer FC, Goldstein G, Franco AC, Bustamante M, Igler E, Jackson P, Caldas L, Rundel PW. 1999. Atmospheric and hydraulic limitations on transpiration in Brazilian Cerrado woody species. Functional Ecology 13: 273–282.

Melo M, Kido E, Andrade P. 2010. Post-market monitoring: legal framework in Brazil and first results. Available from Nature Proceedings. DOI: 10.1038/npre.2010.4528.1

Mendes IdeC, Fernandes MF, Chaer GM, Bueno dos Reis Junior F. 2012.Biological functioning of Brazilian Cerrado soils under different vegetation types. Plant and Soil 359: 183–195.

Miranda HS, Sato MN, Neto WN, Aires FS. 2009. Fires in the Cerrado, the Brazilian savanna. In Tropical Fire Ecology, Cochrane M (ed.).Springer: Berlin; 427–450.

Mittermeier RA, Myers N, Mittermeier CG. 1999. Hot spots Earth's biologically richest and most endangered terrestrial ecoregions.CEMEX, Conservation International: New York.

Ministério do Meio Ambiental (MMA). 2013. PMDBBS-Projeto de Monitoramento do Desmatamento dos Biomas Brasilieiros por Satélitehttp://siscom.ibama.gov.br/monitorabiomas/ (accessed July 15, 2013)

Ministério do Meio Ambiental (MMA). 2005. Resolução Conama N° 357,de 17/03/2005. Dispõe sobre a classificação dos corpos de água ediretrizes ambientais para o seu enquadramento, bem como estabeleceas condições e padrões de lançamento de efluentes, e dá outras providências.http://www.mma.gov.br/port/conama/res/res05/res35705.pdf (accessed August 28, 2013)

Ministério do Meio Ambiental (MMA). 2008. Resolução Conama N° 396,de 03/04/2008. Dispõe sobre a classificação e diretrizes ambientais parao enquadramento das águas subterrâneas e dá outras rovidências. http://www.cetesb.sp.gov.br/Solo/agua_sub/arquivos/res39608.pdf (accessedAugust 28, 2013)

Ministério da Saúde (MS). 2011. Portaria N° 2914 de 12/12/2011. Dispõe sobre os procedimentos de controle e de vigilância da qualidade da águapara consumo humano e seu padrão de potabilidade.Brasília. http://www.suvisa.rn.gov.br/contentproducao/aplicacao/sesap_suvisa/arquivos/gerados/portaria_ms_2914_dez_2011.pdf (accessed August28, 2013)

Monteiro JA, Strauch M, Srinivasan R, Abbaspour K, Gücker B. 2015. Comparison of CFSR and WFDEI weather reanalysis precipitation data with data from meteorological stations in Brazil: Application in river discharge modelling of the Tocantins Basin. SWAT International Conference. Italy 2015.

Moreira JC, Peres F, Simões AC, Pignati WA, de Carvalho Dores E,Vieira SN, Strüssmann C, Mott T. 2012. Contaminação de águassuper ficiais e de chuva por agrotóxicos em uma região do estado do Mato. Ciênc. saúde coletiva 17(6): 1557–1568.

Moreira A. 2000. Effects of fire protection on savanna structure in Central Brazil. Journal of Biogeography 27: 1021–1029.

Moriasi DN, Arnold JG, Van Liew MW, Bingner RL, Harmel RD, Veith TL. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. ASABE, 50(3), 885–900.

Morison JIL. Intercellular CO_2 concentration and stomata response to CO_2. In: Zeiger E, Farquhar GD, Cowan IR (Eds.). Stomata function. Stanfort: Stanfort University, 1987. p. 229–251.

Mulvaney RL. 1994. Nitrification of different nitrogen fertilizers. Illinois Fertilizer Conference Proceedings, pp. 24–26.

Munsell Soil Color Chart. Macbeth Division of Kollmorgen Corporation, Baltimore.

Myers N, Mittermeier RA, Mittermeier CG, Da Fonseca GA, Kent J.2000. Biodiversity hotspots for conservation priorities. Nature 403 (6772): 853–858.

Nascimento FL, Boëchat IG, Teixeira AO, Gücker B. 2012. High variability in sediment characteristics of a neotropical stream impactedby surface mining and gully erosion. Water, Air, & Soil Pollution 223:389–398.

National Center for Atmospheric Research (NCAR) 2012. Community Climate System Model, version 3.0. http://www.cesm.ucar.edu/models/ccsm3.0/ . NCAR/UCAR. Downscaling procedure in: T Hoar and D Nychka. 2008. Statistical Downscaling of the Community Climate System Model (CCSM) monthly temperature and precipitation projections, URL: http://www.gisclimatechange.org/downscaling. GIS data services are provided by NCAR GIS Program through Climate Change Scenarios, version 2.0, 2012. http://www.gisclimatechange.org. Data Access Date: 26th October 2014

Neill C, Coe MT, Riskin SH, Krusche AV, Elsenbeer H, Macedo MN,McHorney R, Lefebvre P, Davidson EA, Scheffler R, Figueira AM, Porder S, Deegan LA. 2013. Watershed responses to Amazon soyabean cropland expansion and intensification. Philosophical Transactions of the Royal Society, B: Biological Sciences, 368(1619):20120425.

Neill C, Piccolo MC, Steudler PA, Melillo JM, Feigl BJ, Cerri CC. 1995. Nitrogen dynamics in soils of forests and active pastures in the western Brazilian Amazon Basin. Soil Biology and Biochemistry 27 (9), 1167–1175.

Neill C, Piccolo MC, Melillo JM, Steudler PA, Cerri CC. 1999. Nitrogen dynamics in Amazon forest and pasture soils measured by 15 N pool dilution. Soil Biology and Biochemistry 31 (4), 567–572.

Neitsch SL, Arnold JG, Kiniry JR, Williams JR, King KW. (2005). SWAT theoretical documentation version 2005. Blackland Research Center, Temple, TX.

Neitsch SL, Arnold JG, Kiniry JR, Williams JR. 2009. SWAT theoretical documentation version 2009. Blackland Research Center, Temple, TX.

Nepstad D, Lefebvre P, Lopes da Silva U, Tomasella J, Schlesinger P,Solorzano L, Moutinho P, Ray D, Guerreira Benito J. 2004. Amazon drought and its implications for forest flammability and tree growth: a basin-wide analysis. Global Change Biology 10: 704–717.

Neto MS, Piccolo MDC, Scopel E, Costa Junior C, Cerri CC, Bernoux M.2009. Carbono total e atributos químicos com diferentes usos do solo noCerrado. Acta Scientiarum Agronomy 31: 709–717.

Neto MS, Scopel E, Corbeels M, Cardoso AN, Douzet J, Feller C, Piccolo MdeC, Cerri CC, Bernoux M. 2010. Soil carbon stocks under no-tillage mulch-based cropping systems in the Brazilian Cerrado: An on-farm synchronic assessment. Soil and Tillage Research 110: 187–195.

Neufeldt H, Ayarza M, Resck D, Zech W. 1999. Distribution of water-stable aggregates and aggregating agents in Cerrado Oxisols. Geoderma93: 85–99.

Neufeldt H, Resck D, Ayarza M. 2002. Texture and land-use effects on soil organic matter in Cerrado Oxisols, Central Brazil. Geoderma 107:151–164.

Nóbrega MT, Collischonn W, Tucci CEM, Paz AR. 2011. Uncertainty in climate change impacts on water resources in the Rio Grande Basin, Brazil, Hydrology Earth System Science. 15, 585–595.

Nogueira E, Dores E, Pinto AA, Amorim RSS, Ribeiro ML, Lourencetti C. 2012. Currently used pesticides in water matrices in Central-WesternBrazil. Journal of the Brazilian Chemical Society 23: 1476–1487.

Nogueira C, Ribeiro S, Costa GC, Colli GR. 2011. Vicariance and endemism in a Neotropical savanna hotspot: distribution patterns of Cerrado squamate reptiles. Journal of Biogeography 38(10): 1907 –1922.

Nunes RDS, Sousa GDe, Goedert WJ, Vivaldi LJ. 2011. Distribuição defósforo no solo em razão do sistema de cultivo e manejo da adubação fosfatada. Revista Brasileira de Ciência do Solode Ciência do Solo 35:877–888.

Oliveira PTS, Wendland E, Nearing MA, Scott RL, Rosolem R, da Rocha HR. 2015. The water balance components of undisturbed tropical woodlands in the Brazilian Cerrado. Hydrology and Earth System Sciences. 19(6), 2899–2910.

Oliveira PTS, Nearing MA, Wendland E. 2015a. Orders of magnitude increase in soil erosion associated with land use change from native to cultivated vegetation in a Brazilian savannah environment. Earth Surface Processes and Landforms. DOI: 10.1002/esp.3738

Oliveira PTS, Nearing MA, Moran MS, Goodrich DC, Wendland E, Gupta HV. 2014. Trends in water balance components across the Brazilian Cerrado. Water Resources Research, 50(9), 7100–7114.

Oliveira PTS, Wendland E, Nearing MA. 2013. Rainfall erosivity in Brazil: A Review. Catena 100: 139–147.

Oliveira RS, Bezerra L, Davidson EA, Pinto F, Klink CA, Nepstad DC,Moreira A. 2005. Deep root function in soil water dynamics in Cerrado savannas of central Brazil. Functional Ecology 19: 574–581.

Oliveira G, Junior MD, Resck DVS, Curi N. 2004. Caracterização químicae físico-hídrica de um Latossolo Vermelho após vinte anos de manejo ecultivo do solo. Revista Brasileira de Ciência do Solode Ciência doSolo 28: 327–336.

Oliveira PE, Gibbs PE. 2000. Reproductive biology of woody plants in a Cerrado community of Central Brazil. Flora 195: 311–329.

Oliveira J, Vilela L, Ayarza M. 2000. Adsorção de nitrato em solos de Cerrado do Distrito Federal. Pesquisa Agropecuária Brasileira 35:1199–1205.

Oliveira-Filho A, Ratter J. 2002. Vegetation physiognomies and woodyfl ora of the Cerrado biome. In The Cerrados of Brazil. Ecology and Natural History of a Neotropical Savanna, Oliviera PS, Marquis TJ (eds). Columbia University Press: New York; 91–120.

Olson DM, Dinerstein E. 2002. The global 200: priority ecoregionsfor global conservation. Annals of the Missouri Botanical Garden89: 199–224.

Panday PK, Coe MT, Macedo MN, Lefebvre P, de Almeida Castanho AD. 2015. Deforestation offsets water balance changes due to climate variability in the Xingu River in eastern Amazonia. Journal of Hydrology, 523, 822–829.

Parron LM, Bustamante MMC, Markewitz D. 2010. Fluxes of nitrogen and phosphorus in a gallery forest in the Cerrado of central Brazil. Biogeochemistry 105: 89–104.

Parron LM. 2004. Aspectos da ciclagem de nutrients em funcão do gradiente topogáfico em uma mata de galeria no Distrito Federal. (Ph.D. thesis), University of Brasília, Brasília (187 pp.).

Pavinato PS, Dao TH, Rosolem CA. 2010. Tillage and phosphorus management effects on enzyme-labile bioactive phosphorus availabilityin Cerrado Oxisols. Geoderma 156: 207–215.

Pavinato PS, Merlin A, Rosolem CA. 2009. Phosphorus fractions in Brazilian Cerrado soils as affected by tillage. Soil and Tillage Research105: 149–155.

Pereira D, Almeida AQ, Martinez MA, Rosa DRQ. 2014 Impacts of deforestation on water balance components of a watershed on the Brazilian East Coast Revista Brasileira de Ciência do Solo, 38(4), 1350–1358

Pereira MG, Camacho CF, Freitas MAV, da Silva NF. 2012. The renewable energy market in Brazil: Current status and potential. Renewable and Sustainable Energy Reviews 16(6): 3786–3802.

Pinheiro ÉFM, de Campos DVB, de Carvalho Balieiro F, dos Anjos LHC, Pereira MG. 2014. Tillage systems effects on soil carbon stockand physical fractions of soil organic matter. Agricultural Systems. In Press, doi: 10.1016/j.agsy.2014.08.008

Pinheiro M, Monteiro R. 2010. Contribution to the discussions on theorigin of the Cerrado biome: Brazilian savanna. Brazilian Journal of Biology 70(1): 95–102.

Piniewski M. 2012. Scenario-based impact assessment of global and regional change on the semi-natural flow regime. Anchor Academic Publishing (aap_verlag).

Pires MO. 2000. Programas agrícolas na ocupação do Cerrado. Sociedade e cultura 3(1): 111–131.

Pivello VR. 2011. The use of fire in the Cerrado and Amazonianrainforests of Brazil: past and present. Fire Ecology 7: 24–39.

Portella CMR, Guimarães MDF, Feller C, Fonseca ICDB, Tavares Filho J. 2012. Soil aggregation under different management systems. Revista Brasileira de Ciência do Solo 36 (6), 1868–1877.

Queiroz RDP, Lazarini E, Lustosa M. 2011. Inter-relation between soybean yield and soil compaction under degraded pasture in Brazilian Savannah. Revista Brasileira de Ciência do Solo 35: 1579–1588.

Quesada CA, Hodnett MG, Breyer LM, Santos AJB, Andrade S, MirandaHS, Miranda AC, Lloyd J. 2008. Seasonal variations in soil water in two woodland savannas of central Brazil with different fire history. Tree Physiology 28: 405–15.

Ramalho M, Silva G, Dias L. 2009. Genetic plant improvement and climate changes. Crop Breeding and Applied Biotechnology 9: 189–195.

Reatto A, Bruand A, Silva EM, Martins ES, Brossard M. 2007. Hydraulic properties of the diagnostic horizon of Latosols of a regional toposequence across the Brazilian Central Plateau. Geoderma 139: 51–59.

Redo D, Aide TM, Clark ML. 2012. Vegetation change in Brazil's dryland ecoregions and the relationship to crop production and environmental factors: Cerrado, Caatinga, and Mato Grosso, 2001–2009. Journal ofLand Use Science 8: 123–153.

Reichenberger S, Amelung W, Laabs V, Pinto A, Totsche KU, Zech W.2002. Pesticide displacement along preferential flow pathways in a Brazilian Oxisol. Geoderma 110(1): 63–86.

Resck B, Resck D, Ferreira E, Gomes A. 2008. Estoque de carbono dosolo sob diferentes sistemas de manejo na bacia hidrográfica do córregotaquara, distrito federal. Simposio Nacional Cerrado: 1–6.

Resck DVS, Vasconcellos CA, Vilela L, Macedo MCM. 1999. Impact of conversion of Brazilian Cerrados to cropland and pasture land on soil carbon pool and dynamics. Global Climate Change and Tropical Ecosystems. Advances Soil Science. CRC Press, Boca Raton, FL, 169–196.

Resende JCF, Markewitz D, Klink CA, Bustamante MMdaC, Davidson EA. 2011. Phosphorus cycling in a small watershed in the Brazilian Cerrado: impacts of frequent burning. Biogeochemistry 105: 105–118.

Ribeiro JF, Walter BM. 1998. Fitofisionomias do bioma Cerrado. InCerrado: Ambiente e Flora, Sano SM, Almeida SP (eds). Embrapa-CPAC: Planaltina; 89–166.

Rodrigues EL, Elmiro MAT, Braga FdeA, Jacobi CM, Rossi RD. 2015. Impact of changes in land use in the flow of the Pará River Basin, MG. Revista Brasileira de Engenharia Agrícola e Ambiental, 19(1), 70–76.

Rodriguez DA, Tomasella J, Linhares C. 2010. Is the forest conversion to pasture affecting the hydrological response of Amazonian catchments? Signals in the Ji-Paraná Basin. Hydrological Processes, 24(10), 1254–1269

Roland F, Huszar VLM, Farjalla VF, Enrich-Prast A, Amado AM, Ometto JPHB. 2012. Climate change in Brazil: perspective on the biogeochemistry of inland waters. Brazilian Journal of Biology 72(3): 709–722.

Rosa RDS, Aguiar ACF, Boëchat IG, Gücker B. 2013. Impacts of fishfarm pollution on ecosystem structure and function of tropical headwater streams. Environmental Pollution 174: 204–213.

Roscoe R, Buurman P. 2003. Tillage effects on soil organic matter in densityfractions of a Cerrado Oxisol. Soil and Tillage Research 104: 185–202.

Roscoe R, Buurman P, Velthorst E, Vasconcellos C. 2001. Soil organicmatter dynamics in density and particle size fractions as revealed by the13C/12C isotopic ratio in a Cerrado's Oxisol. Geoderma 104: 185–202.

Roscoe R, Buurman P, Velthorst EJ, Pereira JAA. 2000. Effects of fire on soil organic matter in a "Cerrado sensu-stricto" from Southeast Brazil as revealed by changes in δ 13C. Geoderma 95(1): 141–160.

Sano EE, Rosa R, Brito JLS, Ferreira LG. 2010. Land cover mapping of the tropical savanna region in Brazil. Environmental Monitoring and Assessment 166: 113–24.

Sano EE, Rosa R, Brito JLS, Ferreira LG. 2008. Notas Científicas Mapeamento semi detalhado do uso da terra do Bioma Cerrado.Pesquisa Agropecuária Brasiliera 43(1): 153–156.

Santos JZL, Neto AEF, de Resende ÁV, Carneiro LF, Curi N, da SilvaMoretti B. 2011. Resposta do feijoeiro à adubação fosfatada em solosde Cerrado com diferentes históricos de uso. Revista Brasileira de Ciência do Solo 35(1): 193–202.

Sawyer D. 2008. Climate change, biofuels and eco-social impacts in the Brazilian Amazon and Cerrado. Philosophical Transactions of the Royal Society, B: Biological Sciences 363(1498): 1747–1752.

Scheffler, R., Neill, C., Krusche, A.V., Elsenbeer, H., 2011. Soil hydraulic response to land-use change associated with the recent soybean expansion at the Amazon agricultural frontier. Agriculture, Ecosystems & Environment 144 (1), 281–289.

Schiesari L, Waichman A, Brock T, Adams C, Grillitsch B. 2013.Pesticide use and biodiversity conservation in the Amazonian agricultural frontier. Philosophical Transactions of the Royal Society,B: Biological Sciences 368: 20120378.

Schiesari L, Grillitsch B. 2011. Pesticides meet megadiversity in theexpansion of biofuel crops. Frontiers in Ecology and the Environment 9: 215–221.

Schindewolf M, Schönke D, Amorim RS, Schmidt J. 2014. Effects of contour banks and no-till measures on run-off and sediment yield in Campo Verde Region, Mato Grosso. In: Hohnwald S, Gerold G (Eds.), Carbon-Optimized Land Management Research for the Southern Amazon—Geographical and Organizational Settings of the Carbiocial-Carbioma Project Consortium. Interdisciplinary Analysis and Modeling of Carbon-Optimized Land Management Strategies for Southern Amazonia, pp. 85–100.

Schoumans OF, Chardon WJ, Bechmann ME, Gascuel-Odoux C, Hofman G, Kronvang B, Rubaek GH, Dorioz JM. 2014. Mitigation options toreduce phosphorus losses from the agricultural sector and improvesurface water quality: A review. Science of the Total Environment 468:1255–1266.

Schuol J, Abbaspour KC. 2007. Using monthly weather statistics to generate daily data in a SWAT model application to west Africa. Ecological Modeling. 201(3–4), 301–311.

Scopel E, Triomphe B, Affholder F, Silva FAM, Corbeels M, Xavier JHV, Lahmar R, Recous S, Bernoux M, Blanchart E, Mendes I, Tourdonnet S. 2013. Conservation agriculture cropping systems in temperate and tropical conditions, performances and impacts. A review. Agronomy for Sustainable Development 33: 113–130.

Silva-Junior EF, Moulton TP, Boëchat IG, Gücker B. 2014. Leaf decomposition and ecosystem metabolism as functional indicators of landuse impacts on tropical streams. Ecological Indicators 36: 195–204.

Silva JSO, Cunha Bustamante MM, Markewitz D, Krusche AV, Ferreira LG. 2010. Effects of land cover on chemical characteristics of streams in the Cerrado region of Brazil. Biogeochemistry 105: 75–88.

Silva D, Ometto J, Lobo G, Lima WDP, Scaranello MA, Mazzi E, Rocha HRDa, 2007. Can land use changes alter carbon, nitrogen and major ion transport in subtropical Brazilian streams? Scientia Agricola 64(4):317–324.

Silva JF, Farinas MR, Fel fi li JM, Klink CA. 2006. Spatial heterogeneity, land use and conservation in the Cerrado region of Brazil. Journal ofBiogeography 33: 536–548.

Silva JD, Resck DV, Corazza E, Vivaldi L. 2004. Carbon storage in clayey Oxisol cultivated pastures in the “Cerrado” region, Brazil. Agriculture, Ecosystems & Environment 103: 357–363.

Smaling EMA, Roscoe R, Lesschen JP, Bouwman AF, Comunello E.2008. From forest to waste: Assessment of the Brazilian soybean chain, using nitrogen as a marker. Agriculture, Ecosystems & Environment128(3): 185–197.

Smith J, Cadavid JV, Ayarza M, de Aguiar JLP, Rosa R. 1999. Land use change in soybean production systems in the Brazilian savanna: the role ofpolicy and market conditions. Journal of Sustainable Agriculture 15(2–3):95–117.

Smyth TJ, Sanchez PA. 1982. Phosphate rock dissolution and availabilityin Cerrado soils as affected by phosphorus sorption capacity. SoilScience Society of America Journal 46(2): 339–345.

Soares-Filho B, Rajão R, Macedo M, Carneiro A, Costa W, Coe M,Rodrigues H, Alencar A. 2014. Cracking Brazil’s forest code. Science 344(6182): 363–364.

Soares-Filho BS, Nepstad DC, Curran LM, Cerqueira GC, Garcia RA,Ramos CA, Voll E, McDonald A, Lefebvre P, Schlesinger P. 2006. Modelling conservation in the Amazon basin. Nature 440: 520–523.

Soccol CR, Vandenberghe LP, Costa B, Woiciechowski AL, deCarvalho JC, Medeiros AB, Bonomi LJ. 2005. Brazilian biofuel program: an overview. Journal of Scientific and Industrial Research 64(11): 897–904.

Soil Conservation Service (SCS). 1972. Engineering Division: Section 4: Hydrology, in: National Engineering Handbook)

Sousa DMG, Rein TA. 2011. Soil fertility evaluation and control for annual crops in the Cerrado. Better Crops 12: 12–15.

Souza ZMD, Alves MC. 2003. Movimento de água e resistência àpenetração em um Latossolo Vermelho distrófico de Cerrado, sob diferentes usos e manejos. Revista Brasileira de Engenharia Agrícola e Ambiental 7(1): 18–23.

Sparovek G, Berndes G, Barretto AGdeOP, Klug ILF. 2012. The revision of the Brazilian Forest Act: increased deforestation or a historic step. Environmental Science & Policy 16: 65–72.

Sparovek G, Berndes G, Klug ILF, Barretto AGOP. 2010. Brazilian agriculture and environmental legislation: status and future challenges. Environmental Science & Technology 44: 6046–53.

Strauch M, Bernhofer C, Koide S, Volk M, Lorz C, Makeschin F. 2012. Using precipitation data ensemble for uncertainty analysis in SWAT streamflow simulation Journal of Hydrology, 414, 413–424.

Strauch M, Volk M. 2013. SWAT plant growth modification for improved modeling of perennial vegetation in the tropics Ecological Modelling, 269, 98–112.

Strauch M, Lima JE, Volk M, Lorz C, Makeschin F. 2013. The impact of Best Management Practices on simulated streamflow and sediment load in a Central Brazilian catchment Journal of Environmental Management, 127, S24–S36.

Teixeira EI, Fischer G, van Velthuizen H, Walter C, Ewert F. 2013. Global hot-spots of heat stress on agricultural crops due to climate change. Agricultural and Forest Meteorology 170: 206–215.

Torres JLR, Fabian AJ, Pereira MG. 2011. Alterações dos atributos físicosde um Latossolo Vermelho submetido a diferentes sistemas de manejo.Ciencia e Agrotecnologia 35: 437–445.

Trabaquini, K., Formaggio, A.R., Galvão, L.S., 2013. Changes in physical properties of soils with land use time in the Brazilian savanna environment. Land Degradation & Development.1–12 (v.x).

Tuppad P, Douglas-Mankin KR, Lee T, Srinivasan R, Arnold JG. 2011. Soil and Water Assessment Tool (SWAT) Hydrologic/Water Quality Model: Extended Capability and Wider Adoption Transactions of the ASABE, 54(5), 1677–1684.

Uzeika T, Merten G, Minella JPG, Moro M. 2012. Use of the SWAT model for hydro-sedimentologic simulation in a small rural watershed. Rev Bras Ciênc Solo 36(2):1–9.

Vasconcelos TNN. 1998. Interpretação morfopedológica da bacia do rio Tenente Amaral — Jaciara/MT: Condição básica para sua caracterização ambiental. (Master thesis). University of Cuiabá.

Vendrame P, Brito O, Guimarães MF, Martins ES, Becquer T. 2010.Fertility and acidity status of latossolos (oxisols) under pasture in the Brazilian Cerrado. Anais Da Academia Brasileira De Ciencias 82:1085–1094.

Vourlitis GL, de Almeida Lobo F, Lawrence S, Holt K, Zappia A, Pinto JrOB, de Souza Nogueira J. 2014. Nutrient resorption in tropical savanna forests and woodlands of central Brazil. Plant Ecology 215: 963–975.

Vrieling A, Rodrigues S. 2004. Erosion assessment in the Brazilian Cerrados using multi-temporal SAR imagery. Proceedings of the 2004 Envisat & ERS Symposium, SP-572. ESA, Salzburg 2004.

Vrieling A, De Jong SM, Sterk G, Rodrigues SC. 2008. Timing of erosionand satellite data: a multi-resolution approach to soil erosion riskmapping. International Journal of Applied Earth Observation andGeoinformation 10(3): 267–281.

Wantzen KM, Mol JH. 2013. Soil erosion from agriculture and mining: a threat to tropical stream ecosystems. Agriculture 3(4): 660–683.

Wantzen KM, Couto EG, Mund EE, Amorim RS, Siqueira A, Tielbörger K, Seifan M. 2012. Soil carbon stocks in stream-valley-ecosystems in the Brazilian Cerrado agroscape. Agriculture, Ecosystems & Environment 151: 70–79.

Wantzen KM. 2006. Physical pollution: effects of gully erosion on benthic invertebrates in a tropical clear-water stream. Aquatic Conservation: Marine and Freshwater Ecosystems 16: 733–749.

Wantzen KM. 2003. Cerrado streams - characteristics of a threatened freshwater ecosystem type on the tertiary shields of South America. Amazoniana 17: 485–502.

Wantzen KM, Siqueira A, da Cunha CN, de Sá MFP. 2006. Stream-valley systems of the Brazilian Cerrado: impact assessment and conservation scheme. Aquatic Conservation: Marine and Freshwater Ecosystems 16:713–732.

WWF- Brasil. 2009. Monitoramento das alterações da cobertura vegetal e uso do Solona Bacia do Alto Paraguai — Porção Brasileira — Período de Análise: 2002 a 2008 (Iniciativa: CI–Conservação Internacional, ECOA - Ecologia e Ação, Fundación AVINA, Instituto SOS Pantanal. Brasília. 58 pp.).

Yamada T. 2005. The Cerrado of Brazil: a success story of production onacid soils. Soil Science and Plant Nutrition 51(5): 617–620.

Zhou J, Liu Y, Guo H, He D. 2014. Combining the SWAT model with sequential uncertainty fitting algorithm for streamflow prediction and uncertainty analysis for the Lake Dianchi Basin, China Hydrological Processes, 28(3), 521–533.

Zimbres B, Furtado MM, Jácomo AT, Silveira L, Sollmann R, Tôrres NM,Machado RB, Marinho-Filho J. 2013. The impact of habitat fragmentation on the ecology of xenarthrans (Mammalia) in the Brazilian Cerrado. Landscape Ecology 28(2): 259–269.

Zimmermann B, Elsenbeer H, De Moraes JM. 2006. The influence of land-use changes on soil hydraulic properties: implications for runoff generation. Forest Ecology and Management 222(1), 29–38.

Zimmermann B, Papritz A, Elsenbeer H. 2010. Asymmetric response to disturbance and recovery: changes of soil permeability under forest–pasture–forest transitions. Geoderma 159 (1), 209–215.

Zinn Y, Resck DV, da Silva JE. 2002. Soil organic carbon as affected by afforestation with Eucalyptus and Pinus in the Cerrado region of Brazil. Forest Ecology and Management 166: 285–294.

Zinn Y, Lal R. 2013. Principles of soil management in Neotropical Savannas. In Principles of Sustainable Soil Management inAgroecosystems, Lal R, Stewart BA (eds). Taylor and Francis: Boca Raton; 57–83.

Appendix A

SWAT model set-up – testing and calibration

The objective of the modelling chapter was to provide an estimation of how different driver inputs such as precipitation affect the simulation of streamflow. Therefore, the model was systematically tested with satellite-derived precipitation data commonly used in data-sparse regions and precipitation data from a neighbouring station of the Brazilian weather network (operated by ANA). In the first step, the model testing should also give an idea on how the uncalibrated model is able to simulate streamflow at daily and monthly time steps as well as with different infiltration approaches (CN and G+A). The iterative process of parameterising the model with simple adjustments of the streamflow-sensitive groundwater parameter should gain insight into model performance. First, in manual testing, some parameters (groundwater, baseflow and Ks) were varied while the others remained constant. The hydrographs were accompanied by visual inspection of daily and monthly hydrographs. The first runs showed almost no baseflow, so that sensitive groundwater parameters needed to adjusted (GW_SPYLD: 0.3 m^3/m^3, alpha baseflow recession constant: 0.01, GW_delay: 100 days). Also, the selection of a warm-up period of 5 years brought the hydrograph closer to reality. The SWAT model was set up in different versions and calculated at different time steps. From the analysis of the drivers (time series from discharge and precipitation), data were acquired on a daily basis from 1990–2006 to calibrate and validate the SWAT model. The testing period was determined as 1995 to 2005 plus an additional five years of model warm-up (1990–1995).In principal, the initial model versions were parameterised with simplified parameter inputs without implementing management practices and fertilization regimes, but with measured soil data to add Cerrado soil types to the SWAT soil database. Minor adjustments to selected model parameters were applied to make more realistic assumptions based on field data or other studies from the Cerrado (Strauch *et al.,* 2013). First, the driver precipitation input data were tested on a monthly time step to figure out the impact of the inputs on streamflow. The SWAT model calibration procedure was used to verify the model performance under simulation conditions. The whole procedure involving the sensitivity analysis, the calibration and validation process and the means for assessing the success of SWAT follows the guidelines of Arnold *et al.,* (2012) who provide a comprehensive overview of the common methods with the SWAT calibration tool SWAT-CUP (Abbaspour *et al.,* 2007).

Sensitivity analysis and calibration with SUFI–2

The major goal in SWAT–CUP is to find the parameters which are sensitive to streamflow. Before calibration, which is essential to reduce parameter uncertainty before a model scenario is applied, a sensitivity analysis helps to identify the most influential parameters on streamflow.

The parameters used for calibration were selected from test simulations by manually changing one parameter at a time (OAT approach) while keeping the others constant (initial absolute sensitivity analysis). As a routine, most SWAT-studies use CN2 (Curve Number), AWC, ESCO, and SURLAG to calibrate streamflow (Arnold *et al.,* 2012). In a next step, ten parameters were selected for relative sensitivity analyses by simultaneously varying all parameters. From the sensitivity analysis of 800–1000 simulations of the model parameter ranges, the sensitivity ranking was used as a criterium by which to select the calibration parameters for each model set up. The procedure was started with 10 commonly used parameters (see Arnold *et al.,* 2012 for an overview) by applying physically meaningful ranges. Out of ~100 simulations, the most sensitive parameters were selected. SWAT–

CUP automatically suggests a refinement of the parameter ranges for the next iteration of 500–1000 simulations. This interactive process lasts until the previously defined objective function (here Nash Sutcliffe Efficiency NSE = 0.5, see the Moriasi *et al.,* 2007) is fulfilled. SUFI–2 combines all sources of uncertainty in a uniform distribution. All sources of uncertainty from the drivers, model, parameters and observed data are accounted for. In a Latin Hypercube sampling scheme, the uncertainty is propagated as a 95 % PPU (prediction uncertainty) at the 2.5 % and 97.5 % level, disallowing 5 % of the worst simulations. The P-factor represents the percentage of the observed data bracketed by the 95 % prediction uncertainty (95PPU) of several hundreds of simulations. In the case of P=100 %, all observations are within the 95PPU bounds. The r-factor gives the relative width of the 95 % probability band (large r–factor indicates high model uncertainty). The global sensitivity and one-factor-at-a-time (OAT) method allowed us to determine by the t-stats and p-value which of the parameters under observation were significantly sensitive and meaningful to adjust. The objective function was defined as the NSE between measured and simulated discharges. In an iterative process of 3–5 iterations with 200–500 simulations, the final parameter ranges to calibrate flow were defined according to the objective function (NSE>0.5) or the calibration procedure is stopped.

Table A–0-1: Sensitive parameters of the initial 800 simulations per model set-up (CN– Curve Number; GA– Green and Ampt). The final parameter ranges were estimated by SUFI–2 from the last iteration in SWAT–CUP and included in the calibration procedure of streamflow. The sensitivity rank is given by the relative sensitivity analysis of the first iteration (blank f ields mean that the parameter was not significantly sensitive according to p< 0.05) (rank from final iteration / rank first iteration with wider parameter ranges) was determined as 250 (CN_month; CN_day; GA_day) to 500 (GA_month) simulations in the last iteration

Parameter description and ranges	CN_month		CN_day		GA_month		GA_day	
	final range	rank first iteration	final range	rank	final range	rank	final range	rank
V__ALPHA_BF.gw Baseflow alpha factor (0–1 days)			0.18—0.3	5	0.24—0.26	6	0.12—0.16	4
V__GW_DELAY.gw Groundwater delay time (0–500 days)	233—319	3	364—463	6	332—404	3	265 —324	1
R__SOL_K(..).sol Saturated hydraulic conductivity (0–2000 mm/h)			–1— – 0.3	3	0.21—0.71	5	–0,6 — –0.3	2
V__ESCO.hru Soil evaporation compensation factor (0.01–1)			0.5—0.9	4	0.21 —0.24	9	0.4—0.6	5
R__SOL_AWC(..).sol Available water capacity in the soil layer (0–1 mm water /mm soil)	–0.1—0.2	4	0.3—0.7	2	–0.87 — –0.77	1	0.65 — 0.79	3
R__CN2.mgt Runoff curve number for moisture condition II (20–90)	–0.8 to –0.47	2	–1.5 — –0.6	1			–0.08 — 0.13	6
V__GW_REVAP.gw Groundwater revap coefficient (0.02–2)	0.073—0.12	1			0.12—0.15	2		
R__SLSUBBSN.hru Average slope length (m)					–0.78 — –0.21	10		
V__GWQMN.gw Threshold depth of water in the shallow aquifer required for return flow (0–5000 mm)					257 — 482	7		
V__CH_N2.rte Manning's roughness coefficients (0–1)					–0.12 — 0.02	4		

SUFI–2 (Sequential uncertainty fitting) algorithm

Parameter estimation was carried out via SUFI–2 (Sequential Uncertainty Fitting Ver.2, Abbaspour *et al.,* 2007), which is a semiautomated algorithm of high computational efficiency. It is increasingly used particularly for streamflow predictions and hydrological calibrations of SWAT, where the users are able to influence the calibration process iteratively (Abbaspour *et al.,* 2007). In a recent study, Zhou *et al.,* (2014) compared the performance of the autocalibration procedure which is implemented in SWAT (PARASOL, Green and van Griensven, 2008) with the SUFI–2 algorithm to calibrate SWAT using streamflow data. The authors came to the conclusion that, with regard to statistical criteria (mainly NSE), the SUFI–2 algorithm performed better than the autocalibration.

The SWAT– Calibration and Uncertainty Program (SWAT–CUP) is directly linked to SWAT. The SWAT model output is transferred to SWAT–CUP in order to apply the SUFI–2 algorithm (Abbaspour *et al.,* 2007), which accounts for all sources of uncertainty, such as driving variables, conceptual models, parameters, and measured data. The user is able to manipulate all parameters without losing spatial heterogeneity by replacing a parameter (v), by adding a quantity (a) or multiplying the initial parameter with a factor (r) for a hydrological group (hydrogrp), soil texture (soltext), land use, subbasin (subbsn) or slope.

x__(v,a,r) <parname>.<ext>__<hydrogrp>__<soltext>__<landuse>__<subbsn>__<slope>

Evaluation criteria and assessment of performance

As measures of model performance, NSE, R^2 and PBIAS (percent bias) (Moriasi et al 2007) were used to compare modeled and observed streamflow at the outlet. Essentially, the closer the model efficiency of NSE and R^2 is to 1, the more accurate the model is. No absolute criteria with which to judge the model performance have been established (Arnold *et al.,* 2012). However, acceptable simulations are often chosen for monthly models with NSE >0.5, R^2>0.6 and PBIAS +–55 % (Bonuma *et al.,* 2012, Moriasi *et al.,* 2007, Bressiani *et al.,* 2015). For daily simulations, such common criteria are not defined.

Author's declaration

I prepared this dissertation myself and without illegal assistance. The work is original except where indicated by references in the text and no part of the dissertation has been submitted for any other degree.

This dissertation has not been presented to any other university for examination, neither in Germany nor in any other country.

Caputh, August 5th , 2015 ________________________________

(Philip Paul Hunke)