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Soil hydraulic response to Amazon land-use change

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Soil hydraulic response to land-use change associated with the recent soybean expansion at the Amazon agricultural frontier

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Abstract

Clearing for large-scale soy production and the displacement of cattle-breeding by soybeans are major features of land-use change in the lowland Amazon that can alter hydrologic properties of soils and the runoff generation over large areas. We measured infiltrability and saturated hydraulic conductivity (Ksat) under natural forest, pasture, and soybeans on Oxisols in a region of rapid soybean expansion in Mato Grosso, Brazil. The forest-pasture conversion reduced infiltrability from 1258 to 100 mm/h and Ksat at all depths. The pasture-soy conversion increased infiltrability from 100 to 469 mm/h (attributed to shallow disking), did not affect Ksat at 12.5 cm, but decreased Ksat at 30 cm from 122 to 80 mm/h, suggesting that soybean cultivation enhances subsoil compaction. Permeability decreased markedly with depth under forest, did not change under pasture, and averaged out at one fourth the forest value under soybeans with a similar pattern of anisotropy. Comparisons of permeability with rainfall intensities indicated that land-use change did not alter the predominantly vertical water movement within the soil. We conclude that this landscape is well buffered against land-use changes regarding near-surface hydrology, even though short-lived ponding and perched water tables may occur locally during high-intensity rainfall on pastures and under soybeans.

Keywords:

Land-cover change; Tropical forest; Pasture; Infiltrability; Saturated hydraulic conductivity, Ksat; Hydrological flowpaths

1 Introduction

The Amazon basin is both the world's largest and most diverse tropical forest region (Phillips *et al.*, 2008) and the location of the highest absolute rates of land clearing on earth (Morton *et al.*, 2006). Historically, cattle ranching was the dominant use of deforested lands (Fearnside, 1987; Serrão, 1992), and although this kind of land use remains the prevailing one, clearing for large-scale production of soybeans now rivals cattle ranching as the driver of new deforestation (Fearnside, 2001, 2005; Grieg-Gran *et al.*, 2007; Morton *et al.*, 2006). This trend is likely to continue (Cerri *et al.*, 2007; Soares-Filho *et al.*, 2006; Vera-Diaz *et al.*, 2008). Economic growth in China coupled with rising meat consumption and the effects of widespread outbreaks of BSE (*bovine spongiform encephalopathy*) in the European Union have created favorable market conditions for Brazil's soybean exports (Cattaneo, 2008; Nepstad *et al.*, 2008). Higher oil prices and enhanced global demand for biofuels have also contributed to increased demand for soy production in the Amazon region (Cattaneo, 2008; Laurance, 2007; Nepstad *et al.*, 2008).

Recently, the impetus to increase soybean production has become a principal driver of deforestation along Amazonia's southern boundary (Morton *et al.*, 2006; Nepstad *et al.*, 2006; Soares-Filho *et al.*, 2006). In 2006–2007, the states of Mato Grosso, Pará, and Rondônia accounted for 85% of Brazil's total deforestation (INPE, 2008). The state of Mato Grosso, which is the center of Amazon soybean agriculture (Jasinski *et al.*, 2005), accounted for 87% of the Amazon's cropland expansion and 40% of new deforestation from 2001 to 2004 (Fearnside, 2005; Morton *et al.*, 2006). Land for expanded soybean production comes from two main sources: (1) the displacement of cattle ranching (Kirby *et al.*, 2006; Nepstad *et al.*, 2008), and (2) the direct conversion of forest to cropland. Morton *et al.* (2006) estimated that during

2001–2004 between 4,670 and 5,463 km^2 of new cropland in Mato Grosso were derived from new forest clearing and 5,930 km^2 were derived from conversion of existing pastures.

Land-use changes in Amazonia have the potential to alter the hydrologic properties of soils (Biggs *et al.*, 2006; Chaves *et al,* 2008; Costa, 2005; De Moraes *et al.*, 2006; Neill *et al.*, 2006; Zimmermann *et al.,* 2006). Infiltrability and hydraulic conductivity are sensitive to disturbances (Alegre and Cassel, 1996; Schoenholtz *et al.*, 2000) and are key soil properties because they determine the activation of surface and near-surface flowpaths that influence runoff generation (Elsenbeer, 2001; Elsenbeer and Lack, 1996). Runoff generation is controlled by the interaction of rainfall characteristics, vegetation, topography and soil physical properties (Dunne, 1978). Depending on these variables, runoff can follow either predominantly vertical flowpaths or predominantly lateral flowpaths. Lateral flowpaths include sub-surface storm flow (SSF), return flow, Hortonian overland flow (HOF), and saturation overland flow (SOF) (Elsenbeer, 2001). The mechanisms of storm flow generation have important consequences for the generation of erosion (Bonell and Bruijnzeel, 2005; Bruijnzeel, 2004; Nortcliff *et al.*, 1990; Ross *et al.*, 1990) and for solute transport because near-surface flowpaths can increase the stream water concentration of biogenic solutes (e.g., Elsenbeer and Lack, 1996; Germer *et al.*, 2009; Johnson *et al.*, 2006; Neill *et al.*, 2006).

Most of our current knowledge of how Amazon land-use change influences soil hydrology and runoff generation comes from examining the effects of clearing forest for pasture production. The replacement of old-growth forest by pasture affects the hydrology of watersheds by increasing soil compaction, which in turn reduces infiltrability and hydraulic conductivity at shallow depths and shifts flowpaths from predominantly vertical towards lateral (Biggs *et al.*, 2006; Chaves *et al.*, 2008; De Moraes *et al.*, 2006; Zimmermann *et al.*, 2006). These changes have been shown to result in a longer duration and greater volumes of storm flow and greater total runoff (Germer *et al.*, 2009; Trancoso, 2006). No study has examined how the current land-use transformations associated with soybean expansion influence soil hydraulic properties and runoff generation.

The objectives of our study were: (1) to compare infiltrability and saturated hydraulic conductivity (hereafter “Ksat”) among forest, pasture, and soybean cropland including their specific changes in soil conductivity with depth, and (2) to assess the potential implications of land-use change for runoff generation by comparing these soil properties with prevailing rainfall intensities.

2 Methods

2.1 Study area

This study was conducted at Tanguro Ranch (12°59´S, 52°23´W, 370 m asl) in the municipalities of Canarana and Querência in Mato Grosso in central Brazil (Fig. 1). Tanguro Ranch is situated in the watershed of the Xingu River, one of the major southern tributaries of the Amazon River. Tanguro Ranch is bordered by the Tanguro River in the west and the Darro River in the east, and covers 80,000 ha.

The climate at Tanguro is humid tropical with a rainy season from October to April and a severe dry season from May to September. This climate corresponds to Köppen’s Aw (Kottek *et al.*, 2006). Mean annual precipitation averaged 1890 mm in a 21-year period from 1987 to 2007 (Grupo A. Maggi, unpublished data). The annual precipitation shows a unimodal pattern with a maximum between January and February. Precipitation within the dry season averages less than 100 mm. Mean annual temperature is 25 °C.

Tanguro Ranch lies on the Brazilian Shield on Tertiary and Quaternary fluvial deposits, which cover Precambrian gneisses of the Xingu Complex (Projeto Radambrasil, 1981). Wide interfluves sloping gently to the waterways form the undulating landscape devoid of pronounced topography. The dominant soils on the broad plateaus are Oxisols (Haplustox / Latossolo vermelho-amarelo distrófico) with a sandy clay texture (mean soil texture of 55 % sand, 2 % silt, and 43 % clay) (Oliviera *et al.*, 1992; Projeto Radambrasil, 1981; Soil Survey Staff, 1999). The pH of the soils determined as mean pH-water (± SE) and mean pH-KCl (± SE) range between 4.7 (± 0.24) and 3.9 (± 0.15) under forest, and 5.9 (± 0.08) and 5.0 (± 0.08) under soybean cropland (M. Figueira and S. Riskin, unpublished data). These soils grade into Gleysols along streams (Projeto Radambrasil, 1981).

Originally the area was completely covered by transitional forest, a vegetation type of evergreen tropical rainforest that represents a transition between the cerradão vegetation to the south and the moist tropical of the central Amazon (Walter, 1979). This forest is characterized by a lower diversity of species, smaller trees, and lower canopy heights than more humid rainforests (Ivanauskas *et al.*, 2004). *Lauraceae* is the dominant tree family of these forests (Balch *et al.*, 2008; Ivanauskas *et al.*, 2004).

Tanguro Ranch has been influenced by agricultural expansion since the early 1980s and consists of a mosaic of old-growth forest, pasture and soybean cropland. Pastures were formed by clearing in 1982 and 1983. Clearing was done by dragging a chain between bulldozers and piling and burning slash. Pastures were planted with

Brachiaria brizantha [(Hochst. ex A. Rich.) Stapf] and *Brachiaria humidicola* [(Rendle) Schweick]. The overall livestock grazing density was approximately one head of cattle per ha. The conversion from pasture to soybeans occurred in 2002 and 2003 and involved: (1) bulldozing pasture vegetation into piles and burning, (2) deep plowing to 50 cm, (3) grading fields to create berms parallel to contour lines, (4) incorporating 1-2 tons/ha lime, (5) replowing to 35 - 40 cm, and (6) shallow disking immediately before planting (Tanguro Ranch, personal communication). New soybean fields were subjected to repeated shallow disking (up to 25 cm) during the first three years after conversion, and were then placed in no-till management (Tanguro Ranch, personal communication). Pearl millet [*Pennisetum glaucum* (L.) R.Br.] was typically planted in November followed by planting of soybeans [*Glycine max.* (L.) Merr] 5 to 6 weeks later (after poisoning millet).

2.2 Sampling design

We selected three areas of intact forest, three areas of pasture and three soybean fields for measurements in the dry season between August and September, 2007 (Fig. 1). All sites were on wide, level interfluves underlain by a Latossolo vermelho-amarelo distrófico (Projeto Radambrasil, 1981). This selection excluded the influence of other, potentially confounding variables such as topography and soil type and allowed us to interpret differences in soil hydraulic properties as a function of land use alone. All areas within the same land use had the same land-use history. The forested areas were undisturbed, old-growth forest. The pasture areas had a history of grazing for 25 years. The soybean areas had been cultivated for four years after 21 years in pasture.

Within each of the nine areas we established one representative 1-ha sampling plot (hereafter “F1” for forest plot 1, “P1” for pasture plot 1, “S1” for soybean plot 1, and so on) (Fig. 1). Within each plot, we selected at random 25 points for measurements of infiltrability and Ksat (summarized as “permeability”).

To minimize the effects of any texture variability, we removed one potential source of texture variability by a sampling design that painstakingly observed the catena principle in the sense that all plots were in precisely the same topographic position, i.e., on interfluves. Furthermore, on each land use we conducted measurements at three replications to capture the effects of variety of soil texture within interfluve positions (Fig. 1). However, to validate the limited variability in soil texture between all sites, we randomly selected 5 (samples A to E) of the 25 measurement points within each plot for collecting soil samples at depths of 0 – 10, 13 – 20, and 30 – 37 cm, the three depths relevant for our study. We estimated soil textural classes manually upon air-drying and sieving.

2.3 Measuring methods

Infiltrability was measured *in situ* with a Hood infiltrometer (UGT, Müncheberg, Germany), which is a special type of a tension infiltrometer (Punzel and Schwärzel, 2007). In contrast to traditional tension infiltrometers, no preparation of the soil surface is required, i.e., no rings have to be driven into the soil surface, and there is no need for a special contact layer. This allows surface properties such as soil crusting, compaction or silting to be measured directly, which may be an important feature in soybean fields and in pastures (e.g., tractor and cattle tracks). The experimental procedure involved (1) placing a circular Plexiglas dome (“hood”, effective infiltration area at soil surface: 242 cm^2), which is connected to a Mariotte device, on the mineral soil surface (litter layer removed), (2) establishing a constant head inside, whose positive pressure potential can be compensated for or adjusted to zero total head by applying a vacuum that is controlled by the Mariotte device, and (3) calculating the infiltrability directly from the steady-state flow, which is reached, when the infiltration rate remains the same for three consecutive time intervals (Punzel and Schwärzel, 2004, 2007; Wooding, 1968).

We measured field-saturated hydraulic conductivity, Ksat, with an Amoozemeter (Ksat Inc., Raleigh), a compact constant head well permeameter designed by Amoozegar (1989a) for in situ measurements above the water table. The procedure involved (1) augering a borehole of radius r (r = 2 cm at 12.5 cm depth and r = 2.5 cm at 30 cm depth), (2) establishing a constant water head H in the hole in order to fulfill the requirement $H/r \geq 5$, and (3) calculating Ksat from the steady-state infiltration rate using the Glover equation (Amoozegar, 1989b). We measured Ksat at 12.5 and 30 cm (“Ksat12.5” and “Ksat30”). The 12.5-cm depth was the shallowest at which Ksat could be measured with our instrumental setup and was a depth known to be affected by cattle trampling (Godsey and Elsenbeer, 2002; Zimmermann *et al.*, 2006). The 30 cm depth was below the shallow disking (up to 25 cm) conducted at Tanguro Ranch during the first three years after conversion but not below the one-time deep plowing (to 50 cm) that followed the conversion from pasture.

Rainfall was determined at two sites (marked as MS in Fig. 1) for a three-year period from 2004 to 2007 with a tipping bucket rain gauge (Rain-Wise Inc., Bar Harbor, ME, USA) and a Campbell 10X data logger (resolution of 0.254 mm).

2.4 Data analysis

In line with our objectives we first compared infiltrability and Ksat data among the three land-use types. Second, we compared these soil hydraulic properties with selected rainfall intensities to determine which land-use type has the potential to generate storm-related “fast” lateral runoff.

For comparisons among land uses, raw and transformed data were tested for normal distribution by applying the Shapiro-Wilk statistic (Shapiro and Wilk, 1965) and for homogeneity of variances by applying the Fligner-Killeen test statistic (Conover *et al.*, 1981). Statistical tests were performed for a significance level of $\alpha = 0.05$. Because all data sets or their possible transformed pendants did not fulfill the requirements for parametric statistics, we analyzed the raw data by application of the non-parametric Kruskal-Wallis rank sum test (Hollander and Wolfe, 1973). If that test detected significant differences in population medians, a Kruskal-Wallis post-hoc test was also performed. The basic idea of this post-hoc test was to conduct a pairwise Mann-Whitney U-test (Bauer, 1972) and then compare the U value to a critical value, U_{crit}, based upon the studentized range, q (Copenhaver and Holland, 1988), which is commonly used in 'regular' post-hoc analyses, e.g., Tukey’s honestly significant difference (HSD) (Crawley, 2002). The critical U value was calculated by the following formula:

$U_{crit} = n^2/2 + q\ n\ [(2n+1)/24]^{1/2}$,

where n is the uniform sample size of each data set. A U-test carries out two values according to the following equation:

$U_1 + U_2 = n^2$,

where U_1 and U_2 are the two possible U values. If the larger one was greater than the calculated critical value, the pairwise comparison was significant (Sokal and Rohlf, 1995). To summarize the results of the Kruskal-Wallis post-hoc analysis, we developed rankings to present the data sets with respect to their medians. For all rankings, there are no significant differences among the members of a group set in parentheses but among these groups.

For tropical regions, several techniques were developed to decide whether or not the observed precipitation patterns can be classified as high-amount or high-intensity rainfall events (hereafter “storms”). We used an approach of Wischmeier and Smith (1978) as modified by Ziegler *et al.* (2004) and selected events according to the following criteria: (1) a storm was a rainfall event accumulating at least 12.7 mm with any rain-free period up to 4 h, or up to 6 h in the case that more than half of the total rainfall occurred following the gap, or (2) a storm was a rainfall event having at least 6.4 mm within any 15-min period. The detailed record of precipitation from both tipping bucket rain gauges was used to calculate the maximum 5-, 10-, 15-, 30-, and 60-min rainfall intensities (MaxI5, MaxI10, MaxI15, MaxI30, and MaxI60) for each storm. Because the calculated values did not differ significantly between both meteorological stations, we pooled these data sets for further statistical analysis.

The possible effects for the hydrological flowpath regime were inferred from the comparison of the medians of infiltrability and Ksat with the medians and other quantiles of maximum rainfall intensities. To specify the findings of the box plot representation, we plotted cumulative distribution functions of permeability data and maximum rain intensities and interpreted them with regard to potential implications for runoff generation.

We used the language and environment of R, version 2.6.1 (R Development Core Team, 2007) for all data analysis.

3 Results

3.1 Infiltrability and Ksat

Infiltrability was highest in the forest, lower in soybean fields and lowest in pasture (Fig. 2, panel A). The within-land-use variability was small, whereas the variability caused by different land-use types was much greater. Among plots, infiltrability ranked: {F2, F1, F3} > {S3, S1, S2} > {P3, P2, P1} showing that there were no significant differences in infiltrability of plots within land uses. The significant differences in infiltrability among land uses were: {forest} > {soybeans} > {pasture}.

Ksat12.5 was higher in the forest than in soybean fields or pasture (Fig. 2, panel B). As with the surface data, the within-land-use variability among the forest plots was small. This was not true for pasture and, in particular, soybeans. For example, median Ksat for S1 was 200 mm/h in contrast to S3 with a median Ksat of only 62 mm/h, which was the second lowest median after P2 with 57 mm/h. Significant differences within the same land use existed between P1 and P2, and S1 and S3, as well as between different land uses for P2 and S1, and P1 and S3, but these differences were small compared with the differences between the land use forest and the other land uses. Among plots, Ksat12.5 ranked: {F1, F2, F3} > {S1, P1} > {S3, P2}, with P3 and S2 indistinguishable from the last two groups (i.e., P3 and S2 are also similar). The significant differences in Ksat12.5 among land uses were: {forest} > {soybeans, pasture}.

Ksat30 was more variable than Ksat12.5 and showed smaller differences among land uses (Fig. 2, panel C). Ksat30 was highest in the forest and most of the cultivated areas had three- to four-fold smaller medians. All soybean fields had lower Ksat30 than forest (all differences were significant except for F2 and S1). The lowest values of Ksat30 were measured at S2 and at S3, resulting in medians of 50 and 73 mm/h, respectively. One pasture plot had Ksat30 comparable to the forest. Among plots, Ksat30 ranked: {F1, F2, P1} > {P3, P2} > {S2}, with the other plots overlapping with two of these groups. According to the Kruskal-Wallis post-hoc test the significant differences in Ksat30 were: {forest} > {pasture} > {soybeans} although the difference between pasture and soybeans was comparatively small.

3.2 Trends in permeability with depth

In the forest, permeability decreased sharply with increasing depth (Fig. 3). Significant differences were found both for all individual plots except F3 between the 12.5 and 30 cm depths and for the pooled data sets. From one depth to the next, median permeability decreased roughly by half. In pasture, permeability did not change significantly with depth both for the individual and the pooled data sets. Under soybean, an even more abrupt reduction than in the forest occurred between the soil surface and 12.5 cm, but not between 12.5 and 30 cm depth. Nonetheless, the decrease in the upper depth interval was still within one order of magnitude.

3.3 Soil texture

Texture of all soil samples from the study plots were estimated as either sandy clay or sandy clay loam (Table 1). Half of the forest samples and one third of the pasture and soybean samples were classified as sandy clay. Therefore, clay content tended to be slightly higher in forest than in pasture or soybeans. Clay content decreased slightly with depth in all land uses.

3.4 Storm characteristics

One hundred and fifty-three rainfall events recorded from September 2004 to August 2007 were classified as storms (Fig. 4). Although this equaled 28% of the total number of all rainfall events, these storms accumulated about 80% of the mean annual precipitation. The percentage of rain that fell within storms varied little over the year. The months November to March contained 7-10 storms each. Thus, more than 80% of all storms occurred within this central part of the rainy season. Monthly averaged maximum rain intensities were highest at the start of the rainy season in October and decreased slightly until the end of this season in April.

4 Discussion

4.1 Effect of land use on infiltrability and Ksat

As a consequence of land-use change, permeability decreased from old-growth forest to cultivated land. These effects were most pronounced at the surface, where infiltrability ranked clearly {forest} > {soybeans} > {pasture}, and at 12.5 cm depth, where an overall difference was found between forest and cultivated land (Fig. 2, panels A, B). Conversion of former pasture to soybeans was associated with a roughly four-fold increase in infiltrability, though not to the high infiltrability found in the original forest. This "recovery" in infiltrability occurred over four seasons of cultivation. At Tanguro, new soybean fields were subjected to repeated shallow disking (up to 25 cm) during the first three years after conversion, which may have enhanced infiltrability. After three years, soybean fields were placed in no-till management (Tanguro Ranch, personal communication). The effects of longer-term no-till management on infiltrability were not investigated because soybean cultivation in this region of Mato Grosso and the entire Amazon is still new.

With increasing depth, the differences in Ksat became weaker and more variable, but were still existent at 30 cm depth. Soybeans and pasture included significant differences between plots. Consequently, the representation as land uses in Fig. 2 (panel C) should be understood as indicating trends rather than statistically firm differences. Relating this higher within-land-use variability of Ksat we assume that, with increasing soil depth, factors such as biological activity (e.g., ants, termites) become more important than the influence of land use (Sobieraj *et al.*, 2002).

The depth-dependent anisotropy under native vegetation (Fig. 3) was similar to that found in several other studies of the humid tropics (Elsenbeer *et al.*, 1992; Godsey *et al.*, 2004; Godsey and Elsenbeer, 2002; Malmer, 1996; Zimmermann *et al.*, 2006). Our finding contrasts with the results of one study conducted on a forested Oxisol (Soil Survey Staff, 1999) near Juruena in Mato Grosso, in which Johnson *et al.* (2006) observed an increase in Ksat with depth. The shape of the permeability-depth function for pasture differed substantially from the one for the forest. Although Ksat30 of pasture was still lower than forest, the difference in permeability and therefore the effect of land use diminished with increasing depth.

This supports the often-observed phenomenon that the effect of cattle trampling is strongly depth-limited (Godsey and Elsenbeer, 2002; Zimmermann *et al.*, 2006). In contrast, the respective depth functions for soybeans and forest were similar. The further decrease in Ksat at 30 cm depth after conversion of former pasture to soybean fields (despite the one-time deep plowing up to 50 cm included in the conversion process) might indicate the development of a compacted layer due to the use of heavy machinery for soybean cultivation. This also suggests that, while cattle pasture causes compaction concentrated at the soil surface, soybean cultivation may have a stronger potential to cause subsoil compaction. Thus, the soil depths at which changes to hydraulic conductivity occur may depend on the source of compaction (cattle trampling vs. heavy machinery).

The infiltrability and Ksat values we obtained in the forest were in the upper spectrum of reported values for tropical forests (Table 2). Zimmermann *et al.* (2006) working on a Kandiudult (Soil Survey Staff, 1999) in the southwestern Amazon state of Rondônia reported the highest infiltrability under forest in sharp contrast to cattle pasture (1690 vs. 113 mm/h). This forest-pasture difference was also detected for an Oxisol (Haplustox) in the eastern Amazon state of Pará (De Moraes *et al.*, 2006). In sub-humid West Africa, Giertz and Diekkrüger (2003) measured lower infiltrability on a Plinthosol (plinthitic crust about 40 cm deep) cultivated with beans compared with forest, though their value of infiltrability of 42 mm/h for bean fields was about one order of magnitude lower than ours for soybeans. In analogy to these studies, our results certainly confirm the often-reported behavior that permeability (in particular, infiltrability) decreases when land-use intensity increases. In this context, the role of soybeans requires clarification, which in turn requires resorting to other areas in the absence of pertinent data from Amazonia. Roth *et al.* (1987), working on an Oxisol in

Paraná (Brazil) under a soybean-wheat rotation, found infiltrability values of about 54 mm/h. Both the infiltrability and Ksat that we measured in soybean fields were higher than most other measurements from the sub-humid tropics (Hati *et al.*, 2007) and temperate regions (Anderson *et al.*, 2005; Bathke *et al.*, 1992; Fesha *et al.*, 2002; Jiang *et al.*, 2006; Rachman *et al.*, 2004). This was consistent with the high infiltrability and high Ksat in the forest at Tanguro compared with other tropical forests.

4.2 Effect of soil texture on permeability

The variability of soil texture within plots and between land uses at Tanguro Ranch was low. This was further confirmed by subsequent analysis of soil texture across a larger number of randomly-selected forest and soybean plots that spanned the entire 80,000 ha Tanguro Ranch (Table 3). This survey showed no significant difference between areas in soybean cropland and those in remaining forest and indicates that the differences in permeability we found were caused by land use and not pre-existing differences in texture at the study sites.

4.3 Permeabilities vs. storm intensities – expected runoff mechanisms

The interaction between soil physical properties, topography, land cover and the rainfall regime plays the decisive role for storm-related response pattern. Moreover, it controls which flowpaths are activated during rainfall events (Elsenbeer, 2001; Godsey *et al.*, 2004). We observed rainfall intensities with maximum values at the beginning of the rainy season in October and decreasing trend after that. Similar patterns have been observed in Paraná (Mondardo *et al.*, 1979) and Rondônia (Scheffler and Porada, unpublished data, 2006).

Rain intensities never exceeded the estimated infiltrability in forest and soybeans (Fig. 5, panel A) and ruled out Hortonian overland flow (HOF) as relevant runoff generating process. In pasture, median infiltrability was exceeded by 5% of all storms for at least one 5-min interval. This indicates that ponding, and therefore HOF, may occur occasionally in some places in pasture. The lack of connectivity with stream channels restricts this to occasional occurrences of short-lived flow largely along cattle tracks (Elsenbeer *et al.*, 1999).

Depending on surface characteristics and storm features (most notably intensity, amount and frequency) the Ksat of the sub-surface soil increments determines at which depth a perched water table, and hence, lateral flowpaths may develop, leading in turn to sub-surface storm flow (SSF) or, in case of saturation up to the soil surface, saturation overland flow (SOF) (Bonell and Gilmour, 1980; Bonell *et al.*, 1991).

Rain intensities never exceeded the estimated Ksat at any depth in the forest plots (Fig. 5, panels B, C). Thus, our results indicated a total dominance of vertical flowpaths in forest over the whole investigated depth interval. This behavior agrees with other studies on Oxisols in the Amazon region, which pointed out the dominance of vertical drainage in undisturbed forested areas (e.g., Nortcliff and Thornes, 1989; Williams and Melack, 1997).

In pasture, Ksat12.5 was exceeded by MaxI5 of 5% of all storms (Fig. 5, panel B), the same percentage as at the soil surface. Because permeability did not change within the upper soil increment but slightly increased to 30 cm depth (Fig. 3), we expect rather HOF than SSF but only within the strongest 5% of storms. Hence, for pasture we expect clearly vertical dominated drainage and a very limited lateral flow component mainly as HOF. This behavior is consistent with reports from other lowland Amazon sites, where land-use conversion from forest to pasture led to the generation of or increase in overland flow, though often to much more pronounced effects. Chaves *et al.* (2008) highlighted the importance of overland flow following forest-to-pasture conversion given a 20-fold increase in stream flow from a pasture on a Kandiudult in central Rondônia, though the mechanism responsible for this increase was saturation overland flow (Germer *et al.*, 2010). Another study in Rondônia (Biggs *et al.*, 2006) found that HOF generation accounted for 8% of annual rainfall and represented a significant flowpath from mature pasture systems on Ultisols. The lesser importance of overland flow in the Tanguro pastures compared with these other studies is consistent with the higher infiltrability and Ksat of the soils of the original forest.

Under soybean, the situation differed slightly. Permeability decreased persistently from the surface to 30 cm (Fig. 3). Consequently, not the soil properties at surface or near surface are most important for the flowpath patterns, as it was in pasture, but the subsoil characteristics, e.g., the occurrence of an impeding layer. MaxI5 of only 4% of the storms exceeded Ksat12.5 but the MaxI5 of 17% of storms and the MaxI15 of 6% of all storms exceeded Ksat30 (Fig. 5, panels B, C). This indicated that for these stronger storms soybean fields formed perched water tables at 30 cm depth and generated SSF, though, variations in the impeding behavior of the horizon and the absence of slope may partially avoid this flow. For all the other storms (as well as the times with lower intensities) vertical flowpaths under soybeans were expected.

To evaluate the probability of the generation of SOF we specifically analyzed the plots that showed the lowest Ksat. For these plots, Fig. 6 illustrates the comparison of median Ksat and rain intensities and allows fast referencing of the mean number of storms per year that exceeded Ksat. In the case of S2 (lowest Ksat), the level of median Ksat30 (50 mm/h) was exceeded by MaxI15 of 15 storms, by MaxI30 of 6 storms, and by MaxI60 of less than 1 storm per year. Maximum possible amounts during 15, 30, and 60 minutes were 29.5, 47.3 and 61.5 mm, respectively. This indicates that the cultivation of soybeans on former pastures has the potential occasionally to activate lateral flowpaths. However, the available water retention of the soil (total pore space in 20 cm depth under S2 was 43.5 %, F. Bäse *et al.*, unpublished data, 2008) and the relatively short duration of high-intensity rainfall during storms suggest that the generation of relevant SOF is unlikely even in circumstances of sufficient rainfall duration and antecedent soil moisture. Bearing in mind that S2 was the most extreme case, this finding can likely be generalized to both land uses – pasture and soybean.

Whereas our expectations of runoff mechanisms on pasture and soybeans differ somewhat from those under forest, the differences between the two land uses are less obvious. Our results still suggest that the cultivation of soybeans on former pastures has the potential to activate lateral flowpaths more frequently.

Conversion of pastures to soybean fields represents a common land-use transition in the area of rapid Amazon soybean expansion in Mato Grosso. Morton *et al*. (2006) reported that pasture conversion to soybeans during 2001–2004 was nearly 6,000 km^2 and exceeded forest cleared for new cropland. We measured the response of soil infiltrability and Ksat to land use change on one large farm that was representative of soils and topography of the area of the southern Brazilian Shield, where rapid soybean expansion is occurring. However, this is only one location with a particular history of land use, pasture management and land-conversion methodology. In addition, soybean cultivation at Tanguro Ranch at the time of this study had occurred for only four years. We currently know relatively little about how permeability differs with different past land-use and land-management history and how permeability changes with time under typical no-till soybean management. We also made measurements during the fallow period in the cropping cycle.

5 Conclusions and outlook

We studied soil hydraulic responses to land-use change by measuring infiltrability and Ksat in an Oxisol landscape in Mato Grosso, Brazil. Cattle grazing reduced infiltrability by an order of magnitude relative to forest. Infiltrability, however, increased four-fold four years after converting pasture to soybean fields, which we attribute to shallow disking. Permeability at the 12.5-cm depth was also considerably lower under pasture and soybeans than under forest, but the impact of land use diminished with depth. The lowest permeability was found at the 30-cm depth under soybeans, which we tentatively attribute to the heavy machinery used in soybean cultivation.

Impressive as these decreases in infiltrability and Ksat may sound, their hydrological consequences are minor because of the respective high base rates. The predominantly vertical nature of hydrological flowpaths did not change with changes in land use, even though localized ponding and short-range overland flow may occur occasionally on pastures, and localized perched water tables may be generated occasionally under soybeans. Thus, our results reveal a soilscape well-buffered with respect to near-surface hydrology in this part of Amazonia and underpin the findings of Hayhoe *et al.* (2011) that the conversion to soybeans did not affect stormflow dynamics.

Nonetheless, one should refrain from any generalizations regarding the hydrological effects of soybean cultivation. We do not know (1) whether other soilscapes are equally well-buffered (but we suspect that Ultisol landscapes are not), (2) how permeability evolves with time under typical no-till soybean management, and (3) if the impeding layer at 30 cm is typical or not. Further studies should focus on the impacts of long-term soybean cultivation across a range of land-use histories and soil characteristics and on the short-term behavior of infiltrability and Ksat during individual cultivation periods. These will help to identify where and if reductions in soil infiltrability and Ksat are likely to be concerns for managing surface runoff from expanding soybean cropping in Amazonia.

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Tables

Table 1 Field determination of soil textural classes.

Sample	Depth [cm]	F1	F2	F3	P1	P2	P3	S1	S2	S3
A	0 - 10	**sC**	**sC**	sCL	sCL	**sC**	**sC**	sCL	**sC**	**sC**
	13 - 20	**sC**	**sC**	sCL	sCL	**sC**	sCL	sCL	**sC**	**sC**
	30 - 37	sCL	**sC**	sCL	sCL	**sC**	sCL	sCL	sCL	sCL
B	0 - 10	**sC**	sCL	**sC**	sCL	**sC**	sCL	**sC**	**sC**	sCL
	13 - 20	sCL	**sC**	sCL	sCL	**sC**	sCL	sCL	**sC**	sCL
	30 - 37	**sC**	sCL	sCL	sCL	sCL	sCL	sCL	sCL	sCL
C	0 - 10	sCL	**sC**	sCL	sCL	**sC**	sCL	sCL	**sC**	**sC**
	13 - 20	sCL	**sC**	**sC**	sCL	**sC**	sCL	**sC**	sCL	**sC**
	30 - 37	sCL	**sC**	sCL	sCL	sCL	sCL	sCL	sCL	sCL
D	0 - 10	**sC**	**sC**	sCL	**sC**	**sC**	sCL	sCL	**sC**	**sC**
	13 - 20	**sC**	**sC**	sCL	sCL	**sC**	sCL	sCL	sCL	**sC**
	30 - 37	**sC**	**sC**	sCL	sCL	sCL	sCL	sCL	sCL	sCL
E	0 - 10	**sC**	sCL	**sC**	sCL	**sC**	**sC**	sCL	**sC**	**sC**
	13 - 20	sCL	**sC**	sCL	sCL	**sC**	**sC**	**sC**	sCL	sCL
	30 - 37	sCL	**sC**	sCL	sCL	sCL	sCL	sCL	sCL	sCL

sC: sandy clay; sCL: sandy clay loam

Table 2 Infiltrability and Ksat for selected land uses in this and 10 other studies in various tropical and temperate regions.

Reference	Region, soil type (as given)	Land use	Infiltrability [mm/h]	Ksat [mm/h]	Depth [cm]	Method
Present study	Mato Grosso/Brazil, Haplustox	F	1258	563 , 320	0, 12.5, 30	HI, Am
		S	469	114 , 80	0, 12.5, 30	
		P	100	100 , 122	0, 12.5, 30	
Anderson *et al.*, 2005	Missouri/USA, Vertic Albaqaulf	S*	10	-	0	SIR
Bathke *et al.*, 1992	S. Carolina/USA, Paleudult[a]	S	-	8	5-12	CHM
Fesha *et al.*, 2002	Alabama/USA, Typic Hapludult	S*	-	47	0-15	Borehole
		P	-	12	0-15	
Giertz & Diekkrüger, 2003	Benin (West Afrika), Plinthosol	F	108	-	0	HI, CHM
		B	42	32	0, 2-15	
Jiang *et al.*, 2006	Missouri/USA, Epiaqualf	S*	-	36	0-10	CHM
Hati *et al.*, 2007	Central India, Typic Haplustert	S*	-	26	0-15	CHM
De Moraes *et al.*, 2006	Pará/Brazil, Haplustox[a]	F	-	230 , 17	≈0, 20-30	Guelph
		P	-	4 , 5	≈0, 20-50	

Rachman *et al.*, 2004	Iowa/USA, Typic Hapludoll	S*	-	115	0-10	CHM
Roth *et al.*, 1987	Paraná/Brazil, Typic Haplorthox	S*	54	-	0	I = Rf - Ro
Zimmermann *et al.*, 2006	Rondônia/Brazil, Kandiudult	F	1690	131, 22	0, 12.5, 20	HI, Am
		P	113	22, 6	0, 12.5, 20	

F: Forest; S: Soybeans; P: Pasture; B: Beans; Am: Amoozemeter; Guelph: Guelph permeameter; HI: Hood infiltrometer; CHM: Constant head method on undisturbed soil samples; Borehole: Borehole method; SIR: Single infiltration rings; I = Rf - Ro: Infiltrability calculated as rainfall minus runoff (rainfall simulator and overland flow protectors).

[a] Plinthic; * Soybean rotations mostly wheat or corn

Table 3 Mean soil texture under forest and soybean fields at Tanguro Ranch (unpublished data from M. Figueira and S. Riskin).

Land use	Sample size (N)	Mean clay content (± SE) [%]	Mean sand content (± SE) [%]
Forest	7	38.2 (± 3.9)	59.3 (± 3.9)
Soybeans*	28	39.6 (± 2.3)	58.4 (± 2.4)

* This land use includes sites, which were pastures at the time of our field campaign but were converted to soybeans shortly after.

Figure captions

Figure 1 Location of the study area.

Tanguro Ranch is 80,000 ha and contains a mosaic of old-growth forest, pasture and soybean cropland. Situation in August, 2007.

Figure 2 Permeability of all plots (left) and as a function of land use (right) at surface (A), at 12.5 cm (B), and 30 cm (C).

The x- axis labels refer to the 9 individual plots (left) and the 3 land uses (right). Non-overlapping notches of box plots indicate a significant difference between 2 medians (at 95% confidence level). MaxI5 / MaxI15 are medians of the maximum 5-/15-min rain intensities (57.9 and 39.6 mm/h).

Figure 3 Permeability as a function of depth under forest, pasture and soybeans.

Symbols mark the positions for medians of plots and lines connect positions for medians of land uses.

Figure 4 Rainfall pattern throughout the year.

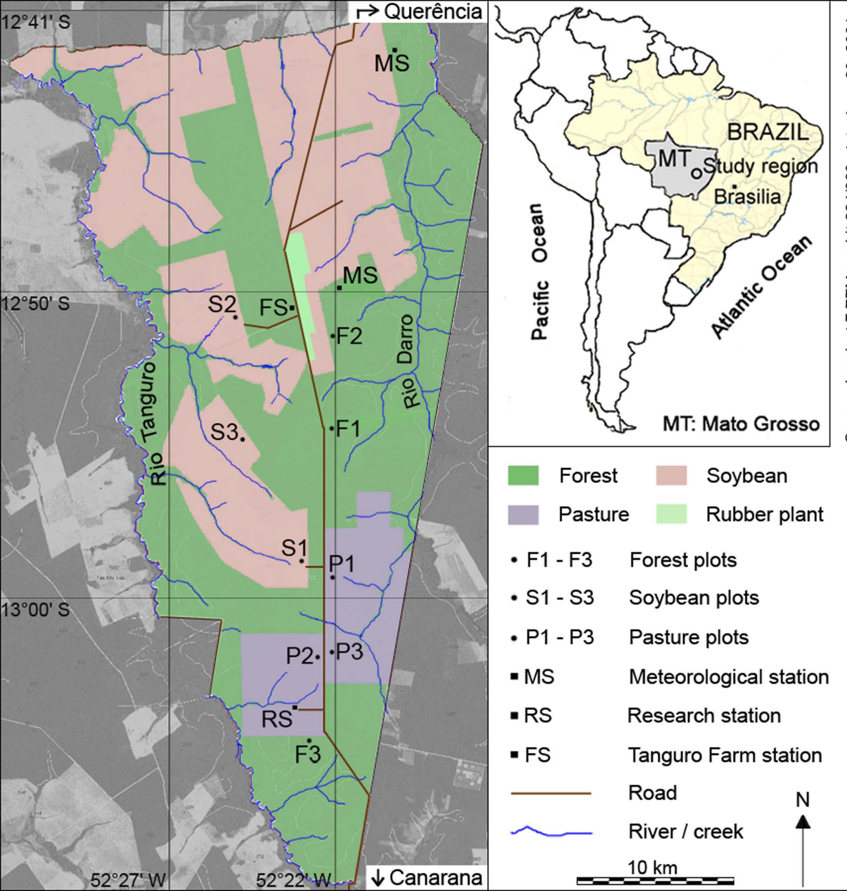
Monthly means visualize the amount of precipitation fallen within all measured rain events and the amount not fallen within the storms (indicated by the ⊥ -bar), the number of storms (on top of the bars), and selected maximum rain intensities. Highest intensities occurred at the start of the rainy season.

Figure 5 Cumulative distribution functions for permeability of land uses vs. the maximum 5-min rain intensity at surface (A), at 12.5 cm (B), and 30 cm (C).

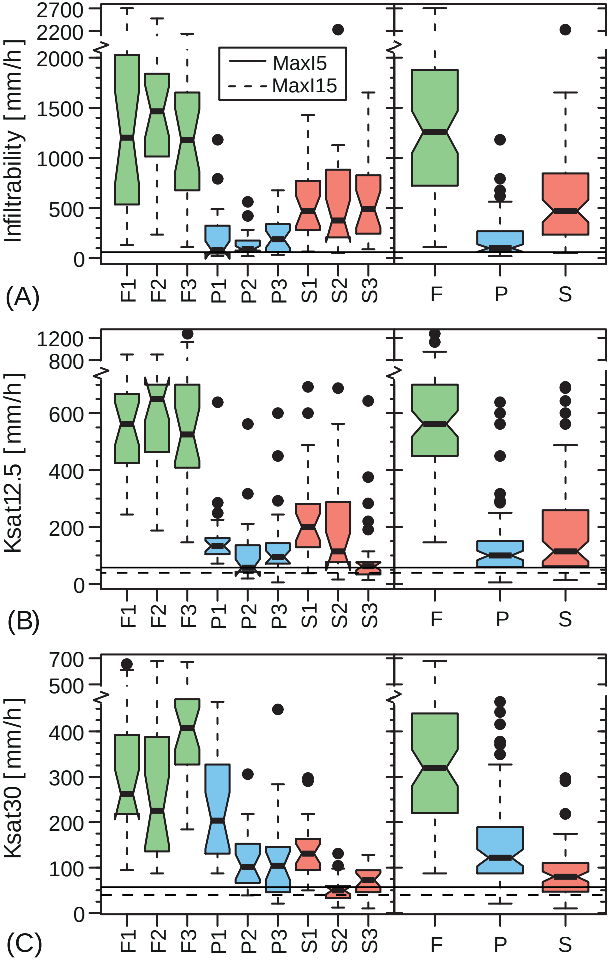
Vertical lines mark quantiles of MaxI5, which have a return interval of about 26, 13, and 5 times per year. The upper parts of all distribution functions were omitted.

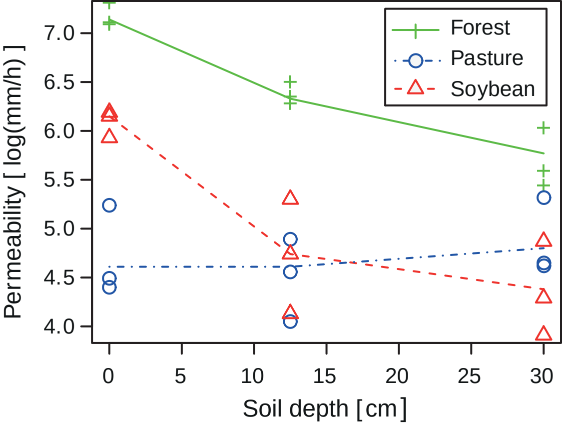
Figure 6 Cumulative distribution functions of maximum rain intensities in comparison with the lowest medians Ksat.

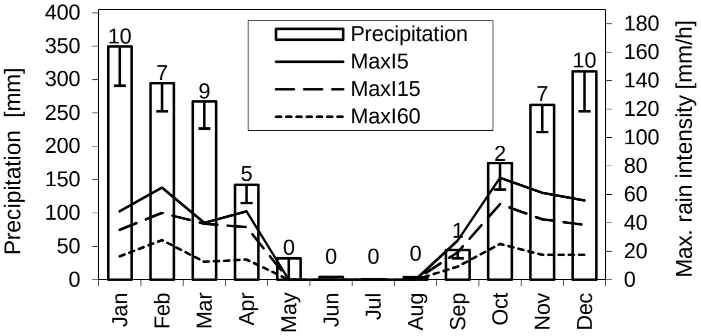
The labels on the distribution functions indicate the maximum rain intensities: “5” for MaxI5 to “60” for MaxI60. The graphic allows direct referencing of the mean number of storms per year exceeding Ksat, e.g., Ksat30 of S2 got exceeded by MaxI5 of about 32 storms per year (i.e., every 7 days on average within the rainy season).

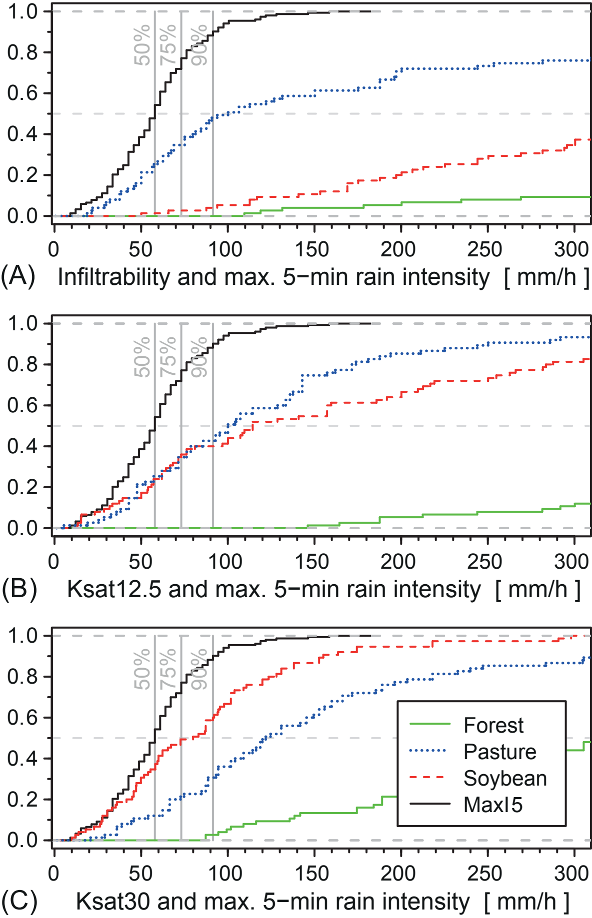


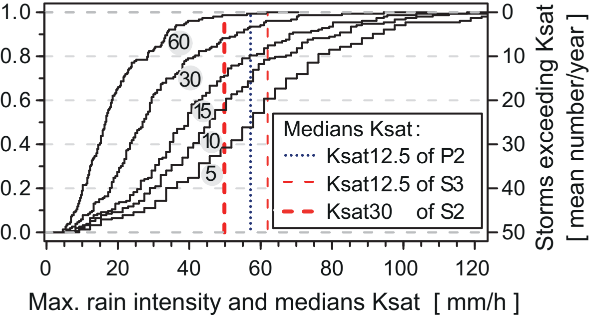
Source: Landsat 7 ETM+, orbit 224/069, date June 23, 2001


Infiltrability [mm/h]
2700
2200
2000
1500
1000
500
0
MaxI5
MaxI15
F1
F2
F3
P1
P2
P3
S1
S2
S3
F
P
S
(A)
Ksat12.5 [mm/h]
1200
800
600
400
200
0
(B)
Ksat30 [mm/h]
700
500
400
300
200
100
0
(C)


Forest
Pasture
Soybean
Permeability [log(mm/h)]
7.0
6.5
6.0
5.5
5.0
4.5
4.0
0
5
10
15
20
25
30
Soil depth [cm]


Precipitation [mm]
400
350
300
250
200
150
100
50
0
Max. rain intensity [mm/h]
180
160
140
120
100
80
60
40
20
0
Precipitation
MaxI5
MaxI15
MaxI60
10
7
9
5
0
0
0
0
1
2
7
10
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec


1.0
0.8
0.6
0.4
0.2
0.0
50%
75%
90%
0
50
100
150
200
250
300
(A) Infiltrability and max. 5−min rain intensity [mm/h]
1.0
0.8
0.6
0.4
0.2
0.0
50%
75%
90%
0
50
100
150
200
250
300
(B) Ksat12.5 and max. 5−min rain intensity [mm/h]
1.0
0.8
0.6
0.4
0.2
0.0
50%
75%
90%
Forest
Pasture
Soybean
MaxI5
0
50
100
150
200
250
300
(C) Ksat30 and max. 5−min rain intensity [mm/h]


60
30
15
10
5
Medians Ksat:
Ksat12.5 of P2
Ksat12.5 of S3
Ksat30 of S2
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
120
Max. rain intensity and medians Ksat [mm/h]
0
10
20
30
40
50
Storms exceeding Ksat
[mean number/year]