Hydrological Impacts of Land Use and Land Cover Changes - LUCC in Brazil: current state of the art and scientific challenges

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With the contribution of:
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LUCC impacts in rural and urban areas

1) LUCC are different in urban and rural areas. LUCC in urban areas are quite severe compared to changes in rural areas. However, in rural areas, changes affect larger areas.

2) Although changes in urban areas are directly related to floods with higher social and economic impacts, most of water management are strongly linked to land use in rural areas.

3) Understanding and predicting the hydrological impacts of LUCC is crucial for water management issues.
Questions to be addressed

1) What are the evidences of the effects of land use and land cover changes (LUCC) on local-scale to large-scale in the Brazilian tropics?

2) What is the ability of existent models to assess the impacts of LUCC on the hydrological response?

3) What further research is necessary.
A brief lecture of Brazilian’s Geography
Brazilian main terrestrial biomes
Brazilian natural biomes and hydrographic regions

Biomas e Regiões Hidrográficas do Brasil

Legenda
- Drenagem (ANA)
- Biomas (IBGE)
  - Amazônia
  - Caatinga
  - Cerrado
  - Mata Atlântica
  - Pantanal

Regiões Hidrográficas
- Tocantins Araguaia
- Amazônia
- Paraguai
- Atlântico NE Oriental
- Atlântico Leste
- Paraná
- Parnaíba
- São Francisco
- Atlântico Sul
- Uruguai
- Atlântico SE
- Atlântico NE Ocidental
Brazilian natural biomes and hydrographic regions

Biomas e Regiões Hidrográficas do Brasil

Legenda
- Antropização (PROVEG)
- Drenagem (ANA)

Biomas (IBGE)
- Amazônia
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- São Francisco
- Atlântico Sul
- Uruguaí
- Atlântico SE
- Atlântico NE Ocidental
“Clearing of a Forest”

Defrichement d’une Forêt (c. 1825). Johann Moritz Rugendas (1802-1858)
Historical occupation of Brazil

From ~1960

From ~1500
1) What are the evidences of the effects of land use and land cover changes (LUCC) on local-scale to large scales in the tropics?

Study case: The replacement of Amazon Forest and *Cerrado* by Pasture
What is the current knowledge?

There is an extensive body of hydrological literature dealing with impacts of land use and land cover change on small (i.e. <1 km²), mainly temperate experimental catchments (Bonell and Bruijnzeel, 2005; Brown et al., 2005; Peel, 2009).

In such controlled conditions, total annual water yield, infiltration and groundwater recharge appeared to increase proportionally to the area of forest removed (e.g. Brown et al., 2005; Van Dijk and Keenan, 2007).
Tocantins River Basin (Costa et al. 2003)

The area of study (upstream of Porto Nacional) has a drainage area of 175 360 km².

Fig. 2. Population trends in the main cities near the area of study. Goiânia was founded in 1942 to be the new capital of the state of Goiás. Brasília was founded in 1960 to be the new capital of Brazil. Palmas was founded in 1989, to be the capital of the new state of Tocantins. Data are from IBGE (1950, 1960a, 1970, 1980, 1991 and 2000) demographic censuses and one IBGE population count (1996). Data for 1991, 1996 and 2000 were downloaded from http://www.ibge.gov.br.

Table 2
Long term mean of hydrological variables in the Tocantins River basin upstream of Porto Nacional

<table>
<thead>
<tr>
<th>Period</th>
<th>P (mm/day)</th>
<th>Q (m³/s)</th>
<th>Q (mm/day)</th>
<th>ET (mm/day)</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1949–1968</td>
<td>4.22</td>
<td>2055.6</td>
<td>1.00</td>
<td>3.22</td>
<td>0.237</td>
</tr>
<tr>
<td>1979–1998</td>
<td>4.35</td>
<td>2532.3</td>
<td>1.24</td>
<td>3.11</td>
<td>0.285</td>
</tr>
</tbody>
</table>

*P is precipitation (calculated from the CRU dataset), Q is discharge (from the ANEEL records), ET is evapotranspiration (P – Q), and C is the runoff coefficient (Q/P).*
“Our analysis indicates that, while precipitation over the basin is not statistically different between period 1 and period 2; annual mean discharge in period 2 is 24% greater than in period 1; and the high-flow season discharge is greater by 28.”
However, if we look an “updated streamflow series”...

\[ Q(1949-1968) = 2055 \text{ m}^3 \text{ s}^{-1} \quad Q(1979-1998) = 2532 \text{ m}^3 \text{ s}^{-1} \]

\[ y = -0.005x + 2367.9 \quad R^2 = 0.0003 \]
Looking into rainfall and streamflow trends in the contiguous Upper Paraguay and Southern Amazon Basins
Paraguay River (Collischonn et al. 2001, JH)

Paraguay River at Ladário: 253 000 km²
Paraguay River (Collischonn et al. 2001, JH)

“Despite the fragmentary nature in the 36 rainfall records, an explanation for the increase of flow since 1970 was found in the increase of rainfall.... “
Interdecadal variability in the Upper Paraguay (Allasia, 2008)
Interdecadal variability in the Amazon (Marengo 2004, IJC)

Fig. 3. Rainfall indices in northern (NAR) and southern Amazonia (SAR) from 1929/30 to 1998/99. Indices are expressed as departures normalized by the standard deviation, from the reference period 1949–1998.
**Interdecadal variability in the Amazon** (Marengo 2004, IJC)

“The decadal analysis suggests shifts in Amazonian rainfall regime in the mid-1940s and the mid-1970s, where northern Amazonia had relatively wetter conditions during the 1945 to 1975, and relatively drier conditions between 1975 and 1998.”

“Variability in the SSTs of the tropical Pacific and Atlantic is likely to play an important role in driving the interdecadal variability in Amazonia’s rainfall.”
It is clear that basins contiguous to the Tocantins show indication of a shift in the interdecadal variability between 1975-1977 which resulted in an increased of rainfall.

Therefore, it is likely to assume that most (perhaps all) of the trend observed in the Tocantins basins are associated to decadal variability rather than LUCC.
The Ji-Paraná River Basin

Madeira river.

Ji-Paraná river

Legend
- Ji-Paraná river basin
- Main river
- Rondônia state
- Pluviometric Stations

Ji-Paraná
Dinâmica Hidrológica na Bacia do Rio Ji-Paraná/RO

Source: Linhares, 2005
Dinâmica Hidrológica na Bacia do Rio Ji-Paraná/RO

Anos

Precipitação (mm)

Taxa de Desflorestamento (km²/ano)

Resposta Hidrológica

Source: Linhares, 2005

1980
Dinâmica Hidrológica na Bacia do Rio Ji-Paraná/RO

Source: Linhares, 2005
Dinâmica Hidrológica na Bacia do Rio Ji-Paraná/RO

Precipitação (mm)  Taxa de Desflorestamento (km²/ano)  Resposta Hidrológica

Source: Linhares, 2005
Dinâmica Hidrológica na Bacia do Rio Ji-Paraná/RO

Anos

Precipitação (mm)

Taxa de Desflorestamento (km²/ano)

Resposta Hidrológica

Source: Linhares, 2005
Dinâmica Hidrológica na Bacia do Rio Ji-Paraná/RO

Precipitação (mm)  Taxa de Desflorestamento (km²/ano)  Resposta Hidrológica

Source: Linhares, 2005
Dinâmica Hidrológica na Bacia do Rio Ji-Paraná/RO

Source: Linhares, 2005
Dinâmica Hidrológica na Bacia do Rio Ji-Paraná/RO

Source: Linhares, 2005
Dinâmica Hidrológica na Bacia do Rio Ji-Paraná/RO

Precipitação (mm)  Taxa de Desflorestamento (km²/ano)  Resposta Hidrológica

1991

Source: Linhares, 2005
### Dinâmica Hidrológica na Bacia do Rio Ji-Paraná/RO

<table>
<thead>
<tr>
<th>Anos</th>
<th>Precipitação (mm)</th>
<th>Taxa de Desflorestamento (km²/ano)</th>
<th>Resposta Hidrológica</th>
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<td>1992</td>
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</tbody>
</table>

Source: Linhares, 2005

![Map of the Rio Ji-Paraná basin with data points and legend](image)

**1992**

Dinâmica Hidrológica na Bacia do Rio Ji-Paraná/RO

Source: Linhares, 2005
Dinâmica Hidrológica na Bacia do Rio Ji-Paraná/RO

Source: Linhares, 2005
Dinâmica Hidrológica na Bacia do Rio Ji-Paraná/RO

Anos

Precipitação (mm)

Taxa de Desflorestamento (km²/ano)

Resposta Hidrológica

1994

Precipitação (mm)  Taxa de Desflorestamento (km²/ano)  Resposta Hidrológica

Anos

Dinâmica Hidrológica na Bacia do Rio Ji-Paraná/RO

Precipitação (mm)  Taxa de Desflorestamento (km²/ano)  Resposta Hidrológica


Source: Linhares, 2005
Dinâmica Hidrológica na Bacia do Rio Ji-Paraná/RO

Precipitação (mm)  Taxa de Desflorestamento (km²/ano)  Resposta Hidrológica

Source: Linhares, 2005
Dinâmica Hidrológica na Bacia do Rio Ji-Paraná/RO


Precipitação (mm) - Taxa de Desflorestamento (km2/ano) - Resposta Hidrológica

Source: Linhares, 2005
Dinâmica Hidrológica na Bacia do Rio Ji-Paraná/RO

Precipitação (mm) Taxa de Desflorestamento (km²/ano) Resposta Hidrológica

Source: Linhares, 2005
Dinâmica Hidrológica na Bacia do Rio Ji-Paraná/RO


Precipitação (mm)
Taxa de Desflorestamento (km²/ano)
Resposta Hidrológica

Source: Linhares, 2005
Dinâmica Hidrológica na Bacia do Rio Ji-Paraná/RO

Precipitação (mm) Taxa de Desflorestamento (km²/ano) Resposta Hidrológica

Source: Linhares, 2005
Dinâmica Hidrológica na Bacia do Rio Ji-Paraná/RO

Source: Linhares, 2005
Ji-Paraná Basin (Rodriguez et al. 2010, HP)

Increased deforestation with the scale

Table I. Streamflow gauge series: temporal coverage

<table>
<thead>
<tr>
<th>BASIN</th>
<th>SB1</th>
<th>SB 2</th>
<th>SB 3</th>
<th>SB 4</th>
<th>SB 5</th>
<th>SB 6</th>
<th>SB 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST</td>
<td>Flor do Campo</td>
<td>Comemoração</td>
<td>Fazenda Expansão</td>
<td>PCH Primavera</td>
<td>Pimenta Bueno</td>
<td>Bela Vista</td>
<td>Ji-Paraná</td>
</tr>
<tr>
<td>LON</td>
<td>-60.86</td>
<td>-61.18</td>
<td>-61.05</td>
<td>-61.24</td>
<td>-61.19</td>
<td>-61.22</td>
<td>-61.94</td>
</tr>
<tr>
<td>AREA [km²]</td>
<td>4230</td>
<td>5940</td>
<td>3686</td>
<td>9705</td>
<td>10114</td>
<td>16092</td>
<td>33012</td>
</tr>
</tbody>
</table>
Ji-Paraná Basin (Rodriguez et al. 2010, HP)

No significant trend in rainfall series
Analysis of the trends in discharges

- Trends detected only in the small sub-basins
- Increase in the peak discharges and decrease in minimum flows
- Decreasing lag-times
- The response depends on the catchment topography

<table>
<thead>
<tr>
<th>Basin</th>
<th>SB 1</th>
<th>SB 2</th>
<th>SB 3</th>
<th>SB 4</th>
<th>SB 5</th>
<th>SB 6</th>
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<td>VMN</td>
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</tbody>
</table>

Are there thresholds?

- Blosch et al., 2007
- Hamilton, 1990 Wilk et al., 2001

The impact depends on the scale
Consistently with these results, signals of LUCC can also be detected in micro-scale catchment studies.
Adjacent forest (1.37 ha) and pasture (0.73 ha) catchments approximately 400 m apart.
And what happen at the Amazon wide scale?
Since 1929, long-term tendencies and trends have been detected in a set of regional-average rainfall time series in the Amazon basin and supported by the analysis of some river streamflow time series. These long-term variations are more characteristic of decadal and multi-decadal modes, indicators of natural climate variability, rather than any unidirectional trend towards drier conditions (as one would expect, due to increased deforestation or to global warming)
How unique are those results found in the Ji-Paraná basin?

Detecting changes in streamflow after partial woodland clearing in two large catchments in the seasonal tropics

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a CSIRO Land and Water, GPO Box 1666, Black Mountain, Canberra ACT 2601, Australia
b Environmental Monitoring and Modelling Research Group, Department of Geography, King's College London, Strand, London WC2R 2LS, UK
c Faculty of Earth and Life Sciences, VU University Amsterdam, De Boelelaan 1085-1087, 1081 HV Amsterdam, The Netherlands

In the Comet catchment, findings from a simple coupled water-energy balance framework suggested that most of the observed changes in annual streamflow were related to climate variability. However, the period immediately after clearing showed an increase in interannual streamflow that suggested a decrease in interannual evapotranspiration associated with LUCC. An overall increase in annual streamflow in the post-LUCC period (1971–2007) was mainly attributed to higher than average rainfall linked to La Niña conditions in the wet 1970s. Results from applying a Budyko-type model to assess changes in evapotranspiration efficiency for pre- (1920–1953) and a climatically similar post-LUCC (1979–2007) showed a slight decrease in evapotranspiration of 3.1–3.8% with negligible (i.e. 1%) increase in streamflow. Likely causes for
However, this is not the case for all meso-scale basins in the tropics

<table>
<thead>
<tr>
<th>Catchment (Country)</th>
<th>Area (km²)</th>
<th>Forest cover change (%)</th>
<th>Period pre- and post-LUCC</th>
<th>Method(s)</th>
<th>Effects on</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ji-Paraná (southwestern Amazonia, Brazil)</td>
<td>33,012</td>
<td>-50</td>
<td>1978–2000</td>
<td>TSA</td>
<td>No change</td>
<td>Linhares (2005) and Rodriguez et al. (2010)</td>
</tr>
<tr>
<td>Pearl River and East, North and West Rivers (Guandong Province, China)</td>
<td>179,752</td>
<td>+37</td>
<td>1965–1986, 1993–2006</td>
<td>TSA</td>
<td>No change</td>
<td>Zhou et al. (2010)</td>
</tr>
</tbody>
</table>

* No distinctive pre- and post-LUCC periods.

* No distinctive pre- and post-LUCC periods but transitory changes of LUCC and streamflow.

Peña-Aranciaba et al. (2012)
In conclusion:

At small scales (< ~500 km²), signals of LUCC can be clearly detected.

At the meso scale (~10 Thousand km²), the detection of signal is sometimes contradictory, mainly because of the interdecadal variability.

At the large scales (millions of km²) signals of LUCC are not detectable.
However......

Although the impacts of LUCC at local-scale appear to be “diluted” at larger scales, it is likely to assume that there are “threshold values” of disturbance (or “tipping points”) when the local-scale signals become significant at large scales.

Probably, the basin capacity to attenuate the effect of local disturbance depends on a unique combination of natural climate variability and soil, vegetation, geology, etc, heterogeneity.
2) What is the ability of existent models to assess the impacts of LUCC on the hydrological response?
Ji-Paraná Basin (Rodriguez et al, submitted to HSJ)

Performance coefficients for daily discharges (NSE, KGE, R2 and LR2) and volumes (BIAS) for six sub-basins of the Ji-Parana basin

<table>
<thead>
<tr>
<th></th>
<th>NSE (daily)</th>
<th>KGE (daily)</th>
<th>R2 (daily)</th>
<th>LR2 (daily)</th>
<th>BIAS [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SB1</td>
<td>0.63</td>
<td>0.80</td>
<td>0.71</td>
<td>0.73</td>
<td>-8.98</td>
</tr>
<tr>
<td>SB2</td>
<td>0.73</td>
<td>0.85</td>
<td>0.87</td>
<td>0.78</td>
<td>-10.75</td>
</tr>
<tr>
<td>SB3</td>
<td>0.54</td>
<td>0.76</td>
<td>0.66</td>
<td>0.72</td>
<td>1.24</td>
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<tr>
<td>SB4</td>
<td>0.67</td>
<td>0.78</td>
<td>0.78</td>
<td>0.78</td>
<td>-7.75</td>
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<tr>
<td>SB5</td>
<td>0.77</td>
<td>0.88</td>
<td>0.85</td>
<td>0.85</td>
<td>-3.48</td>
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<tr>
<td>SB6</td>
<td>0.80</td>
<td>0.89</td>
<td>0.86</td>
<td>0.86</td>
<td>-2.74</td>
</tr>
<tr>
<td>SB7</td>
<td>0.83</td>
<td>0.89</td>
<td>0.80</td>
<td>0.90</td>
<td>3.43</td>
</tr>
</tbody>
</table>

Hydrological model
MHD-INPE calibration
Three experiments

- **EFLOR** LUCC equivalent to the 1978 vegetation map

- **EPAST** all deforestation turned into pasture and remained as such

- **ECAPO** a fraction of deforested areas turned into a secondary regrowth (*capoeira*)

*Neef et al., 2006*
The effect of secondary regrowth (*capoeira*):

Higher albedo at the beginning of the regrowth

Evaporation rates higher than a primary forest

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*Figure 1. Albedo of secondary vegetation as a function of years since abandonment of clearing for sites in eastern Amazon Basin and northern Thailand; based on data from Giambelluca et al. (1997, 1999)*

*Figure 3. Evaporative fraction (ratio of energy used for evaporation to net radiation) of secondary vegetation as a function of years since abandonment of clearing for sites in eastern Amazon Basin and northern Thailand; based on data from Hölscher et al. (1997) and Giambelluca et al. (2000)*
According to the model, the larger the scale, the higher the impact.
Qualitative similar results have been obtained using several other models
“The simulations with IBIS and THMB offline indicate that the local ET decrease and subsequent discharge increase can be a significant fraction of the water balance when greater than 50% of a watershed is deforested” (Coe et al 2009, JH).

Results with the VIC model suggests that “the replacement of forests by annual crops such as soybeans might result in an increase of Ji-Paraná river discharges up to 37% during the wet season and 90% during the dry season” (Santiago, 2005, thesis).
“We analysed impacts of deforestation on streamflow of the river Ji-Paraná (southern Amazon) using the MGB-IPH hydrological model. Three forest cover scenarios were simulated: pristine condition with predominant (~100%) forest cover; current condition with about 57% deforestation; and a hypothetical 100% deforestation scenario. Results suggest that average annual discharge of the river Ji-Paraná increases by about 31 mm for each 10% of the basin drainage area that is deforested. These results are consistent with worldwide experimental studies, but are not verified in observed streamflow records of the Ji-Paraná River” (Bayer and Collischonn, 2013)
“The semi-distributed hydrological model SLURP was applied in the Jamari River basin, Brazil, to investigate the impacts on hydrological processes caused by changes in surface land cover and land use, as well as climate change. Realistic and extreme scenarios of deforestation were analyzed. An increase was found of runoff when deforestation occurred“ (Nobrega et al., 2010)

“The model SWAT was calibrated for the Ji-Paraná river basin using sediment and flow discharge data provided by ANA. ..The model produced satisfactory r2 values in most of the sub-basins for flow calibration. However, the values of r2 for sediment concentrations were not significant.“ (Dinato, 2013)
In conclusion:

Almost (if not all) models predict that the effects of LUCC will amplify across scales, while observations suggest the opposite: signals are diluted at larger scales.

Because the effect of LUCC can be modelled at small scales, the most likely explanation for the amplification of signals is related to the inability of models to upscale nonlinear processes at larger scales due to spatial heterogeneity.
In conclusion:

Besides this, models assumed a quasi-dynamic state of equilibrium, while observations of rainfall-runoff responses due to LUCC are time-lagged.

That creates uncertainties for the determination of threshold values of disturbance for which the large-scale hydrological response becomes clear.
3 What further research is necessary.
There are several scale related differences that may preclude the direct verification of the results in small experimental catchments at larger scales. Among then (Blöschl et al., 2007; Donohue et al., 2010):

(i) climate gradients;
(ii) the mosaic of land uses;
(iii) vegetation types and
(iv) spatially variable soils and geology across the catchment.
Besides this, in-stream processes also affect the impacts at larger scales (McIntyre, 2010)

Geomorphological dispersion: the configuration of the drainage network controls the arrival times of impacts downstream

Hydrodynamic dispersion: channel friction attenuate the impacts
In addition, the effects of fragmentation on surface runoff.
Conceptual design of a hydrological model

- Vegetation
- Land use
- Saturated contributed areas
- Transpiration
- Canopy Evaporation
- Rainfall
- Evaporation
- Surface flow
- Subsurface flow
- Baseflow

Runoff separation

Discharge vs. Time

River Routing

Quickflow and Baseflow routed to the edge of the gridcell

Surface and subsurface flows

Flow routed from cell to cell to network outlet
Conceptual design of a hydrological model

Paz et al. 2011.
The effect of forests fragmentation in hydrological processes along a hillslope.
In conclusion:

LUCC are clearly scale dependent. While most models predict that LUCC amplify across scales, observations suggest the opposite: signals seem to disappear across scales, at least in several catchments.

The most likely explanation for these contradictory results could be attributed to the increase of heterogeneity across scales, including geology, soil types, climate, and land uses fragmentation, which local-scale interactions are not (or poorly) represented in hydrological models.

That creates uncertainties for the assessment of impacts.
The ability of hydrologists to quantify the impact of rural land use change on the water cycle is however limited and we are not able to provide consistently reliable evidence to support planning and policy decisions.

This shortcoming stems mainly from lack of data, but also from lack of modelling methods and tools.”
Thank you!

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