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2 Modeling the hydrological impact of land-use 3 change in West Africa

4 K.Y. Li ^a, M.T. Coe ^{b,*}, N. Ramankutty ^c, R. De Jong ^d

5 ^a Center for Sustainability and the Global Environment, University of Wisconsin-Madison, WI, United States

6 ^b The Woods Hole Research Center, 149 Woods Hole Rd, Falmouth, MA 02540-1644, United States

7 ^c McGill University, Montreal, Canada

8 ^d Eastern Cereal and Oilseed Research Center, AAFC, Ottawa, Canada

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KEYWORDS

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Summary Numerical simulations of idealized deforestation and overgrazing are performed for the Niger and Lake Chad basins of West Africa with a terrestrial ecosystem model IBIS (integrated biosphere simulator) and an aquatic transport model THMB (terrestrial hydrology model with biogeochemistry). The study reveals how land use changes affect hydrological regimes at the watershed scale. The results show that tropical forests, due to being situated in the regions of highest rainfall and exerting strong influence on evapotranspiration, have a disproportionately large impact on the water balance of the entire basin. Total deforestation (clearcutting) increases the simulated runoff ratio from 0.15 to 0.44, and the annual streamflow by 35–65%, depending on location in the basin, although forests occupy only a small portion (<5%) of the total basin area. Complete removal of grassland and savanna, which occupy much greater areas of the basins, result in an increase in simulated annual streamflow by 33–91%. The numerical simulations indicate that the hydrological response to progressive land cover change is non-linear and exhibits a threshold effect. There is no significant impact on the water yield and river discharge when the deforestation (thinning) percentage is below 50% or the overgrazing percentage below 70% for savanna and 80% for grassland areas; however, the water yield is increased dramatically when land cover change exceeds these thresholds. This threshold effect is a combined result of the non-linearity of the separate response of transpiration and soil and canopy evaporation to the imposed land cover changes.

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Introduction

In the past 50 years, West Africa has experienced large land-use changes including deforestation, overgrazing and

* Corresponding author. Tel.: +1 508 540 9900; fax: +1 508 540 9700.

E-mail address: mtcoe@whrc.org (M.T. Coe).

15 reclamation (Ramankutty, 2004; Brunner et al., 1995;
16 Stephenne and Lambin, 2001), and a persistent drought
17 since the 1960s (Wang and Eltahir, 2000). Land-use and cli-
18 mate changes may have both immediate and long-lasting
19 impacts on terrestrial hydrology, altering the balance be-
20 tween rainfall and evapotranspiration and the resultant
21 runoff. In the short-term, destructive land use change
22 may disrupt the hydrological cycle either through increas-
23 ing the water yield or through diminishing, or even elimi-
24 nating the low flow in some circumstances (Croke et al.,
25 2004; Pereira, 1992; Bruijnzeel, 1990). In the long-term,
26 the reductions in evapotranspiration and water recycling
27 arising from land-use changes may initiate a feedback
28 mechanism that results in reduced rainfall (Savenije,
29 1995). It has been argued that the persistent Sahelian
30 drought since the 1960s may be attributable, at least in
31 part, to vegetation changes (e.g., Wang and Eltahir,
32 2000; Zeng et al., 1999; Charney, 1975).

33 Climate change and variability directly alter the hydro-
34 logical cycle as well as the type and abundance of vegeta-
35 tion, which may change the behavior of lakes and water-
36 courses (Sircoulon et al., 1999). In countries of the Sahel,
37 the aforementioned persistent drought has greatly reduced
38 discharge rates of the rivers and has reduced the area of
39 Lake Chad from 23,500 km² to about 1500 km² (Coe and Fo-
40 ley, 2001; Sircoulon et al., 1999; Olivry et al., 1996;
41 Pouyaud and Colombani, 1989).

42 Extensive alterations in land cover and land use, which in
43 turn impact the hydrological system both at basin and regio-
44 nal scales, have occurred throughout West Africa in the last
45 50 years. These changes are a result of multiple factors
46 including climate change and variability, demographic
47 growth, macroeconomic activities and development policies
48 (Legesse et al., 2003). Physical understanding of the inter-
49 actions between hydrology, climate, and land-use change
50 is important not only for after-the-fact analyses, but also
51 for understanding and perhaps predicting the potential
52 hydrological consequences of existing land-use practices
53 and climate trends in West Africa.

54 While field experiments can conclusively demonstrate
55 the consequences of land use change, modeling studies of-
56 ten provide more insight into the mechanisms. Therefore,
57 physically based and spatially distributed ecosystem, land-
58 surface, and hydrological models are increasingly used to
59 address the hydrological impacts of land-use changes
60 (e.g., Bathurst et al., 2004; Legesse et al., 2003; VanShaar
61 et al., 2002; Lorup et al., 1998; Calder et al., 1995; Bathurst
62 and O'Connell, 1992; Refsgaard, 1987; Abbott et al., 1986).
63 Modeling studies have advantages over basin experimental
64 studies in being more flexible and rigorous in experimental
65 design, and enabling mechanistic interpretation. In addi-
66 tion, models are able to provide results immediately with
67 much less cost in staffing and operation. Numerical simula-
68 tions depend on field experiments and observations for their
69 construction, calibration, and validation and therefore can-
70 not replace field experiments. However, numerical simula-
71 tions can, in some cases, extend the scope and overcome
72 the limitations of traditional field experiments, which is
73 particularly true when addressing regional and global issues
74 including land use and climate change impacts. In this re-
75 spect, numerical simulations are a complement to and an
76 extension of field experiments.

This study employs an integrated modeling approach
aimed at mechanistic interpretation, to address the hydro-
logical sensitivity to land cover changes in West Africa,
including: (1) deforestation by means of clearcutting and
progressive thinning and (2) overgrazing as progressive thin-
ning of grassland and savanna vegetation.

Methodology

Model description

A terrestrial ecosystem model – IBIS (Kucharik et al., 2000;
Foley et al., 1996) and an aquatic transport model – THMB
(formerly know as HYDRA) (Coe et al., 2002; Coe, 2000,
1998) are jointly used to investigate the hydrological sensi-
tivity to land cover changes. As an ecosystem model, IBIS
provides a physically-sound framework for modeling land
surface hydrology under different natural vegetation covers
and crops. In terms of the hydrology, IBIS simulates canopy
interception of rainfall, surface and sub-surface runoff, soil
moisture, soil and canopy evaporation, and plant transpira-
tion. However, IBIS does not simulate river discharge, which
is an observable, practical indicator of land cover changes.
Therefore, THMB is used to simulate the river discharge
from the runoff estimated by IBIS.

IBIS terrestrial ecosystem model

IBIS is a physically-based model that integrates a variety of
terrestrial ecosystem processes within a single, mechanistic
model to simultaneously calculate a wide range of pro-
cesses, including the land surface water and energy bal-
ances. The model has two vegetation canopies with an
upper layer of trees and a lower layer of shrubs, grasses
and crops, and 15 types of natural vegetation cover com-
prised of a combination of 12 plant functional types includ-
ing woody and herbaceous plants. The soil module has six
soil layers (with a total of 4-m depth in this study). The
dynamics of soil volumetric water content are simulated
for each layer. The soil moisture simulation is based on
Richards' flow equation, where the soil moisture change in
time and space is a function of soil hydraulic conductivity,
soil water retention curve, plant water uptake and upper
and lower boundary conditions. Plant transpiration is a
mechanistic process governed by stomatal physiology, in
IBIS it is tightly coupled to photosynthesis through the
Ball-Berry formulation (Ball et al., 1986). The plant root-
water uptake is a complex function of atmospheric demand,
soil physical properties, root distribution, and soil moisture
profile (Li et al., 2005; Kucharik et al., 2000). IBIS explicitly
simulates surface and sub-runoff on a grid cell basis as a
function of the soil, vegetation, and climate characteristics.
Horizontal runoff transport between grid cells is subse-
quently simulated by the THMB hydrological routing model.
Since IBIS has already been described by Foley et al. (1996)
and Kucharik et al. (2000), and a thorough introduction of
the hydrological modules of IBIS over West Africa was made
by Li et al. (2005), further details are omitted here.

THMB hydrological routing model

THMB transports local surface and subsurface runoff across
the land surface to oceans or inland basins, estimating flows

133 and storage at all points in the basin at 5-min horizontal res-
 134 olution (Coe et al., 2002). The model is based on a linear
 135 reservoir model that simulates water transport in terms of
 136 river routing directions derived from water head, residences
 137 times within a grid cell, and effective flow velocities. The
 138 total water influent into each grid cell is the sum of the land
 139 surface runoff (R_s), subsurface runoff (R_d), precipitation
 140 (P_w) and evaporation (E_w) over the surface waters, and
 141 the water flow from upstream and to downstream grid cells
 142 ($m^3 s^{-1}$). The water transport is represented by the time-
 143 dependent change of three water reservoirs: river water
 144 reservoir (W_r), surface runoff pool (W_s) and subsurface
 145 drainage pool (W_d). W_r contains the sum of upstream and lo-
 146 cal water in excess of that required to fill a local surface
 147 water depression. W_s represents the water that has run
 148 off the surface locally, while W_d is the water that has
 149 drained through the local soil column. All three reservoirs
 150 are represented in m^3 and flow is governed by the following
 151 differential equations:

$$\begin{aligned} d(W_s)/dt &= R_s - W_s/T_s \\ d(W_d)/dt &= R_d - W_d/T_d \\ d(W_r)/dt &= (W_s/T_s + W_d/T_d) \times (1 - A_w) + (P_w - E_w) \\ &\quad \times A_w - (W_r/T_r) + \sum F_{in} \end{aligned} \quad (1)$$

154 where A_w is the fractional water area in the grid cell that is
 155 simulated by THMB, ranging from 0 (no water present) to 1
 156 (the grid cell completely covered by a lake, wetland, or res-

ervoir); T_s , T_d and T_r are the residence times (s) of the
 water in each of the reservoirs; P_w and E_w are the precipita-
 tion and evaporation rates ($m^3 s^{-1}$) over the surface water,
 respectively, and $\sum F_{in}$ is the net water flux (m^3/s^{-1}) into
 the cell (+ or -) and is the sum of the fluxes in from up-
 stream grid cells minus the flux out to downstream cells.
 For details of the model, readers are referred to Coe
 (2000, 1998) and Coe et al. (2002).

Experimental design

Two large basins, the Lake Chad Basin (hereinafter referred
 to as LCB) and the Niger River Basin (referred to as NRB),
 were selected for the simulations (Fig. 1). The former is lo-
 cated in northern central Africa, spreading over seven coun-
 tries. The latter, the second largest basin in Africa located
 in western Africa, is shared by 11 countries. Both basins,
 each with an area of over 2 million km^2 , straddle the bound-
 ary between the Sahara desert and moist tropical forest to
 the south and are characterized by high precipitation vari-
 ability at various time and space scales (Nicholson, 2000,
 1988). The annual rainfall varies from less than 100 mm in
 the north to more than 1300 mm in the south, with an aver-
 age of 373 mm/yr for the LCB and 425 mm/yr for the NRB
 in the simulation area. There is little vegetation in the arid
 northern part of the basins, while in the south the vegeta-
 tion is dominated by savanna and grassland, with a small
 portion of tropical forest distributed along the south edge

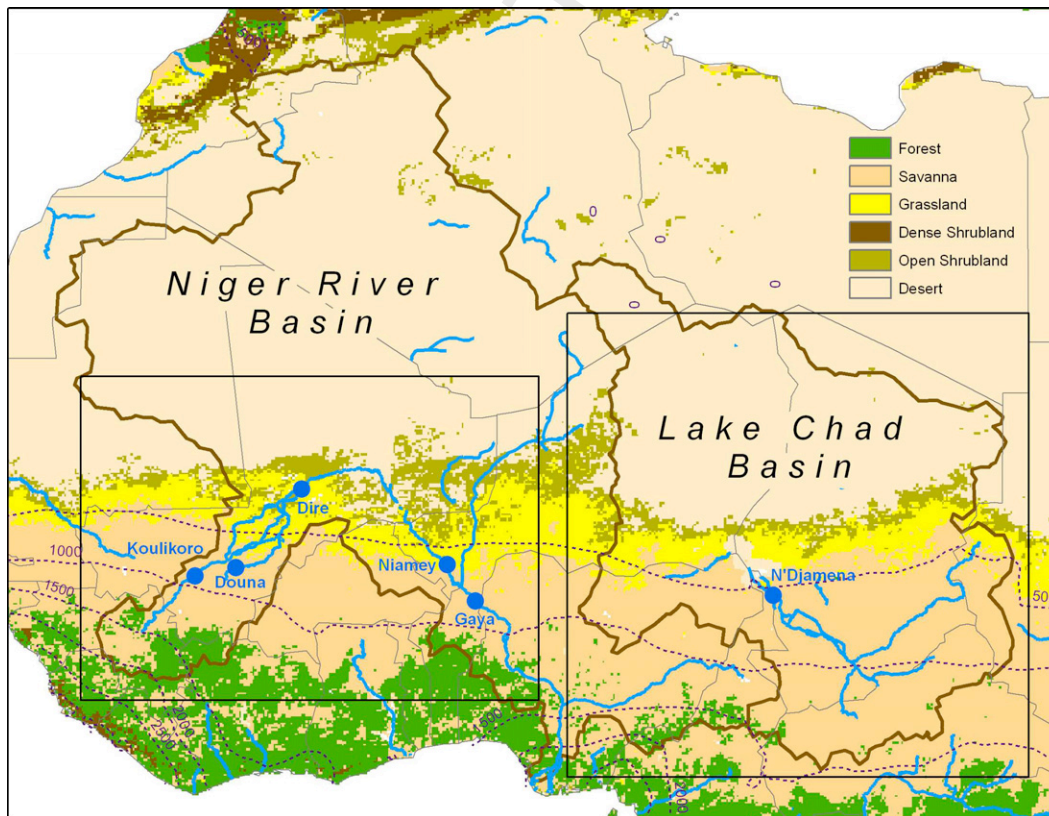


Figure 1 The Lake Chad Basin (LCB) and the Niger River Basin (NRB) (outlined in dark blue) and the simulation domains (black boxes). The potential vegetation (Ramankutty and Foley, 1999) is shown at 1 km resolution. Precipitation contours are overlaid as dashed black lines and discharge stations reported in text are shown in light blue.

183 of the NRB. This strong north-south gradient of precipitation
184 and vegetation is ideal for simulations aimed at mechanistic
185 interpretation of the land cover change impact. IBIS was
186 calibrated with the vegetation fixed to the potential natural
187 types by Li et al. (2005), and the experimental simulations,
188 in this study, were conducted based on the same potential
189 vegetation types (derived from Ramankutty and Foley,
190 1999).

191 The idealized land cover change experiments in this
192 study represent deforestation (or thinning) and overgrazing.
193 Forest thinning and overgrazing of grasslands were simu-
194 lated across a wide range of degrees, including 25, 50, 60,
195 70, 80, 90 and 100%, where 100% thinning was regarded as
196 clearcutting or complete removal of grasses. Within IBIS,
197 the implementation of forest thinning and overgrazing by
198 various degrees involved proportionally decreasing paramete-
199 r values of the potential leaf area index and canopy frac-
200 tional cover for each vegetation type in question.

201 The experiments include a control simulation (with po-
202 tential natural vegetation and modern climate for the peri-
203 od 1935–1995) and a series of land cover simulations as
204 indicated above. For all experiments IBIS was run at the res-
205 olution of $0.5^\circ \times 0.5^\circ$ and a time step of 1 h, and THMB at
206 the resolution of $5' \times 5'$ and a time step of 1 h. The control
207 simulation used monthly mean climate data for a period of
208 61 years from 1935 to 1995 (New et al., 2000), potential nat-
209 ural vegetation type derived from Ramankutty and Foley
210 (1999) and soil type from IGBP-DIS (1998) as used by Coe
211 and Foley (2001). IBIS generates daily and hourly weather
212 from monthly weather data using a stochastic weather gener-
213 ator. The land cover change scenarios used the same cli-
214 mate and vegetation data over the same period of time,
215 with our vegetation perturbations superimposed on them.

216 **Model calibration and validation**

217 The basin integrated mean annual runoff from IBIS was cal-
218 ibrated and validated by Li et al. (2005) using long-term riv-
219 er discharge data. The control (potential vegetation)
220 experiment used in this study is the same as that calibrated
221 and validated by Li et al. (2005). The validation by Li et al.
222 (2005) showed good agreement between simulated annual
223 mean runoff and river discharge, with the normalized root
224 mean square error for all station-years not used in the cal-
225 ibration being 16% and the relative error being 3%. There-
226 fore, the water budget as a function of the climate and
227 land surface characteristics is well simulated by IBIS in these
228 basins. For details of the calibration and validation of IBIS
229 for the study basins, readers are referred to Li et al. (2005).

230 **Results and discussion**

231 In both LCB and NRB, about one half of the simulated area is
232 covered by desert in the north and the other half by vegeta-
233 tion in the south: desert plants, open shrub, grass/steppe,
234 savanna and tropical broadleaf evergreen green trees are
235 successively distributed from north to south (Fig. 1). The
236 different vegetation types correspond to the rainfall re-
237 gimes (Fig. 2), with observed average annual precipitation
238 (calculated from the New et al., 2000 dataset for the period
239 1935–1995) being 230 mm (in LCB) and 236 mm (in NRB) for

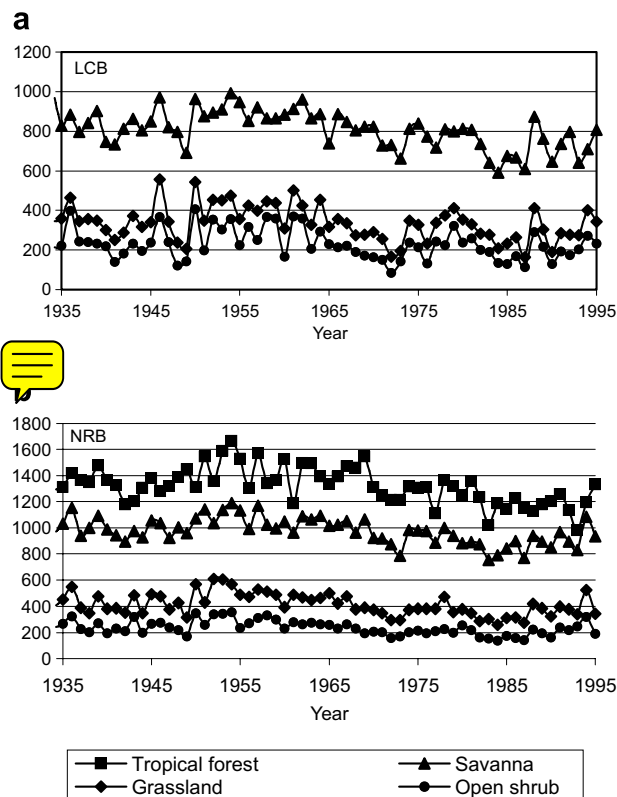


Figure 2 Annual rainfall (mm/yr) from 1935 to 1995 for the different potential vegetation zones in: (a) Lake Chad Basin (LCB); and (b) Niger River Basin (NRB). Rainfall values from New et al. (2000).

the open shrub, 336 mm (in LCB) and 412 mm (in NRB) for
the grassland, 808 mm (in LCB) and 976 mm (in NRB) for
the savanna, and 1322 mm (in NRB) for the tropical ever-
green forest.

244 **Deforestation**

245 In this section, we discuss the experimental results for
246 deforestation of the tropical broadleaf evergreen forest
247 vegetation type, first for 100% removal of all vegetation
248 and then for progressive fractional thinning of the forest.
249 Although the mode of deforestation applied in this study is
250 unrealistically simple (complete removal of all vegetation),
251 the results are instructive because they provide a clearer
252 understanding of the non-linear responses of the hydrologi-
253 cal cycle to progressive vegetation changes. Tropical broad-
254 leaf evergreen forest constitutes a very small portion of the
255 potential vegetation of this region. In the LCB there is no
256 tropical evergreen forest in our experiments, while in the
257 NRB it covers less than 5% of the basin area. However, as
258 discussed below, that small portion of the NRB, i.e., the
259 tropical broadleaf evergreen forest, represents a very
260 important part of the NRB water budget.

261 With 100% removal of the tropical forest vegetation the
262 runoff rate in the forest area averaged for the entire 61-
263 year period increases by 378 mm/yr, from 203 mm/yr (with
264 potential vegetation) to 581 mm/yr (with no vegetation)
265 (Fig. 3), which is equivalent to an increase of 186%. The run-

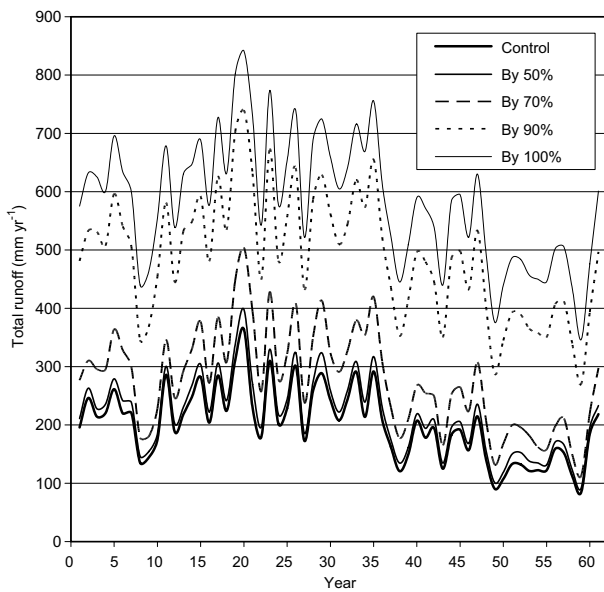


Figure 3 Comparison of total runoff (mm/yr) summed over the tropical forest region of NRB for the potential vegetation (control) experiment (thick black line) and deforestation experiments. Shown are results for 50%, 70% and 90% and 100% removal of vegetation. The x-axis shows the year since 1935.

266 off ratio (the ratio of annual runoff to annual rainfall) in-
267 creases from 0.15 in the control experiment to 0.44 (with
268 100% deforestation).

269 Because of the relatively high precipitation rates in the
270 tropical forest area of the NRB, this region provides a large
271 portion of the water in the Niger River system despite occu-
272 pying less than 5% of the total NRB area. The runoff gener-
273 ated from the forest region before deforestation accounts
274 for 21% of all runoff generated in the entire basin, and this
275 increases to 44% when 100% deforestation is applied. As a
276 result, the impact of the clearcutting experiment extends
277 to the downstream unforested portions of the basin. For
278 example, the runoff increase in the forested area results
279 in a large increase in streamflow in all downstream stations
280 (some 1000s of km downstream, Fig. 4). The long-term aver-
281 age increase in annual river discharge is about 35% at Koulik-
282 ora, Dire, Niamey, and Gaya on the mainstem of the river,
283 and 65% at Douna, which is a heavily-forested sub-
284 watershed.

285 The very large increase in total runoff (378 mm/yr) in our
286 100% deforestation experiment is due to an equally large de-
287 crease in total evapotranspiration (the sum of the plant tran-
288 spiration and evaporation from the soil surface and of
289 rainfall intercepted by the canopy leaves and stems). In
290 our idealized clearcutting experiment all vegetation is re-
291 moved in the forested region (both upper and lower canopy)
292 and as a result, there is no transpiration or evaporation of
293 rainfall intercepted by the canopy leaves and stems. There-
294 fore, evaporation is limited to that from the bare soil. Evap-
295 oration from the bare soil is substantially increased in the
296 deforestation experiment (to about 738 mm/yr, Fig. 5), be-
297 cause more soil is exposed, more moisture and energy reach
298 the land surface, and the land surface temperature in-

creases. However, this increase in surface evaporation is
much less than the total evapotranspiration (1121 mm/yr)
that occurred with intact vegetation because surface evap-
oration cannot access water in the deeper soil layers and
because evaporation of intercepted water from the forest
canopy is eliminated.

In our deforestation experiment both surface and sub-
surface runoff increase. About 20% of the 378 mm/yr in-
crease in total runoff is due to surface runoff increase
because some of the water that was formerly vegetation-
intercepted evaporation became overland flow (Fig. 5).
About 80% of the increase is due to an increase in sub-sur-
face drainage of soil moisture that would have been tran-
spired by plants in the control experiment. In the control
experiment, only about 18% of the total runoff is from
sub-surface drainage. In the deforestation experiment
sub-surface drainage becomes about 60% of the total,
which indicates that in the control experiment, most of
the water that enters the soil column is eventually tran-
spired by the forest.

The magnitude and individual proportions of the simu-
lated runoff changes are unrealistic to the extent that we
have maximized the vegetation change and not changed
the soil compaction characteristics. However, they do
clearly illustrate the pathways to changing hydrology as a
result of vegetation changes. As natural vegetation is re-
moved, decreased root water uptake results in increased
soil moisture content and thus increased baseflow, even
when total soil water infiltration may decrease. While evap-
oration at the surface is increased, due to higher tempera-
tures and less vegetation cover, greater soil saturation and
surface water ponding result in greater overland flow dur-
ing rain events. This is consistent with observed increases
in both overland runoff and baseflow following deforestation
(Costa et al., 2003; Bruijnzeel, 1990; Bosch and Hewlett,
1982).

In order to better understand the response of hydrology
to progressive forest removal we made a series of simula-
tions with progressive thinning of the forest in NRB, includ-
ing 25, 50, 60, 70, 80, and 90%. The results show a non-
linear response of the water balance to vegetation removal:
runoff and discharge did not markedly increase until more
than 50% of the vegetation was removed (Fig. 3). This
non-linear runoff change with the progressive thinning can
be explained, as discussed below, by the non-linear re-
sponse of transpiration and evaporation.

To illustrate the hydrological response to land cover
change, an exponential equation was developed to fit the
data for evapotranspiration or transpiration changes with
deforestation and overgrazing, expressed as

$$W = W_0 - aRe^{(bR)} \quad (2)$$

where W can be either evapotranspiration (ET, mm/yr) or
transpiration (T , mm/yr); W_0 is either baseline evapotran-
spiration (ET_0 , mm/yr) or baseline transpiration (T_0 , mm/yr)
without deforestation or overgrazing; R is either the defor-
estation (R_d , %) or overgrazing percentage (R_g , %); and a
and b are fitting parameters. Similarly, another exponential
equation was developed for evaporation (excluding plant
transpiration), represented as

$$E = (E_0 - c) + ce^{(dR)} \quad (3)$$

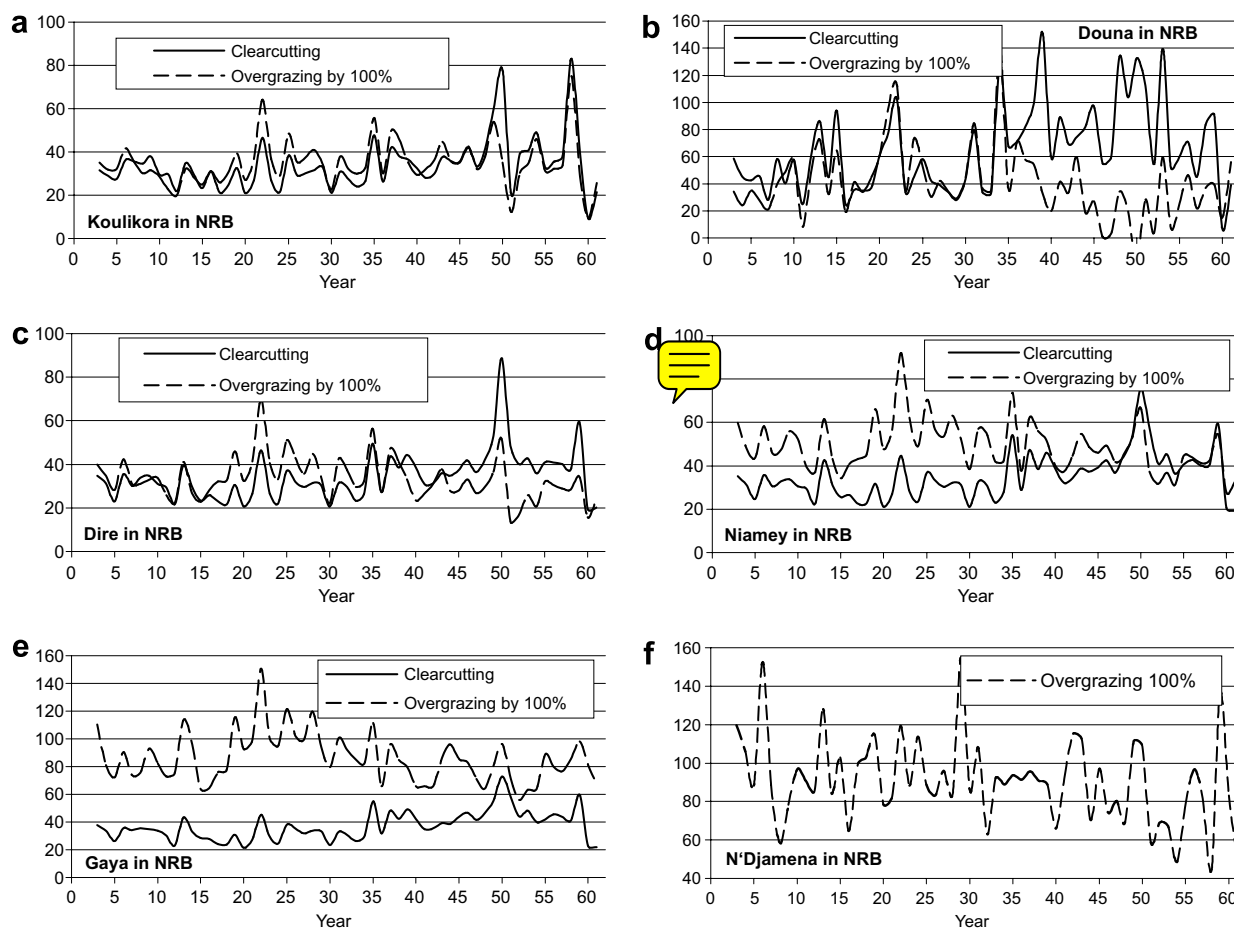


Figure 4 The percent increase in annual mean river discharge compared to the control due to 100% removal of the tropical forest (clearcutting, solid line) and 100% lower canopy vegetation removal in savanna and grassland areas (overgrazing, dotted line) in Niger River Basin (NRB) and Lake Chad Basin (LCB). The time series a–f refer to individual stations, a–e within the Niger River system moving from upstream to downstream, f on the Chari River in the Lake Chad Basin (see Fig. 1 for station locations).

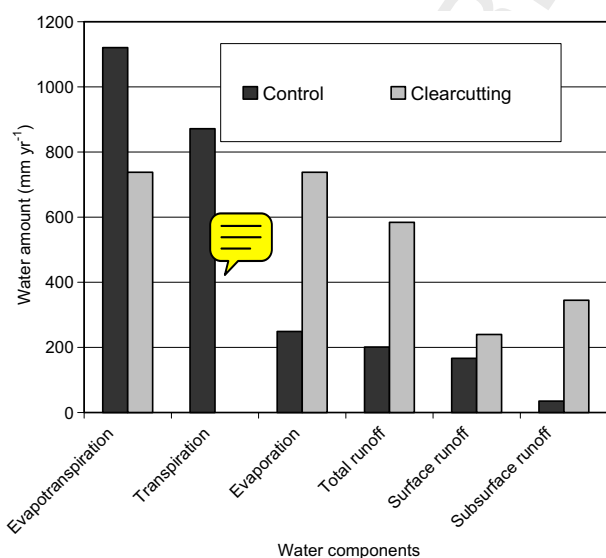


Figure 5 Simulated water balance components for control (potential vegetation) and deforestation (clearcutting) experiments in the NRB summed over the forest region (see Fig. 1).

where E is evaporation (mm/yr), E_0 is baseline evaporation without deforestation or overgrazing (mm/yr); R is the deforestation or overgrazing percentage (%); and c and d are the fitting parameters.

With 60% of the vegetation removed in the tropical forest region the simulated total evapotranspiration has decreased by only a few percent (Fig. 6). However, with greater than 60% deforestation evapotranspiration decreases rapidly to about 16% less evapotranspiration at 80% deforestation, 26% less at 90% and 34% less at 100% deforestation. The non-linear response is a result of the competition between increasing evaporation and decreasing transpiration (Fig. 6). The evaporation term increases non-linearly with increasing deforestation but the exponent is relatively small. Less water is intercepted by vegetation (not shown) and evaporated as deforestation progresses but more water reaches the ground and the thinning forest steadily exposes more bare ground for evaporation. The transpiration term, however, responds more slowly to initial forest reduction. For example, the experiment with 50% forest cover reduction has a transpiration decrease that is 23% of the decrease that occurs in the 100% forest removal experiment (Fig. 6). The slower transpiration response is because initially forest

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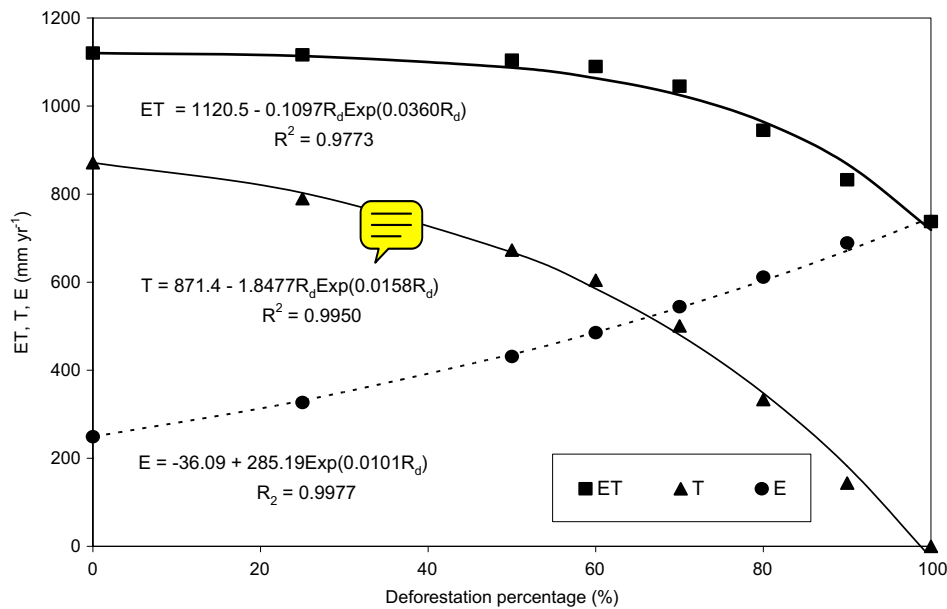


Figure 6 The relationships between the percentage removal of tropical evergreen forest (R_d) in the Niger River basin (NRB) and evapotranspiration (ET), transpiration (T) and evaporation (E).

386 thinning is largely compensated by an increase in the tran-
387 spiration rate per unit leaf area and the concomitant in-
388 crease in extraction of water from the soil per unit root
389 mass. There is less competition between individual leaves
390 (or stomata) and roots for the relatively limited water re-
391 source and thus the total amount of water transpired does
392 not greatly decrease. Additionally, more water reaches
393 the surface and likely infiltrates the soil, since the soil char-
394 acteristics are not changed in the simulation. However,
395 after about 60% of the vegetation is removed the vegetation
396 water stress is greatly reduced, the evaporative demands
397 are more frequently met (not shown), and any reduction
398 in vegetation leads directly to reduction in total transpira-
399 tion. The runoff variations are inversely consistent with
400 the evapotranspiration changes and therefore, there is no
401 marked increase in runoff when the deforestation percent-
402 age is below 60% (not shown).

403 To test how precipitation amount influenced the struc-
404 ture and location of the non-linear response we re-ran the
405 suite of deforestation simulations with the monthly
406 precipitation increased by 33% over the forest region.
407 We limited our sensitivity analysis to this one region and
408 precipitation change because of the large number of
409 simulations required (8 simulations for each vegetation
410 and precipitation combination). The results indicate a
411 modest shift in the threshold at which evapotranspiration
412 begins to decrease greatly but no change in the basic
413 shape of the response curve. For example at 60% forest
414 removal, there is a 10% decrease in evapotranspiration
415 and at 80% removal a 25% decrease, compared to a few
416 percent and 16% decrease for our initial experiments,
417 respectively (not shown). At 100% removal there is a 41%
418 decrease compared with 34% in the original experiment.
419 This shift towards earlier onset of the threshold and great-
420 er total decrease in evapotranspiration is consistent with
421 there being more moisture in the soil with the higher

precipitation rate, reduced plant water stress under these 422
conditions, and therefore less ability at any given defores- 423
tation amount to compensate for decreased LAI with in- 424
creased water use per leaf area compared to the lower 425
precipitation rate. 426

Our numerical simulation results on forest thinning are 427
consistent with a field experiment made in Finland (Heiku- 428
rainen, 1967), for which there were four treatments of for- 429
est thinning with stand removal of 31, 33, 60, and 86%, 430
respectively. The groundwater levels were monitored for 431
the experiment, and the results showed that the treatments 432
of 31% and 33% did not markedly increase the groundwater 433
levels, while the treatment of 60% slightly and the treat- 434
ment of 86% greatly increased the groundwater levels. Our 435
simulation results on the impact of forest clearcutting and 436
thinning are also consistent with a field experimental study 437
in China, reported in a review by Shi and Li (2001), wherein, 438
clearcutting induced a runoff increase of 14.4%, while thin- 439
ning, that reduced the canopy cover from 95% to 60%, 440
caused only a 0.9% increase. 441

Overgrazing 442

Overgrazing in this study was simulated by progressively 443
thinning the lower canopy vegetation of both grassland 444
and savanna vegetation types. The savanna, also known as 445
tropical grassland, is a grassland with scattered shrubs and 446
isolated trees, and is found in a wide band on either side 447
of the equator poleward of tropical rainforests. In NRB 448
and LCB, savanna and grassland are the dominant vegeta- 449
tion types, distributed to the south of the Sahara desert 450
and to the north of the tropical rainforest. Overgrazing in 451
this region has become a major environmental concern 452
(Nicholson et al., 1998; Xue and Shukla, 1993; Charney, 453
1975), and an evaluation of its impact on the hydrological 454
cycle is useful. 455

456 Similar to the forest thinning experiments, overgrazing
457 was simulated at 25, 50, 60, 70, 80, 90 and 100% of the
458 grassland and savanna regions but applied to the lower canopy
459 vegetation only. There is no noticeable increase in simulated
460 runoff with overgrazing less than 70% on savanna or
461 80% on grassland, and the runoff increases rapidly when
462 the overgrazing percentage is greater than these thresholds
463 (not shown). Eq. (2) was fitted to the evapotranspiration
464 and transpiration data, respectively, and Eq. (3) to the
465 evaporation data. For reasons similar to the deforestation
466 experiment, there is no significant reduction in evapotranspiration
467 and hence no significant increase in runoff, provided
468 the overgrazing is below the threshold (Fig. 7a and
469 b). The threshold for grassland (80%, not shown) and for savanna
470 (70%, Fig. 7a and b) is greater than that for the tropical
471 forest (50%). This suggests that water yield is less
472 sensitive to grassland change than savanna change, and
473 far more sensitive to tropical forest change. The differences
474 in the response among vegetation types can be attributed to

the different rainfall regimes they are associated with (Fig. 2): the higher the precipitation rate, the more sensitive the hydrology is to land cover change (Bosch and Hewlett, 1982), and to the changes in canopy structure and surface roughness. At low precipitation rates the very large difference between the relatively small water supply and large evaporative demand means that increased transpiration per unit leaf area and evaporation from the soil and ephemeral pools can compensate for the progressive loss of vegetation (Fig. 7a and b). Only when vegetation cover becomes small (<30% for savannah and <20% for grassland) does the available water begin to exceed evaporative demand and the soil moisture becomes cut off from surface evaporation so that runoff increases.

While precipitation in savanna and grassland areas is much lower than in tropical rainforest areas, savanna and grasslands cover a much larger portion of the basins. Hence, large-scale overgrazing can cause substantial increases in streamflow in the river systems within both basins (Fig. 4).

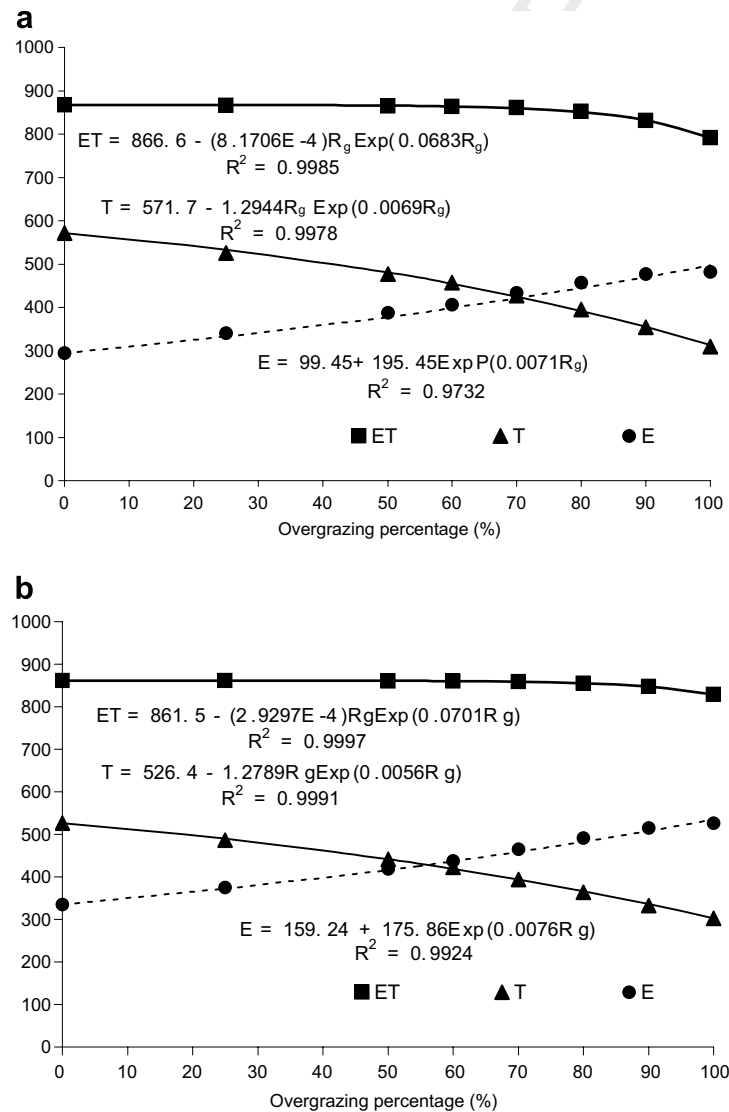


Figure 7 The relationships between the overgrazing percentage (R_g) and evapotranspiration (ET), transpiration (T) and evaporation (E) rates (mm/yr) for savanna in: (a) Niger River Basin (NRB); and (b) Lake Chad Basin (LCB).

494 The long-term average increase in streamflow with 100%
495 overgrazing is 91% for N'Djamena in LCB, and in NRB are
496 33% for Dire, 35% for Koulikora, 41% for Douna, 49% for Nia-
497 mey and 86% for Gaya. Similar to deforestation, the large in-
498 crease in streamflow is mainly due to enhanced baseflow
499 (data not shown). Fig. 4 shows the extreme case (i.e., over-
500 grazing is 100%); when the overgrazing percentage is de-
501 creased, there is very little impact of vegetation thinning
502 on runoff below the threshold of 70–80% removal of savan-
503 nas and grasslands, respectively (not shown). It should,
504 however, be noted that in the long term overgrazing may
505 lead to other ecological and hydrological problems such as
506 desertification and climate change (Zeng et al., 1999; Wang
507 and Eltahir, 2000) and that these effects can be more persis-
508 tent in drier areas because of the slow recovery of
509 vegetation.

510 Runoff ratios of deforestation and overgrazing

511 The observed runoff ratio (the ratio of average annual run-
512 off to average annual rainfall) is higher in moist areas than
513 in dry areas. Observed values in Africa range from much less
514 than 5% for precipitation <500 mm/yr to greater than 50%
515 for precipitation greater than 2000 mm/yr (Ashton, 2002).
516 Within a region, the runoff ratio is a useful measure to eval-
517 uate the effect of land cover change because the effect on
518 runoff is normalized by the precipitation regime. Similar to
519 the function used to fit simulated evaporation (Eq. (3)), the
520 following exponential equation was used to fit the simulated
521 runoff ratio data:

$$523 \quad r = (r_0 - g) + ge^{hR} \quad (4)$$

524 where r is the simulated runoff ratio, and r_0 simulated base
525 runoff ratio without deforestation or overgrazing, R defor-
526 estation or overgrazing percentage (%), and g and h are
527 empirical fitting parameters. Different vegetation types
528 have different baseline runoff ratios (Fig. 8): the baseline
529 runoff ratio for tropical forest (0.154) is larger than for sav-
530 anna (0.113 for NRB and 0.048 for LCB), and that for savan-
531 na is greater than for grassland (0.016 for NRB and 0.001 for
532 LCB). The simulations indicate that the precipitation regime
533 has a large influence on the runoff ratio (Fig. 8). However
534 the vegetation cover does have an influence: when defores-
535 tation or overgrazing is greater than the threshold the run-
536 off ratio rises dramatically.

537 Summary and conclusions

538 We used a terrestrial ecosystem model (IBIS) and an aquatic
539 transport model (THMB) to investigate the sensitivity of the
540 hydrological cycle and water resources to land cover
541 changes in West Africa. The land cover changes involved
542 progressive removal from 25–100% of forest, savanna, and
543 grassland.

544 The numerical simulation results show that although
545 tropical forests represent only a very small portion of this
546 region (none in the LCB and <5% of the NRB), total defores-
547 tation results in a substantial increase in simulated stream-
548 flow of the Niger River (by 35% to 65%, depending on the
549 location). Overgrazing also has a considerable impact on
550 the water yield, with simulated streamflow increases (for

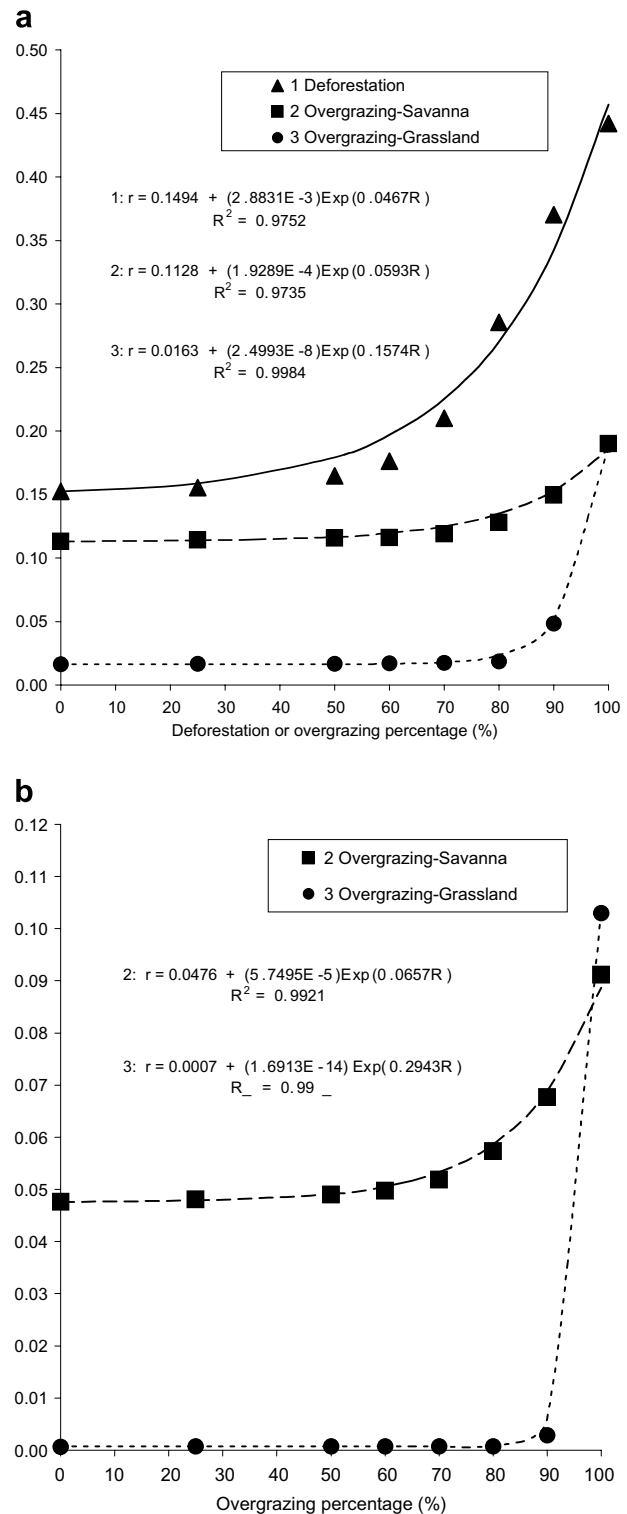


Figure 8 The relationship between runoff ratio (r) and the deforestation thinning percentage or overgrazing percentage (R) in: (a) Niger River Basin (NRB); and (b) Lake Chad Basin (LCB).

100% overgrazing) ranging from 33% to 91%. Importantly, 551
the numerical results also indicate that the hydrological re- 552
sponse to the land cover change is non-linear with thresh- 553
olds: there is little impact on the simulated water yield 554

555 when the deforestation (thinning) is below 50% and the
556 overgrazing is below 70% for savanna and 80% for grassland;
557 however, water yield rapidly increases when above these
558 thresholds.

559 This threshold effect is a function of the way in which
560 transpiration and evaporation separately respond to the
561 land cover changes. Initially with clearing, transpiration de-
562 creases more slowly than evaporation increases, because
563 the plants not cleared are able to increase their transpira-
564 tion per unit leaf area and root water uptake per unit root
565 mass to meet plant water demands. As a result, runoff does
566 not markedly increase until deforestation or overgrazing
567 reaches a point at which the plant water stress becomes
568 very small such that any further reduction of vegetation re-
569 sults in a direct reduction of the net transpiration. After this
570 threshold is reached the increase in soil evaporation cannot
571 compete with the decrease in plant transpiration, thus total
572 evapotranspiration decreases and runoff increases rapidly.

573 Although, the particular method we chose in this study to
574 investigate the response of the hydrology to land cover
575 change is likely unrealistic (complete conversion of very
576 large regions to bare soil) the change is similar to well-doc-
577 umented regional-scale degradation of vegetation due to
578 overgrazing, conversion to crops, and fuelwood extraction
579 (Dregne et al., 1992; Lambin and Erlich, 1997; Favreau
580 et al., 2002; Ramankutty, 2004). Further, observations have
581 confirmed large increases in water yield with destruction of
582 natural vegetation. For example, observational analysis in
583 the Niger basin has documented, decreased evapotranspira-
584 tion, an order of magnitude increase in ground water re-
585 charge, and the formation of surface water ponds in
586 regions where natural savannah has been replaced with less
587 water demanding millet in the last 50 years (Leduc et al.,
588 2001; Favreau et al., 2002).

589 The exact nature of these results is, of course, experi-
590 ment dependent. We did not include changes to soil infiltra-
591 tion rates or water holding capacity with vegetation
592 changes. These factors have an impact on the location of
593 the non-linear water yield threshold through their controls
594 on generation of surface runoff and available soil moisture.
595 Soil compaction and decreased infiltration generally accom-
596 panies deforestation and overgrazing and can significantly
597 increase surface runoff (Leduc et al., 2001; Favreau
598 et al., 2002). Therefore, it is likely that our simulated
599 threshold is conservative: including realistic changes in soil
600 properties may lower the threshold at which runoff in-
601 creases drastically with vegetation change.

602 The exact response of the model to vegetation changes is
603 also a function of the model itself: how physical processes
604 and parameterizations are represented and the structure
605 of the model. Processes of particular importance (e.g., sur-
606 face water ponding, soil evaporation, canopy water stress,
607 and root water uptake) have been carefully addressed and
608 numerous improvements have been made to IBIS by Li
609 et al. (2005, 2006) to better represent them. Therefore, it
610 is most likely that the representation of these processes
611 and the overall response of the model (if not the exact mag-
612 nitude) is reasonable. However, the model does not cur-
613 rently take into account sub-grid spatial variability in
614 climate forcing, soil physical properties, and vegetation
615 type, which may introduce some bias. For example, the
616 structure of the model dictates that any vegetation change

is uniform within each grid cell: 50% deforestation or over-
grazing means that the entire grid cell has a 50% reduction
in biomass (above and below ground). Whereas, in the real
world changes can be more heterogeneous; a 50% reduction
could be 100% reduction over 50% of the area. This is impor-
tant because in this particular example, the total runoff
from the real world would be significantly increased over
50% of the area, while in the model, for a comparable area,
the threshold would not yet be crossed and the runoff would
not measurably increase. Therefore, again, the simulated
water yield threshold may be conservative.

This study does not consider the ecological conse-
quences of vegetation changes, which are likely to be large
and may outweigh the gains from increased water avail-
ability. Nor does it consider atmospheric feedbacks that
may be important when vegetation changes occur across
large spatial extent (100,000 km²). For example, Wang
and Eltahir (2000) showed with a numerical model that
when feedbacks between the land surface changes and
atmosphere are included, removal of as little as 20% of
the vegetation of the entire Sahel can cause a significant
reduction in simulated regional rainfall, thus counter-bal-
ancing runoff gains that may be incurred from decreased
transpiration. Net changes to runoff when all aspects are
considered therefore, remain uncertain. The results of this
study are an exploration of the sensitivity of hydrology to a
particular aspect of the larger ecosystem dynamics. They
are likely to be representative of the response of the
hydrology to vegetation changes over small regions but
atmospheric feedbacks must be considered when the total
area affected becomes large. Nevertheless, this study,
which provides insight into how hydrology responds to land
use change, will be useful in the analyses of interactions
and feedbacks between climate, hydrology and land-use
change.

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