Conversion to soy on the Amazonian agricultural frontier increases streamflow without affecting stormflow dynamics

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Abstract

Large-scale soy agriculture in the southern Brazilian Amazon now rivals deforestation for pasture as the region's predominant form of land use change. Such landscape level change can have substantial consequences for local and regional hydrology, which remain relatively unstudied. We examined how the conversion to soy agriculture influences water balances and stormflows using stream discharge (water yields) and the timing of discharge (stream hydrographs) in small (2.5 to 13.5 km^2) forested and soy headwater watersheds in the Upper Xingu Watershed in the state of Mato Grosso, Brazil. We monitored water yield for one year in three forested and four soy watersheds. Mean daily water yields were approximately four times higher in soy than forested watersheds, and soy watersheds showed greater seasonal variability in discharge. The contribution of stormflows to annual streamflow in all streams was low (< 13% of annual streamflow), and the contribution of stormflow to streamflow did not differ between land uses. If the increases in water yield observed in this study are typical, landscape-scale conversion to soy substantially alters water-balance, potentially altering the regional hydrology over large areas of the southern Amazon.

Introduction

By altering important biotic and abiotic properties like vegetation and the permeability of the ground surface, land use change can affect the hydrologic cycle across multiple scales, from the local to the global. These effects are important components of human-influenced global change, altering water availability, water quality, channel morphology, runoff generation, flood frequency, and even climate (Dunne & Leopold 1978, Millenium Ecosystem Assessment 2005, Foley *et al.* 2005). While the effects of land use change on the hydrologic cycle have been documented for diverse ecosystems across various spatial scales, relatively little is known about the effects of tropical agricultural expansion on hydrology, but it is the tropics where conversion to industrial-scale agriculture and deforestation are currently expanding cropland most rapidly.

In the Brazilian Amazon in particular, the world's largest watershed, the consequences of land use changes for hydrology are not now understood, while new and expanding market forces and technologies are driving rapid agricultural expansion (Morton *et al.* 2006, Nepstad *et al.* 2006, Nepstad *et al.* 2008). Beginning in the 1970s, deforestation in the region was driven predominantly by cattle ranching and government incentive programs encouraging land settlement and development (Fearnside 2001, Laurance et al. 2001, Nepstad et al. 2006). More recently, however, industrial-scale soybean agriculture has been rapidly expanding, replacing cattle ranching in some cases, and extending farming infrastructure and the extent of deforestation deeper into the Legal Amazon (defined as the nine Brazilian states with area in the Amazon Basin) (Fearnside

2001, Nepstad et al. 2006). The area of land under soy cultivation approximately doubled in the last decade, increasing to 21 million ha by 2005, in large part driven by global demand for animal feed (Naylor et al. 2005, Nepstad et al. 2006). Between 2001 and 2004, 87% of this cropland expansion occurred in the Brazilian state of Mato Grosso (Morton et al. 2006). Here we examine the consequences of the conversion to soy on watershed-scale hydrology in Mato Grosso. We assess two important metrics of hydrologic impacts: the amount of water discharged from streams (water yield), and the timing of this discharge in response to rainfall.

As has been shown since pioneering work at a number of temperate experimental forests (Hewlett & Hibbert 1961, Hibbert 1966, Likens *et al.* 1969, Likens *et al.* 1970), the removal of forest cover from a landscape reduces ecosystem evapotranspiration (ET), thereby increasing both daily and annual water yield (Bosch & Hewlett 1982, Hornbeck *et al.* 1993, Sahin & Hall 1996, Brown *et al.* 2005). This pattern is generally true for tropical ecosystems as well, and a review by Bruijnzeel (1990) additionally highlights the importance of both soil characteristics and the methods of forest clearing for the control of water yield in the tropics. Soil compaction following mechanical clearing can lead to lower infiltrability, reducing the vertical movement of water. Reduced vertical flow can reduce groundwater recharge leading to lower dry season (baseflow) water yields (Bruijnzeel 1991, 2004). In this way, the net the response of tropical stream discharge to forest clearing depends on the balance between decreased ET and decreased infiltrability (Bruijnzeel 1991, Aylward 2005).

Changes to infiltrability have also been shown to affect runoff generation and the contribution of stormflow to streamflow following mechanical clearing and development.

This effect is obvious in urbanized watersheds, where increases in impervious ground cover increase lateral water flowpaths like overland flow, creating larger and flashier stormflow (Dunne & Leopold 1978, Arnold & Gibbons 1996, Paul & Meyer 2001) and has likewise been observed following mechanical clearing and agricultural conversion in the tropics and specifically in the Amazon (Bruijnzeel 1991, Zimmermann *et al.* 2006, Germer *et al.* 2010). Contrary to popular belief, however, focusing only on infiltrability as a proxy for increased runoff generation can be misguided: a decrease in infiltrability is not in itself an indicator of hydrological consequences; it is the magnitude of decrease relative to precipitation characteristics that matters (Zimmermann *et al*., 2006).

We compared water yield, hydrograph characteristics, stormflow, and baseflow among seven first-order watersheds on a large soy farm (~800 km^2) in Mato Grosso, Brazil. The area of three of these watersheds was covered by intact primary forest. The area of four others was converted to pasture in the early 1980s and to soy agriculture in either 2004 or 2007. Additionally, we monitored a single first-order watershed draining pasture and a second-order watershed draining soy for comparison. We used these data to address the following questions: Are daily and annual water yields in the soy and pasture higher than in forested watersheds? Is this increase most pronounced during the wet season when streams should be least influenced by groundwater flows? And, is an increased fraction of streamflow contributed by stormflow in soy watersheds following mechanical clearing and industrial-scale agricultural practices?

Methods

Site Description

Tanguro Ranch is an 800 km^2 farm located in Mato Grosso, Brazil near the southeastern edge of the Legal Amazon (Fig. 1), between 52° 23' 30" and 52° 18' 50" W and between 13° 9' 12" and 12° 41' 40" S. The forested areas are closed-canopy (~25 m height) evergreen tropical forests in the ecotone between cerrado to the south and more humid and diverse Amazon forests to the north (Ivanauskas et al. 2004, Balch et al. 2008). Average annual precipitation (MAP) between 1987 and 2007 was 1900 mm·yr^{-1}, and ranged from 1500 to 2500 mm·yr^{-1} (Tanguro Ranch, unpublished data). The dry and wet seasons are pronounced, with heavy rains between September and April and almost no rain (a mean of 2% of MAP) between May and August. Precipitation during the dry period contributed no rainfall during six of these years. Mean annual temperature is 27° C.

The site is underlain by Tertiary and Quaternary fluvial deposits, which cover Precambrian gneisses of the Xingu Complex typical of the Brazilian Shield (Projeto Radambrasil, 1981). Plateaus with little topographic variation dominate most of the landscape with gentle slopes toward stream channels. The soils are generally medium-textured, well-drained ustic Oxisols (Latossolo vermelho-amarelo distrófico, Oliviera *et al.* 1992, Soil Survey Staff 1999) along the topographic plateaus, grading to aquic Inceptisols (Gleysolo) in riparian zones along streams (Projeto Radambrasil, 1981).

We measured stage and discharge in eight first-order watersheds (soy N=4, forest N=3, pasture N=1) and one second-order soy watershed from August 2007 through mid-August 2008, when the last pasture watershed was converted to soy and the stream diverted. Watersheds ranged from 2.51 to 27.5 km^2 (Table 1). All fields were originally cleared for pasture in 1982 and 1983 and conversion to soy in the monitored watersheds took place in 2004 and 2007 (Table 1, Tanguro Ranch, personal communication). This conversion from pasture to soy cropland is common to the region, and this transition occurred over nearly 6,000 km^2 in Mato Grosso between 2001 and 2004 (Morton *et al.* 2006). As part of the farm's pasture legacy, all first-order soy watersheds have small impoundments at the headwaters, originally created as a water source for cattle. These impoundments are representative of small watersheds originally cleared for pasture in this region of the Amazon (Claudia Stickler, unpublished data).

Stream Discharge

Each monitored watershed was instrumented with a staff gauge and a HOBO pressure logger (Onset, Bourne, MA) (Fig. 1). A reference logger recorded ambient air pressure and temperature in the field laboratory. Daily precipitation has been measured at Tanguro Ranch headquarters since 1987. Beginning in 2006, daily rainfall was measured in between 8 and 23 rain gauges in cleared areas of the farm. We were provided monthly mean precipitation data based on these records by the staff at Tanguro Ranch.

We developed stream rating curves based on discharge measurements taken in August 2007, January and early February 2008, August through November 2008, and January through March 2009. We measured flow velocity with a Global Water FP-100 flow meter (Gold River, CA) and calculated instantaneous stream discharge (Q, $liters \cdot sec^{-1}$) from stream cross sections (Gore 2007). We determined rating curves fit to power functions to calculate stream discharge over time based on the cross-section discharge measurements for each stream.

We derived watershed boundaries from vegetation-corrected Shuttle Radar Topography Mission (SRTM) data. Raw SRTM data contains a bias due to vegetation height. This can be problematic in farmland that abuts closed canopy forest, and must be removed before any derivatives are generated (Sun *et al.* 2003, Kellndorfer *et al.* 2004). Using ERDAS 9.3 image processing software, we ran a 100-class unsupervised classification of a Landsat Thematic Mapper (TM) satellite image from June 23, 2001, and then created a binary vegetation mask by grouping the classes into vegetated and cleared categories. In ArcGIS 9.2 we extracted raw SRTM elevation values for pairs of adjacent pixels inside and outside of the edge derived from the binary mask, and calculated the local height difference within each vegetation class. We calculated a mean height bias for each of the original 100 vegetation classes, subtracted this bias from the raw SRTM data and smoothed the result. Finally we derived stream basins from the SRTM using the standard ArcGIS hydrology tools: we determined flow directions and flow accumulations for each SRTM pixel, used this to define stream channels, and delineated the watershed for each stream monitoring point used in the study by identifying all pixels upstream of this point which contributed water to streamflow past this point.

We calculated daily, monthly, and annual water yields for each watershed based on hourly stream discharge data and watershed areas. We analyzed both mean and median water yields normalized by watershed area ($\text{mm}\cdot\text{day}^{-1}$).

Hydrograph Separation

To compare the influence of forest or soy land cover on the proportion of base- and stormflows, we separated all hydrographs into baseflow (background discharge) and stormflow (precipitation driven increases in flow), using a modification of the local-minima method (Sloto & Crouse 1996). This method defines discharge minima over short time intervals (interval, Fig. 2) and defines maxima based on discharges that exceed a threshold based on daily fluctuations (threshold, Fig. 2). The discharge between a maximum and the two closest bounding minima are then defined as discharge responses to precipitation events (the flow between min 1 and min 2, Fig. 2).

Because most discharge peaks observed lasted for less than 24 hours, and because we used an hourly data collection time step, the interval length algorithm defined by Sloto and Crouse (1996) with a minimum of 24 hours, was too large for our method. We chose a 22-hour interval, such that 11 hours before and after each datum was examined. If the datum was the lowest flow value within this interval, it was defined as a minimum. A sensitivity analysis of this 22-hour interval was performed using intervals varying in length between 10 and 46-hours. The percentage of stormflow contributing to total streamflow increased with increasing interval length, but showed an average of <4% change across all watersheds between the minimum and maximum interval lengths tested.

We defined streamflow maxima (stormflows) as 5 multiplied by the standard deviation of 500 hours of baseflow (SD_{500}), a threshold that was effective in capturing peaks that appeared to be associated with stormflows as opposed to daily variations in flow (threshold, Fig. 2). The 500 hours of baseflow was defined for the same time period with no precipitation events across the farm but was generated independently for each watershed. As a sensitivity analysis of this threshold for maxima, we performed the hydrograph separation varying the maxima threshold between SD_{500} and $9*SD_{500}$. Increasing this threshold will exclude increasing numbers of small events while decreasing it may include daily fluctuations in flow as stormflows (max 1 vs. max 2, Fig. 2). The average change to the results of the separation between the maximum and minimum threshold values tested was 5%. We chose $5*SD_{500 \text{ as}}$ the threshold with which to accurately capture precipitation peaks while excluding daily variations in discharge.

Using the defined 22-hour interval and the $5*SD_{500}$ maxima threshold described above, we separated defined precipitation peaks from baseflow by drawing a straight line between two local minima bounding a precipitation maximum (dotted line, Fig. 2). Discharge above this line represented stormflow and the rest baseflow.

We used single factor ANOVA to compare the percentage baseflow by land use (soy N=4, forest N=3) (Matlab 7.5.0). Statistical analyses were performed using the maxima and minima of hydrograph separation parameters examined as part of the sensitivity analysis as well as the chosen parameters. Using the maxima or minima interval and threshold did not change the statistical results of the analyses from those reported here.

Seasonal flow analysis

We examined monthly stream discharge to look at seasonal differences in water yields between forest and soy watersheds. Using a univariate split-plot approach with a repeated measures design, we fit a linear model to our data with the equation:

$$Y_Q = \beta_0 + \beta_1 x_{type} + \beta_2 x_{ppt} + \beta_3 x_{type} \cdot x_{ppt} + \varepsilon \qquad \text{(Eq. 1)}$$

Where Y_Q is the predicted mean daily flow for a particular month, x_{type} is a binomial variable indicating the watershed type as soy or forest, x_{ppt} is precipitation in mm from two months prior to the month of observation, and ε is the associated error term. The interaction term, $x_{type} \cdot x_{ppt}$, is a measure of the land use effect. We used a lagged measure of precipitation inputs based on the relationship between precipitation and flow response. We examined different lags (between 0 and 3 months) to look for the model with the greatest predictive power and chose a lag of two months. The individual effect of each watershed was nested within the land use type parameter and was specified as a random effect, which then was used as the error term in the model (Matlab 7.5.0).

To look at the magnitude of flow changes each month in the two land uses, we calculated a mean flow index (MF index). The MF index was defined as the difference between the mean monthly flow and the mean annual flow for each watershed over the year of observation.

Hydrograph characteristic analyses

To look at differences in the timing and volumes of stormflows between forest and soy, we calculated indices to compare hydrograph characteristics among watersheds. We analyzed skewness in daily flows (SK; SK=mean daily water yield / median daily water yield), and the coefficient of variation for daily flows (CV; CV=standard deviation (SD) of daily water yield / mean daily water yield) (Clausen & Biggs 2000, Olden & Poff 2003). We compared the shape of hydrograph peaks using (1) flow acceleration (FA), defined as: $FA = \Delta Q / \Delta t$ for the rising limb of the peak (between min 1 and max 1, Fig. 2), where Q is discharge measured in liters$\cdot$sec^{-1} and t is time measured in hours (Tetzlaff et al. 2005) and using (2) the receding limb slope (RLS), defined as RLS = log (Δ Q) / Δ t, for the receding limb of each peak (between max 1 and min 2, Fig. 2). Each peak was defined using the same criteria for maxima as described for the hydrograph separation. We compared FA and RLS using varying thresholds (between $5*SD_{500}$ and $20*SD_{500}$) of flow maxima to isolate differences between all storm peaks as well as only large storm peaks (threshold, Fig. 2).

Statistical comparisons between land use types were limited to the seven first-order forest and soy watersheds, and we used single factor ANOVA to compare daily water yield by land use and by season, the hydrograph indices, flow acceleration, and the receding limb slopes (soy N=4, forest N=3) (Matlab 7.5.0). Varying the thresholds of flow maxima did not change the statistical results of the analyses.

Results

Water Yield

Daily water yields were higher in soy than in forest watersheds throughout the monitoring period (Fig. 3, Table 2). The mean daily water yield in forest watersheds for the period of observation was 0.41 $mm \cdot day^{-1}$ (SD=0.43) while in soy watersheds the mean daily water yield was 1.6 $mm \cdot day^{-1}$ (SD=0.70). This difference, an approximately 4-fold increase, was not significant (p=0.054), but showed a strong trend despite the small sample size. Mean daily water yield in second-order soy and pasture was 2.7 $mm \cdot day^{-1}$ (SD=1.0) and 0.49 $mm \cdot day^{-1}$ (SD=0.38), respectively. The median daily water yield was significantly different between the soy (0.40 mm·day^{-1}, SD=0.41) and forested watersheds (1.48 mm·day^{-1}, SD=0.51)(p=0.03; Table 2).

As with daily water yields, the mean annual water yield in the soy watersheds was 580 mm·yr^{-1} (SD=160), approximately 4-times larger than the mean annual water yield in the forest, 150 mm·yr^{-1} (SD=260) (p=0.054). The annual water yield for the second-order soy watershed was 970 mm·yr^{-1} and was 180 mm·yr^{-1} for the pasture watershed (Table 2).

Seasonal Water Yield

Our model based on watershed type and precipitation inputs two months prior to the current month (hereafter "lagged precipitation") showed a significant flow response to both lagged precipitation and the interaction between land use type and precipitation ($R^2 = 0.83$). Water yields increased significantly in both forest and soy watersheds in response to lagged precipitation inputs ($p<0.0001$) and the increases in water yields in response to precipitation were significantly larger in soy than in forest watersheds ($p<0.0001$). The MF Index offers additional evidence of increased response to rainfall in the soy streams and a more stable MF index across the year in forested watersheds (Fig. 4c). Although watersheds in both land uses respond to lagged precipitation inputs, in forested watersheds the largest increase in flow, or the most positive mean MF Index value, occurred in February, the month with the highest rainfall inputs (Fig. 4a,b), while the largest increase in discharge in soy watersheds was not simultaneous with increased rain inputs. Instead, the highest flows occurred in April, two months after the month with the most rain (Fig. 4a,b).

Hydrograph Indices

The hydrographs for all monitored watersheds had similar shapes despite variation in watershed size (Fig. 5). All hydrographs were dominated by baseflow and punctuated by brief and steep stormflow peaks. The hydrographs also demonstrated the spatial and temporal heterogeneity of many rain events, with few streams showing peak flows simultaneously. As expected, the streams closest to each other geographically, the Soy_1 b and Soy_1 c watersheds and the Forest a and Forest b watersheds (Fig. 1), showed more synchronized peaks than other watersheds. The largest storm peaks in all watersheds occurred on February 2, 2008 following a rain event that continued over a series of days across a large geographic area.

The contribution of stormflow to total stream flow was less than 15% in all nine watersheds. There was no significant difference between the first-order soy and forest watersheds (p=0.60), with a mean of 96% (SD=2.5) baseflow in forest watersheds and a mean of 94% (SD=4.6) baseflow in soy watersheds.

The hydrologic indices examining the shape of precipitation peaks were not predictable based on land use type. Neither SK, the skewness in daily flows, nor CV, the coefficient of variation of daily flows, varied significantly between forest and soy watersheds (SK: p=0.74; CV: p=0.81; Table 3). Flow acceleration (FA), the slope of the rising limb of precipitation peaks, varied widely within and among watersheds, but did not vary significantly between soy and forested watersheds (p=0.53) (Fig. 6, Table 3). Receding limb slope (RLS), the semi-log transformed slope of the receding limb of hydrograph peaks was higher in soy watersheds (0.20, SD=0.07) compared to forest watersheds (0.12, SD=0.08), but this trend was not significant (p=0.20).

Discussion

The approximately four-fold increase in discharge from soy compared with forested watersheds was consistent with other studies that show higher water yield following forest clearing (Bosch & Hewlett 1982, Hornbeck *et al.* 1993, Sahin & Hall 1996, Brown *et al.* 2005). As opposed to forested watersheds, soy fields have much lower rates of ET: these fields have vegetation only a few months each year and this vegetation is of much lower stature with shorter roots that limit plants' ability to access stored soil water (Nepstad *et al.* 1994, Canadell *et al.* 1996, von Randow *et al.* 2004).

The soy watersheds showed a larger response to precipitation during the rainy season, and this increase in flow lagged behind precipitation inputs. We hypothesize that, similar to the increase in water yields, these changes are driven by differences in ET. In forest, ET rates may remain relatively constant over time, as vegetation can easily access shallow soil water during the wet season and deep-rooted trees are able to access deep soil water during dry periods (Nepstad *et al.* 1994, Canadell *et al.* 1996, von Randow *et al.* 2004). In the soy, as in previously observed pastures, only shallow soil water above 2 meters is available to plants (von Randow *et al.* 2004) and, in the absence of the crop, no water will be taken up by vegetation leaving a larger volume of water to move through and be exported from the watersheds. During the ~8 months when the fields are not being cultivated there may be increased evaporation but almost no transpiration, and water will instead likely travel vertically through the soil column and reach streams over time.

The soy watersheds also had higher water yields than the pasture watershed. While we are not able to treat these data statistically (only one pasture watershed remained on the property), we had expected ET in pasture to be consistently lower than forest with the greatest difference during the dry season when transpiration is greatly reduced (Maia Alves *et al.* 1999, Sakai *et al.* 2004, von Randow *et al.* 2004). We expected this decrease to be nearly analogous in soy, with the soy and pasture watersheds behaving similarly. These data suggest that it is possible that soy fields, left bare during the dry season, have greater reductions in ET than pasture. Indeed, Sakai *et al.* (2004), monitoring ET over a field as pasture and during the bare soil conversion of pasture to rice cultivation, measured the lowest rates of ET while the field was bare. It appears that the considerable difference between forest and bare fields has a substantial effect on water balance, both for ET and, consequently, stream discharge.

In the forested watersheds, the contribution of stormflow to streamflow at Tanguro Ranch was similar to that observed at other sites in the Amazon with similar soils (Lesack 1993a, b, Leopoldo *et al.* 1995, Bonell 2005). In Central Amazônia, a study at Reserva Ducke near Manaus reported 91% baseflow for a 1.3 km^2 forested catchment (Leopoldo *et al.* 1995), and Lesack (1993a, b) reported 92% of streamflow as baseflow for a 0.23 km^2 forested watershed at Igarape Mote near the Solimoes River.

While the low contribution of stormflow to total streamflow observed in forested watersheds is not unusual for watersheds dominated by vertical flowpaths in the lowland humid tropics (Bruijnzeel 1990, Bonell 2005), we expected an increase in stormflow in response to decreases in soil infiltrability following the mechanical land clearing of both the original forest and of the pasture during the conversion to soy cultivation (Bruijnzeel 1990, 2004, Zimmermann *et al.* 2006, Germer *et al.* 2010). However, <13% of annual streamflow is contributed by stormflow across land uses.

The small fraction of streamflow contributed by stormflow reiterates the point made in the introduction: a decrease in infiltrability, no matter how impressive, has no hydrological consequence if it is not large enough. This is borne out by infiltrability measurements for Tanguro Ranch: the median infiltrability of forest soils (with 95% confidence intervals) is 1258 $\mathrm{mm \cdot hr^{-1}}$ (+/- 247), 469 $\mathrm{mm \cdot hr^{-1}}$ (+/- 130) in soils under soy, and 100 $\mathrm{mm \cdot hr^{-1}}$ (+/- 45) in soils under pasture (Scheffler *et al.* unpublished). While this decrease is substantial, even the heaviest downpours bring less rain than the soil can accommodate, with a median measure for 5-min rainfall intensity of 57.9 $\mathrm{mm \cdot hr^{-1}}$ (Scheffler *et al.* unpublished). We attribute this non-relevant decrease in infiltrability to the structural, i.e., soil-intrinsic, macroporosity (Ringrose-Voase 1991) of this Oxisol, which is more resilient to compaction than non-structural, i.e., biologically-controlled, macroporosity.

It appears that the tillage of soy fields has partially restored infiltrability following conversion from pasture. Such fields are tilled for the first two years of production and then left untilled (Tanguro Ranch, personal communication). Nevertheless, the oldest soy watershed sampled for this study and the oldest soy fields monitored for infiltrability by Scheffler *et al.* (unpublished) were planted in 2004. Compaction may increase with the continued use of heavy machinery on untilled fields, and over time we may see soy basins become more hydraulically similar to the pasture watershed observed.

Uncertainties

The goal of this project was to document the hydrologic changes associated with soy cultivation, the novel and rapidly expanding agricultural land use in Mato Grosso. It is worth noting, however, that several authors have debated the accuracy of hydrograph separation (Sloto & Crouse 1996, Lin *et al.* 2007, Schwartz 2007), as graphical or even algorithm-based separations have a degree of subjectivity, with these separations often producing different results when performed by different investigators (Sloto & Crouse 1996, Lin *et al.* 2007, Schwartz 2007). The use of hydrograph separation in comparisons of multiple basins, however, can provide important information about regional trends or, in this case, trends in response to land use change (Schwartz 2007). Here, we used the same algorithm and parameters across all watersheds and suggest that while these choices may influence the results from any one watershed (e.g., change the ratio of stormflow to baseflow) they are unlikely to bias our comparison between land use types. Additionally, we performed a sensitivity analysis using a range of parameters and showing an average of <5% variation in our results and showing consistent statistical results. Thus, we believe the inter-basin comparison to be robust (Dunne & Leopold 1978).

The landscape of Tanguro Ranch also bears further discussion, as the legacy of pasture can be seen in the morphology of the soy streams. Each headwater in soy begins with an impoundment or series of impoundments providing a different amount of control over flow in each of the soy watersheds. These impoundments, originally built to provide water for cattle, may influence the discharge behavior of the soy streams. Because this landscape feature is common to the Amazonian frontier in this region (Stickler, unpublished data), we see this response as part of the pattern of land use legacy and land use change. Additionally, we would expect these impoundments to mute the effects of storms, and perhaps lower water yield, in the soy streams. Despite this, we see increases in water yield in soy, and the similarity in observed hydrograph patterns between all watersheds suggest that the impoundments do not play a large role in controlling discharge.

Finally, all of our watersheds are in a flat tropical landscape dominated by deep well-drained soils, and it is possible that there is underflow beneath the monitored streams as well as flow between the basins (Bruijnzeel 1990, Bonell 2005). This means that some water exported from the watersheds through streams may not be captured by the headwater gauging stations but instead may be joining the system farther downstream. Larger watersheds, then, should capture more of the flow. This can be seen in the second-order soy watershed monitored, where annual discharge was 1.7 times higher than the mean annual discharge across the first-order soy watersheds (Table 2). The average forested watershed area, 8.4 km^2, is higher than that of soy, 3.1 km^2, yet the water yields in forest were much lower. Therefore, if underflow is measurable in these catchments, the land use effect is actually greater than what is captured by our data.

A recent analysis of evapotranspiration in tropical landscapes estimates annual evapotranspiration rates between 1300 and 1400 $mm \cdot yr^{-1}$ for this region of the Amazon (Fisher *et al.* 2009). The evapotranspiration rates for Tanguro Ranch based on our data are similar, 1300 $mm \cdot yr^{-1}$ in forest watersheds and 870 $mm \cdot yr^{-1}$ in soy, as calculated based on the proportion of incident rainfall as streamflow (Table 2). However, the year of observation had lower than average precipitation (1450 mm), and others suggest that evapotranspiration should account for between 67 to 75% of annual precipitation in the region. Annual streamflow at Tanguro Ranch for the year of observation represents 10% of incident rainfall in forest watersheds and 40% of incident rainfall in soy catchments, resulting in lower than predicted fractions of rainfall as streamflow across land uses. In this way, discharge measurements in a second-order soy catchment and estimates of evapotranspiration suggest that underflow may lead us to underestimate total discharge, but the land use effect should only be exacerbated by this pattern.

Regional Implications

The Amazon Basin is the world's largest watershed, responsible for ~20% of global freshwater discharge. Thus, large-scale changes to Amazon hydrology have important local and global implications. Substantial increases in water yield integrated over an ever-expanding deforested area will likely be important downstream, potentially altering the water availability, flow regime, and hydrological function of watersheds like the Upper Xingu. Within stream channels, increases in discharge can alter channel morphology with increasing water volumes and sediment loads, as has been shown following agricultural conversion in the humid tropics (Odemerho 1984), and across ecosystems following urbanization (Chin 2006). Stream habitats important for invertebrate and fish communities can also be altered (Paul & Meyer 2001, Bunn & Arthington 2002), and the annual stream sediment and solute transport can increase, potentially decreasing local water quality (Williams & Melack 1997). Downstream, increased discharge can increase flood risk, and increase the need for water management during high flows (Dunne & Leopold 1978).

The observed increases in water yield support what large-scale studies and hydrological models have shown for the Amazon. Costa *et al.* (2003) show an increase in daily water yields for the Tocantins River basin (drainage area 767,000 km^2) from 1.0 mm$\cdot$day^{-1} to 1.24 mm$\cdot$day^{-1} between 1949-1968 and 1979-1998, a period over which land cover went from 30.2 to 49.2% cleared. A comparison of regional-scale models by Coe *et al.* (2009) shows increases in stream discharge at the micro- and meso-scale as described here, but competing atmospheric feedbacks at larger scales. These atmospheric changes may reduce precipitation and water inputs, thereby potentially decreasing regional water yields and discharge if these resultant decreases are larger than changes in ET and runoff. Although these climate feedbacks are complex, our results can be used to calibrate and validate future hydrological and climate models for the region.

Exporting a greater proportion of available water across cleared areas is likely to have climate consequences for the region. The Amazon is estimated to generate 25-50% of its own precipitation through the evapotranspirative pumps that are its trees (Eltahir & Bras 1994, Fearnside 2005). Deforestation decreases the rate of this recycling, leaving increased volumes of water to be exported through stream conduits from the local system. Losing what was once locally recycled water via increased stream export also has the potential to create a feedback resulting in reduced local precipitation leading to a drier regional climate, thus contributing to the pattern of drying, or forest dieback, predicted for southern Amazon forest (Shukla *et al.* 1990, Oyama & Nobre 2003, Malhi *et al.* 2008, Nepstad *et al.* 2008, Coe *et al.* 2009).

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Table 1 Watershed name, year converted from pasture, and watershed area for nine watersheds at Fazenda Tanguro. Soy_1 watersheds are first order soy watersheds; soy_2 is the second-order soy watershed.

Watershed	Year Converted	Area (km^2)
Forest a	-	6.73
Forest b	-	13.52
Forest c	-	4.89
Soy_1 a	2007	3.30
Soy_1 b	2004	2.51
Soy_1 c	2004	2.51
Soy_1 d	2004	3.93
Soy_2	2004	27.53
Pasture	2008	6.08

Table 2 Percent baseflow, annual water yield, and the percent of annual precipitation as streamflow, mean, and median daily water yield for nine watersheds at Fazenda Tanguro. Soy$_1$ watersheds are first order soy watersheds; soy$_2$ is the second-order soy watershed.

Watershed	% Baseflow	Annual water yield ($mm \cdot year^{-1}$)	% ppt (Annual water yield / Annual ppt (mm))	Mean water yield ($mm \cdot day^{-1}$)	Median water yield ($mm \cdot day^{-1}$)
Forest a	94.60	333.83	0.23	0.91	0.88
Forest b	98.88	57.49	0.04	0.16	0.16
Forest c	94.60	62.80	0.04	0.17	0.17
Soy$_1$ a	95.19	339.42	0.23	0.93	0.98
Soy$_1$ b	96.25	774.95	0.53	2.12	1.91
Soy$_1$ c	87.67	827.45	0.57	2.26	1.93
Soy$_1$ d	98.31	374.36	0.26	1.02	1.11
Soy$_2$	92.57	973.69	0.67	2.66	2.46
Pasture	94.26	177.27	0.12	0.48	0.54

Table 3 Hydrologic indices including skewness (SK= mean daily water yield / median daily water yield), the coefficient of variation (CV=standard deviation (SD) of daily water yield / mean daily water yield), flow acceleration (FA), defined as the slope of the ascending limb of hydrograph peaks (the change in discharge in $L \cdot sec^{-1}$divided by the change in time in hours), and the receding limb slope (RLS), defined as the semi-log transformed slope of the receding limb of hydrograph peaks. Soy_1 watersheds are first order soy watersheds; soy_2 is the second-order soy watershed.

Watershed	SK	CV	FA	RLS
Forest a	1.0	0.28	18	0.20
Forest b	0.96	0.11	0.84	0.05
Forest c	1.0	0.59	3.6	0.11
Soy_1 a	0.95	0.26	8.0	0.26
Soy_1 b	1.1	0.29	9.6	0.18
Soy_1 c	1.2	0.71	40	0.24
Soy_1 d	0.92	0.23	2	0.11
Soy_2	1.1	0.37	57	0.26
Pasture	0.91	0.77	12	0.17

Figure Legends

Fig. 1: The location of Tanguro Ranch within the legal Amazon. The inset map of the Ranch shows the locations and areas for each watershed.

Fig. 2: Schematic hydrograph showing the parameters and result of our method for hydrograph separation. Closed circles represent flow maxima while open circles represent flow minima. Minima are defined for each data point that is the lowest flow value in the illustrated interval. The interval is examined for each data point. Because the discharge at max 1 is higher than the illustrated threshold, flow between min 1 and min 2, above the dotted line, represents stormflow. The remaining discharge, including the dotted line, represents baseflow. The threshold is based on the standard deviation of baseflow in order to exclude daily variation from flow increases associated with rain inputs.

Fig. 3: Mean daily water yields by land use type. Soy_1 are the first order soy watersheds; soy_2 is the second order soy watershed. Mean soy watershed water yields are higher than forest watershed water yields ($p=0.054$).

Fig. 4: (a) Monthly precipitation based on daily precipitation records for Tanguro Ranch. **(b)** Mean daily flow for each month between August 2007 and August 2008 for soy watersheds (closed circles, N=4) and forest watersheds (open circles, N=3). Circles represent median daily flow and error bars show the maximum and minimum daily flow

by month for each watershed type. **(c)** MF Index (monthly mean daily flow – annual mean daily flow). Error bars show 1 SD.

Fig. 5: Hydrographs for the seven first-order watersheds used in statistical comparisons, followed by the second order soy catchment and the first-order pasture catchment. The gray area represents the wet season as defined by the first and last precipitation events detected in more than four watersheds. The graph includes approximately one year beginning in August 2007 and continuing through August 2008. Note the different y-axis scales.

Fig. 6: Flow acceleration (FA) for each watershed by land use type. Soy_1 are the first order soy watersheds; soy_2 is the second order soy watershed. The number of examined peaks (N) ranged from 36 to 74 based on the number of precipitation peaks defined as maxima by the hydrograph separation function. There was no trend in FA values between land use types.

F

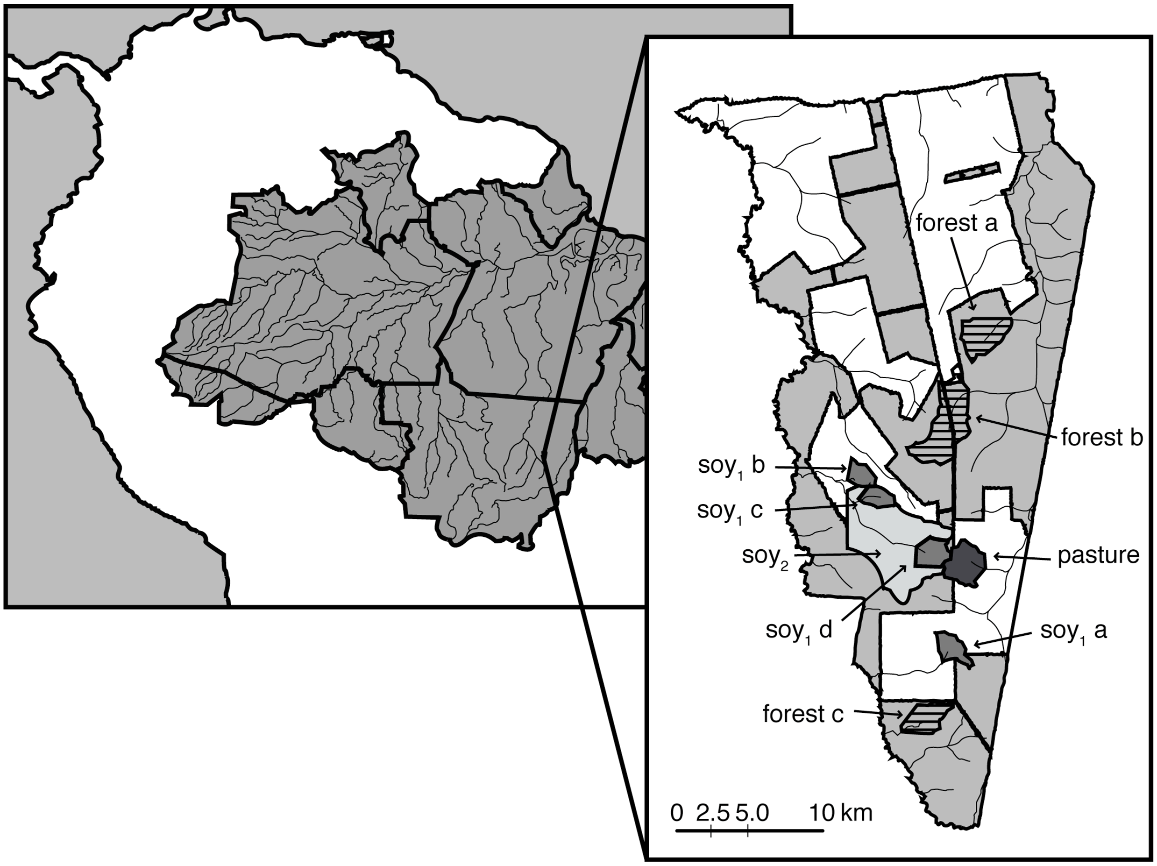

forest a
forest b
soy$_1$ b
soy$_1$ c
soy$_2$
pasture
soy$_1$ d
soy$_1$ a
forest c
0 2.5 5.0 10 km

Fig. 1

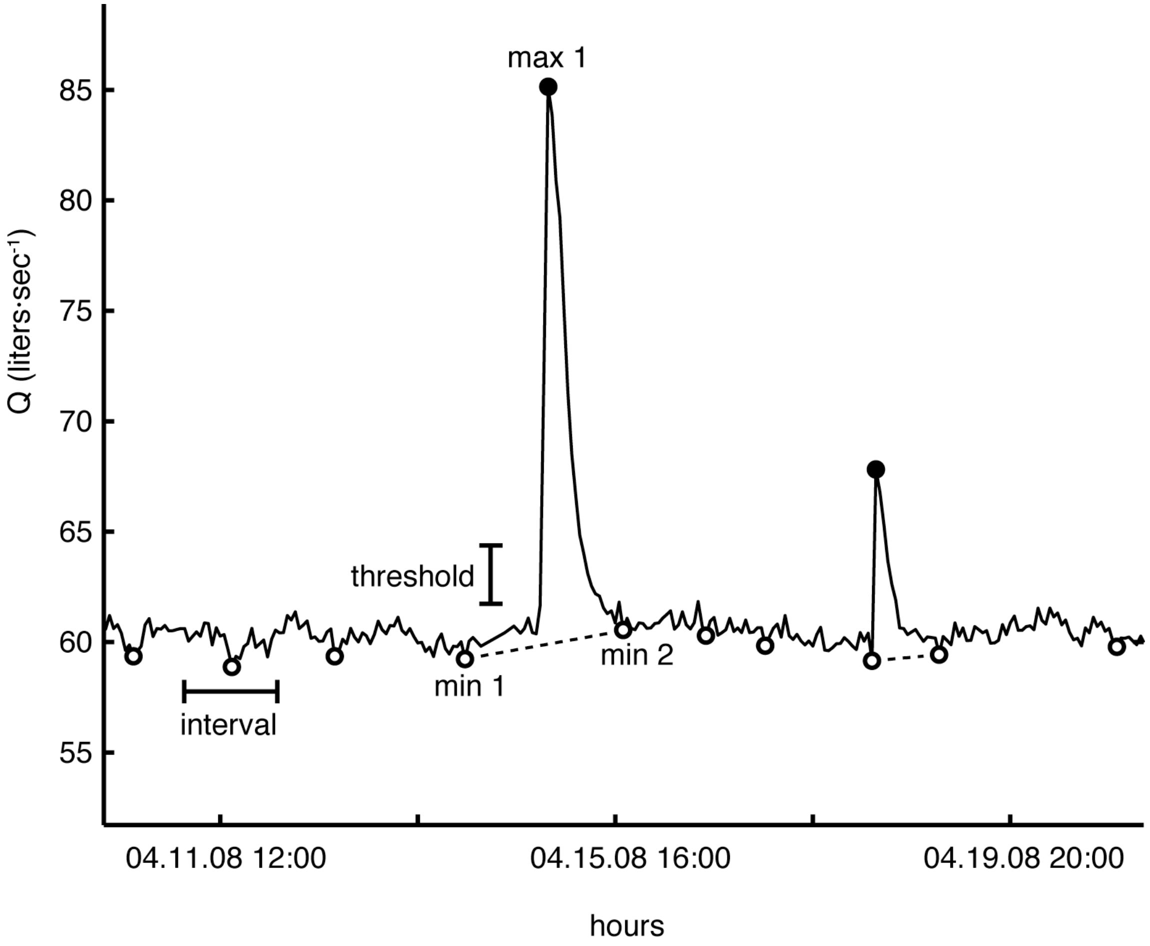
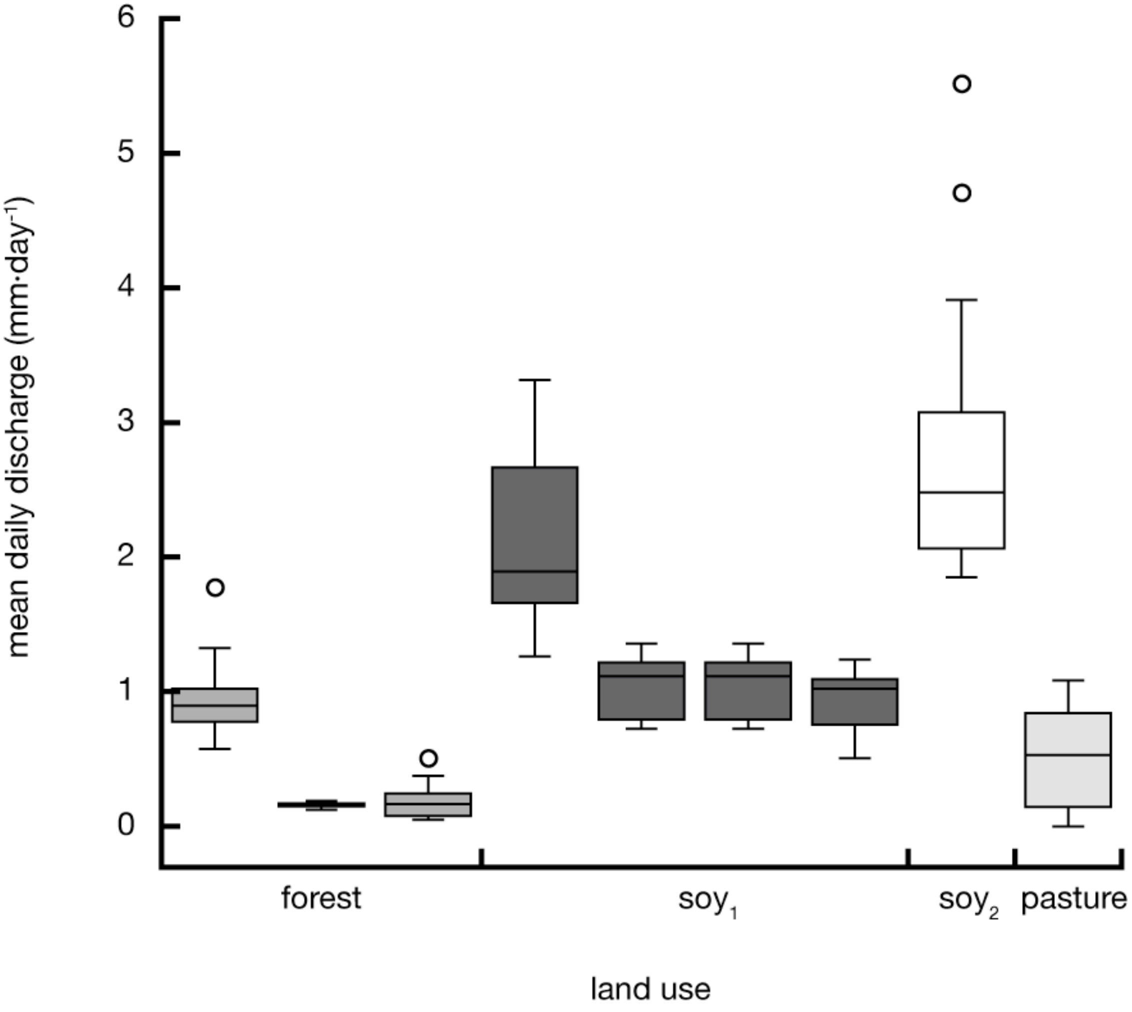
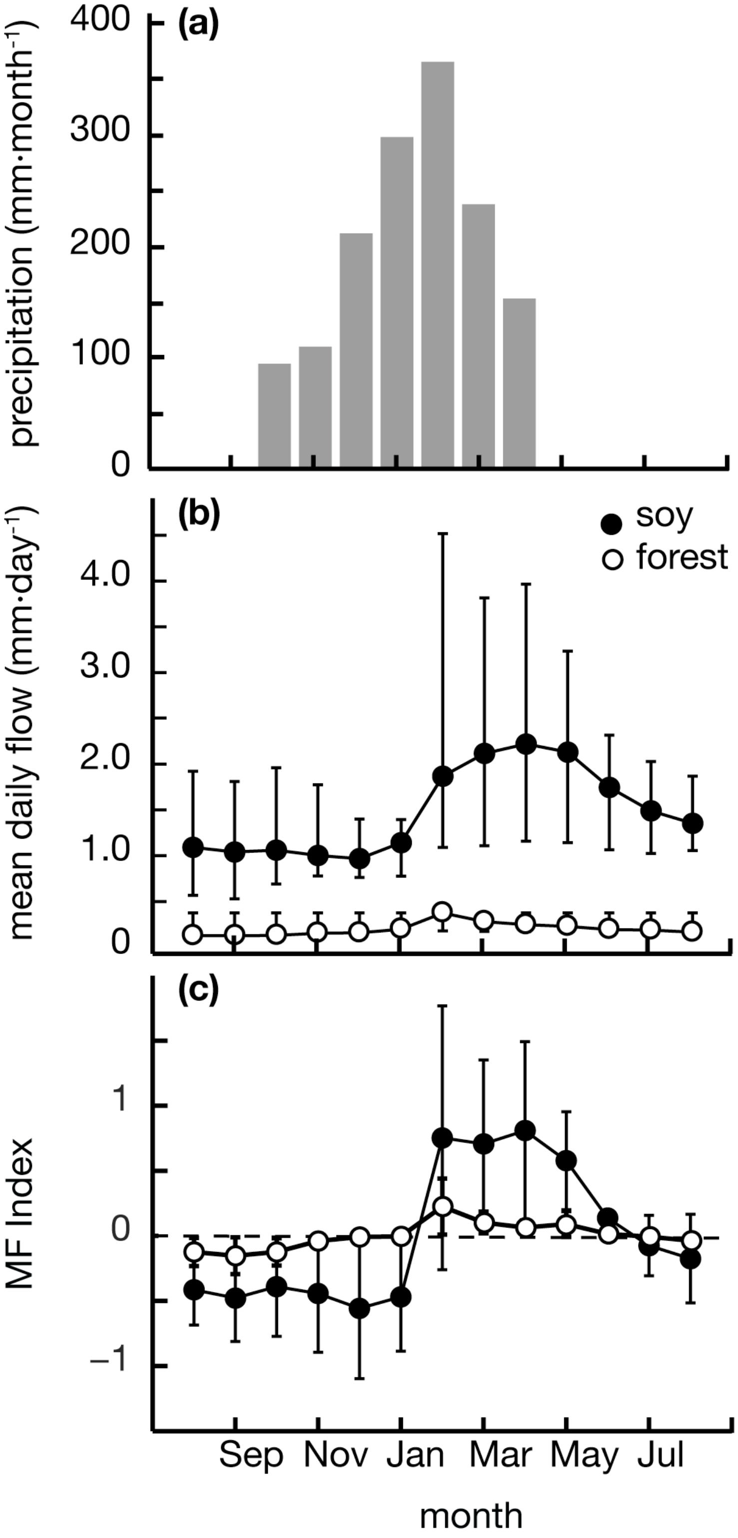

max 1
85
80
75
70
65
60
55
Q (liters·sec-1)
threshold
interval
min 1
min 2
04.11.08 12:00
04.15.08 16:00
04.19.08 20:00
hours

Fig. 2



mean daily discharge (mm·day⁻¹)
6
5
4
3
2
1
0
forest
soy1
soy2
pasture
land use

Fig. 3



(a)
precipitation (mm·month⁻¹)
400
300
200
100
0
(b)
● soy
○ forest
mean daily flow (mm·day⁻¹)
4.0
3.0
2.0
1.0
0
(c)
MF Index
1
0
−1
Sep
Nov
Jan
Mar
May
Jul
month

Fig. 4

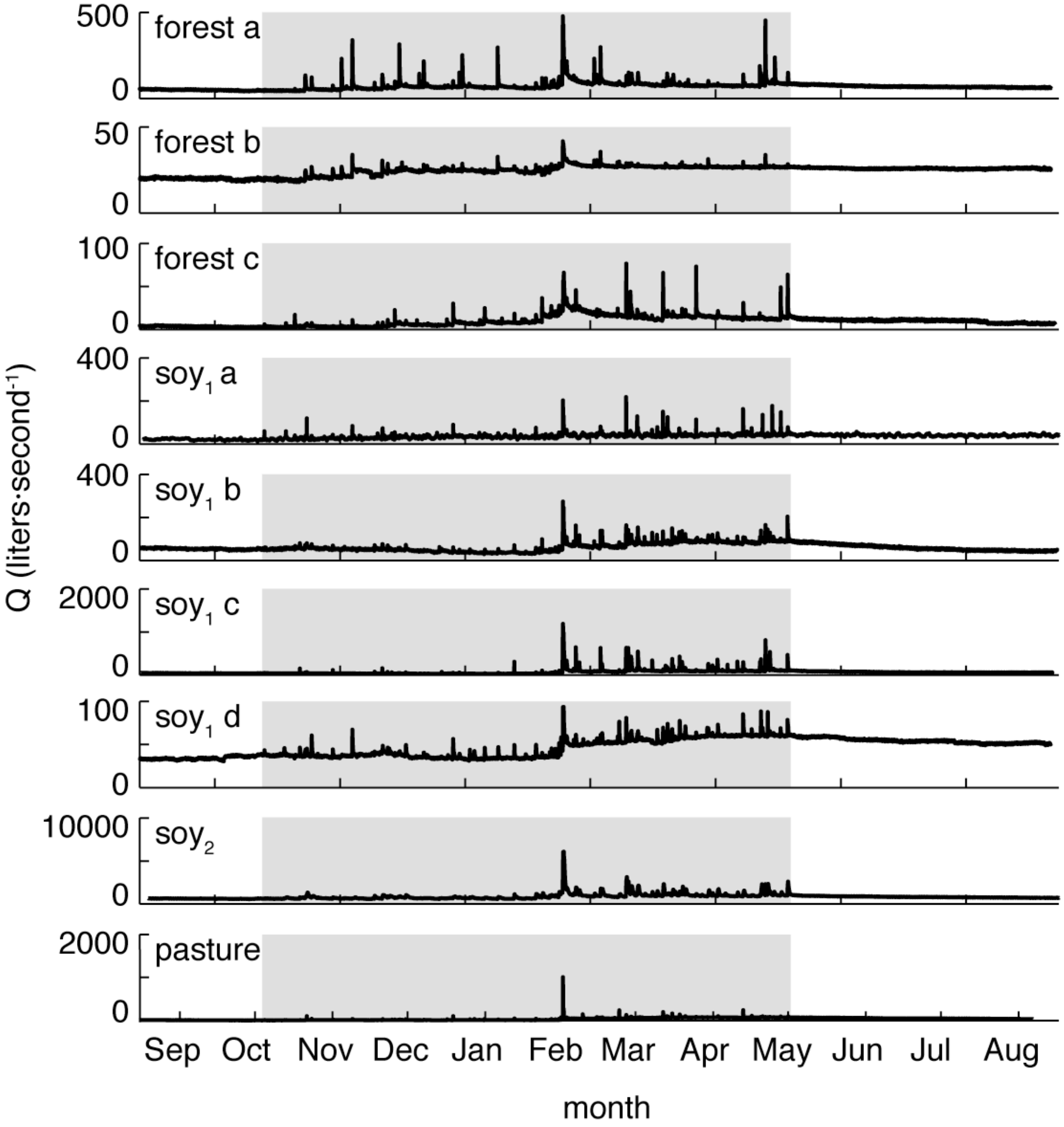

Q (liters·second^{-1})
500
0
forest a
50
0
forest b
100
0
forest c
400
0
soy$_1$ a
400
0
soy$_1$ b
2000
0
soy$_1$ c
100
0
soy$_1$ d
10000
0
soy$_2$
2000
0
pasture
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
month

Fig. 5

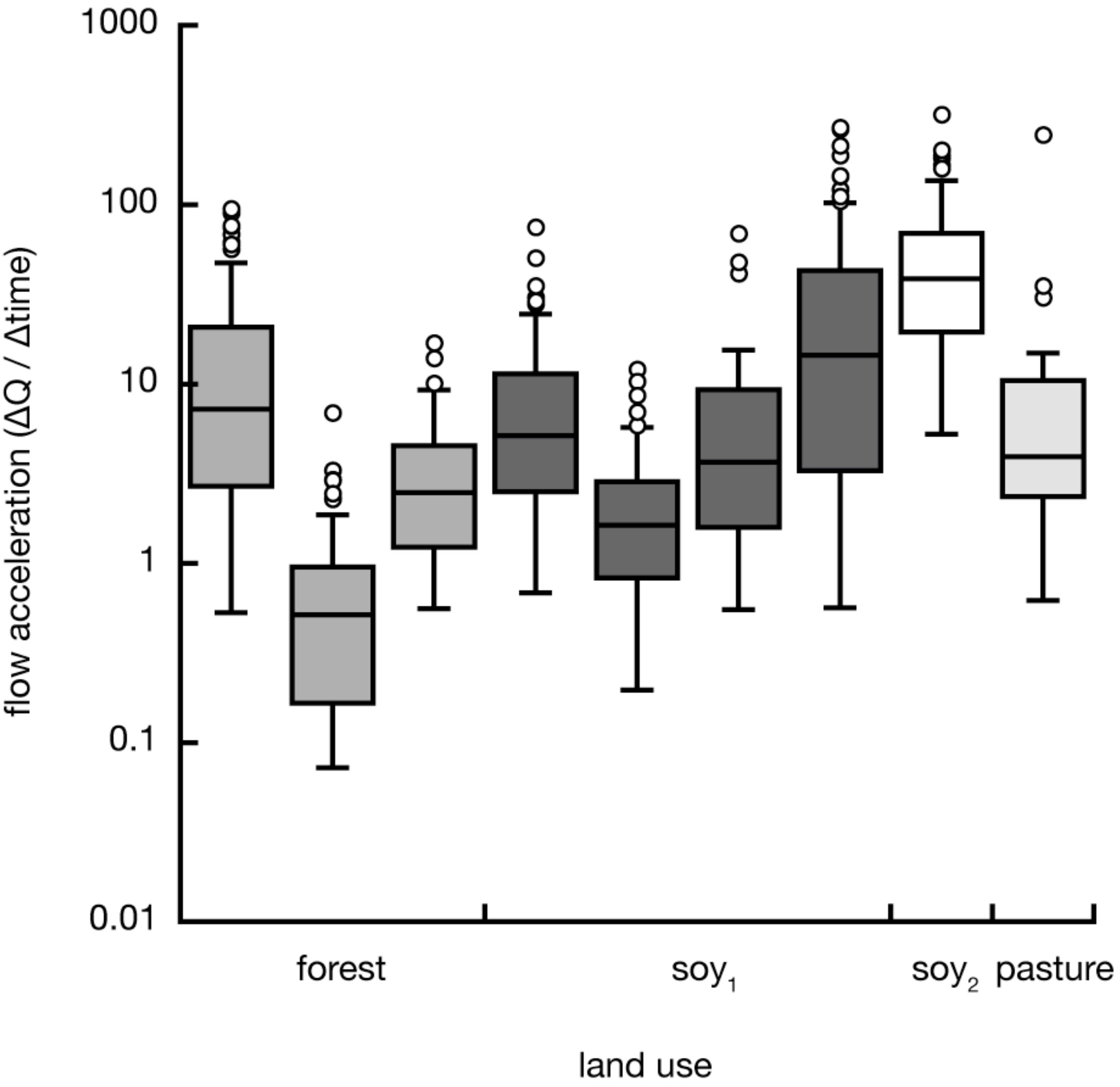

1000
100
10
1
0.1
0.01
flow acceleration (ΔQ / Δtime)
forest
soy1
soy2
pasture
land use

Fig. 6