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LETTER

# Intensive rainfall recharges tropical groundwaters

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## Abstract

Dependence upon groundwater to meet rising agricultural and domestic water needs is expected to increase substantially across the tropics where, by 2050, over half of the world's population is projected to live. Rare, long-term groundwater-level records in the tropics indicate that groundwater recharge occurs disproportionately from heavy rainfalls exceeding a threshold. The ubiquity of this bias in tropical groundwater recharge to intensive precipitation is, however, unknown. By relating available long-term records of stable-isotope ratios of O and H in tropical precipitation (15 sites) to those of local groundwater, we reveal that groundwater recharge in the tropics is near-uniformly (14/15 sites) biased to intensive monthly rainfall, commonly exceeding the ~70th intensity decile. Our results suggest that the intensification of precipitation brought about by global warming favours groundwater replenishment in the tropics. Nevertheless, the processes that transmit intensive rainfall to groundwater systems and enhance the resilience of tropical groundwater storage in a warming world, remain unclear.

## Introduction

Groundwater is an invaluable, distributed source of freshwater throughout the tropics where it plays a primary role in enabling access to safe water and food security through irrigation. The long-term viability of groundwater resources as well as the ecosystems and livelihoods that they sustain, depends upon replenishment of groundwater by recharge. At present, groundwater withdrawals in the tropics are accelerating [1] and the sustainability of these increases is in doubt [2].

The conversion of precipitation into groundwater recharge at low latitudes is constrained by continuously high rates of potential evapotranspiration [3]. Rare, long-term piezometric data [4, 5] and recharge modelling in this region [6, 7] point to a non-linear relationship between rainfall and groundwater recharge in which intensive rainfalls—defined here as exceeding the median (50th) percentile of local rainfall intensity—contribute preferentially to groundwater recharge. However, the ubiquity of soils across low latitudes that are able to convey intensive rainfall to groundwater via direct or indirect (i.e. via surface waters) recharge pathways is unknown [8]. A fundamental concern is how the intensification of precipitation brought about by anthropogenic warming [9–11] and most pronounced in the tropics, will affect groundwater recharge.

Stable isotope ratios of O ($^{18}O/^{16}O$) and H ($^{2}H/^{1}H$) in rainwater and groundwater can be used to trace the intensity of rainfall that replenishes groundwater resources [12–14]. Outside of the tropics these ratios are closely correlated with surface air temperature, but in the tropics these ratios are strongly determined by site-scale precipitation intensities (figure S1; [15]). Due to differences in the upwind distillation of light versus heavy storm clouds [16], low-intensity rainfalls are relatively enriched in heavy isotopes ($^{18}O$, $^{2}H$) whereas high-intensity rainfalls are comparatively depleted in heavy isotopes. As a result, comparisons of long-term integrated precipitation isotope compositions capturing all rainfall events with sampled groundwater isotope compositions that record recharge-generating rainfall, can trace rainfall intensities that produce groundwater recharge.

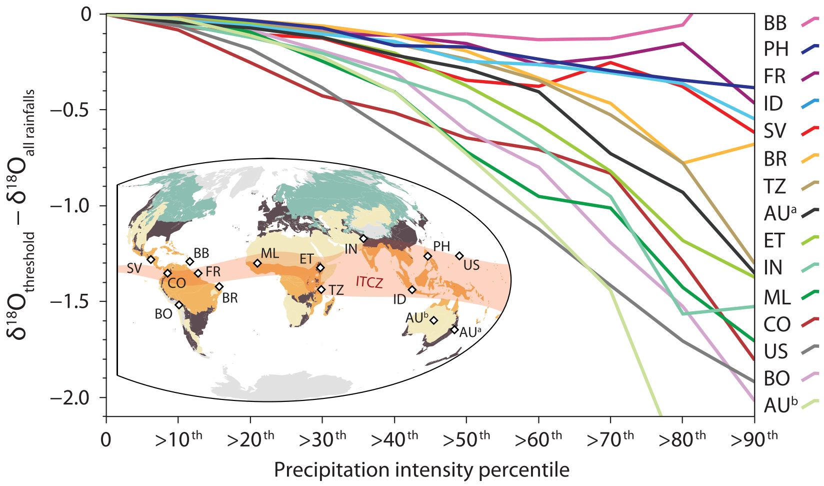


**Figure 1.** Differences between long-term precipitation $\delta^{18}O$ and precipitation $\delta^{18}O$ using data exceeding precipitation intensity thresholds. Each line represents the amount-weighted isotope composition of precipitation using data exceeding a given intensity threshold (e.g., amount-weighted precipitation $\delta^{18}O$ using all precipitation events exceeding the 10th percentile shown as '>10th'). Precipitation $\delta^{18}O$ progressively decreases as precipitation intensity increases. The locations shown in the legend on the right side are ranked in order of calculated '>90th' precipitation $\delta^{18}O$ values The inset map shows locations of study sites (diamonds), ecoregions [31] and the approximate range of the Intertropical Convergence Zone (ITCZ).

Here, we examine the relationship between the stable-isotope composition of precipitation and groundwater at multiple locations across the tropics that feature different climates, land covers and geological contexts. The objective of our study is to test whether intensive rainfalls contribute disproportionately to groundwater recharge across the tropical landmass. Our analysis builds upon and extends a recent global review of stable isotope ratios that demonstrated the seasonality of global groundwater recharge focusing on the extratropics [17].

## Methods

To examine the relationship between the stable-isotope composition of precipitation and groundwater in the tropics we (1) synthesized a pan-tropical isotope dataset, (2) screened groundwater isotope data to isolate observations representing modern recharge, and (3) compared precipitation and groundwater isotope content to evaluate potential biases in precipitation generating groundwater recharge.

We synthesized stable isotope data for groundwater and precipitation at 15 locations (figure 1) that are influenced by monsoonal climates associated with the Inter-tropical Convergence Zone (ITCZ). These locations span a wide range of environments characterized by different geologies and precipitation rates (table 1) and represent all of the available long-term (>7 yr) precipitation isotope records where proximate (less than ∼100 km) groundwater isotope data in the tropics exist. We employ long-term records of precipitation isotope compositions compiled by the IAEA GNIP [15] and a large number of published studies of stable isotope ratios in groundwater (see supplementary material) including data recently compiled by the IAEA TWIN [15]. Groundwater isotope data derive from spot (one-time) sampling campaigns.

Observations of stable isotope ratios of O and H in groundwater were carefully screened to prevent the possibility that these data derive from historical climates (i.e. palaeogroundwaters) or remote climates. The screening process was based on radiochemical ($^{3}H$ and $^{14}C$ activities) and well-depth data (supplementary information) presented in the compiled studies. The screening process is of critical importance since palaeogroundwaters have $\delta^{18}O$ values that differ from modern groundwaters by up to ∼3‰ in the tropics and subtropics [18]. We specifically discounted groundwaters that may have been recharged from leaking rivers sourced from upland precipitation depleted in heavy isotopes as a result of the progressive distillation of air masses driven by orographic rainout (e.g. [19]). Amassed stable isotope observations of groundwater and precipitation from 15 locations are summarized in table 1 and discussed further in the supplementary materials.

After carefully scrutinizing the compiled groundwater data, modern groundwater isotope compositions ($\delta^{18}O_{gw}$) were compared with the amount-weighted precipitation isotope compositions ($\delta^{18}O_{p}$) to test for recharge biases to heavy or light rains. To test for recharge biases to either intense or less intense rainfall, we quantified the long-term precipitation $\delta^{18}O$ integrated by precipitation amount ($\delta_{P\text{-}AW}$):

$$\delta_{P-AW} = \frac{\sum_{j=1}^{n} P_j \cdot \delta_{P_j}}{\sum_{j=1}^{n} P_j}, \quad (1)$$

where $P$ represents monthly precipitation (mm/month), $\delta_P$ represents measured the monthly

**Table 1.** Comparison of tropical precipitation ($p$) and groundwater (gw) $\delta^{18}$O.

| Cntry. | Aquifer | $\delta^{18}O_p$ | $\delta^{18}O_{gw}$ | $n^t$ | Threshold intensity decile[b] | Lithology | Precipitation (mm/year) |
|---|---|---|---|---|---|---|---|
| SV | Chipilapa-Ahuachapin | −6.68 | −7.39 ± 0.26 | 29 | >90th (>80th to >90th), ∼400 mm/month | Volcanics | 1800 |
| CO | Bogota | −9.71 | −10.21 ± 0.71 | 49 | >30th (>0th to >70th), ∼50 mm/month | Alluvium, sandstone | 950 |
| BO | La Paz | −13.99 | −16.46 ± 0.81 | 7 | >90th (>80th to >90th ), ∼160 mm/mo. | Alluvium | 530 |
| BB | Barbados | −1.33 | −2.91 ± 0.84 | 27 | >80th (>70th to >80th), ∼170 mm/month[c] | Limestone | 1240 |
| FR | Guiana Shield | −2.29 | −3.07 ± 0.59 | 10 | >40th to >90th, >300-400 mm/mo. | Weathered gneiss, volcano-sedimentary | 3620 |
| BR | Potiguar Basin | −2.50 | −3.03 ± 1.31 | 6 | >70th (0th to 90th), ∼210 mm/month | Sandstone | 600 |
| ML | Bamako | −4.51 | −5.71 ± 0.86 | 10 | >70th (>40th to >90th), ∼220 mm/month | Sandstone, gneiss, schist | 920 |
| TZ | SE Tanzania Coast | −2.93 | −3.56 ± 1.17 | 9 | >70th (>0th to >90th), ∼140 mm/month | Sandstone | 1140 |
| ET | Akaki Volcanic | −1.26 | −2.28 ± 0.91 | 13 | >70th (>30th to >90th), ∼210 mm/month | Volcanics | 1100 |
| IN | Gangetic Plain | −5.59 | −7.10 ± 0.65 | 49 | >80th (>70th to >90th), ∼160 mm/month | Alluvium overlying quartzites and schists | 770 |
| ID | Jakarta Basin | −5.59 | −6.12 ± 0.49 | 32 | >90th (>10th to >90th), ∼280 mm/month | Alluvium, volcano-sedimentary | 2200 |
| PH | Manila | −6.96 | −6.92 ± 1.00 | 27 | No recharge bias detected | Alluvium, volcano-sedimentary | 2260 |
| US | Guam | −5.02 | −6.61 ± 0.53 | 12 | >70th (>60th to >90th), ∼310 mm/month | Limestone | 2410 |
| AU[a] | Gatton | −4.27 | −4.84 ± 0.55 | 36 | >60th (>10th to >80th), ∼100 mm/month | Sandstone | 1210 |
| AU[b] | Alice Springs | −6.38 | −8.02 ± 1.27 | 7 | >70th (>40th to >80th), ∼30 mm/month | Sandstone | 290 |

[a] $\Delta\delta^{18}O_{gw}$ defined as $\delta^{18}O_{groundwater} - \delta^{18}O_{annual\ precipitation}$ (±1 s.d. from average $\delta^{18}O_{groundwater}$)$^t$ number of modern groundwater $\delta^{18}$O values.

[b] Best estimate shown, thresholds in parentheses represent ±1 s.d. of groundwater $\delta^{18}$O.

[c] Groundwater $\delta^{18}$O values are exceedingly low relative to amount-weighted precipitation. Threshold shown was calculated excluding rains exceeding the >90th decile intensity.

precipitation isotope content, and subscript $j$ refers to a month reporting both isotope content and precipitation amount. Precipitation isotope records that had less than seven years of monthly data were not considered in this study. To quantify potential recharge thresholds we calculated amount-weighted precipitation isotope compositions using a moving lower-limit threshold (e.g., >10th percentile, describes the amount-weighted isotope composition for all precipitation isotope compositions with intensities between the 10th–100th deciles). We then matched groundwater $\delta^{18}$O values with closest matching amount-weighted precipitation isotope composition and report the matching precipitation intensity threshold as the threshold intensity.

## Results

Our analysis is predicated upon an empirical relationship between precipitation isotope ratios and rainfall intensity [20]. In figure 1, we plot the normalized, amount-weighted heavy isotope ($^{18}$O) content of precipitation at each location as a function of progressively more intense rainfall expressed in deciles. For example, 0 represents the precipitation-weighted composition of all monthly rainfalls, whereas >50th precipitation intensity percentile is the precipitation-weighted composition restricted to monthly rainfalls exceeding the median. Figure 1 shows that the heavy isotope ($^{18}$O) content of precipitation throughout the tropics decreases as the monthly precipitation intensity increases. At Barbados (BB), four observations of very intensive (>90th decile) rainfall over a brief period (1973–1974) are anomalously enriched in the heavy isotope content and skew the cumulative distribution (figure S12).

Mean groundwater $\delta^{18}$O values (table 1, figure 2) are lower than the amount-weighted precipitation $\delta^{18}$O at 14 of the 15 locations (figure 2). As high-intensity rainfalls are $^{18}$O-depleted relative to low-intensity rainfalls in the tropics (figure 1), the isotopic data show that groundwater recharge is biased to intensive rainfall (figure 2), consistent with a limited number of site-scale isotopic studies in the tropics [7, 12–14]. Critically, our analysis reveals for the first time that this bias is pan-tropical occurring in a wide range of hydrogeological environments that include alluvial, volcanic, consolidated sedimentary and weathered crystalline rock aquifers. The single exception is at Manila (PH: The Philippines) where the observed depletion in the heavy isotope content of intensive precipitation is minimal (figure 1) with the most intense rains differing by less than 0.04‰ from the long-term precipitation-weighted mean.

Notably, we use isotopic data to trace threshold precipitation intensities producing groundwater recharge. We match mean groundwater isotope compositions with amount-weighted isotope compositions of precipitation under varying precipitation

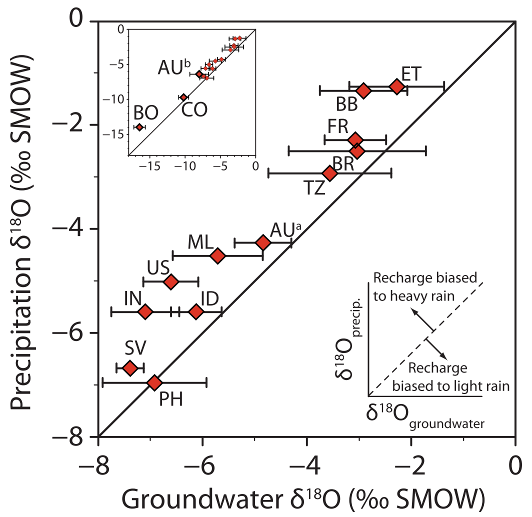


**Figure 2.** Groundwater and amount-weighted precipitation isotope compositions at 15 pan-tropical locations. Most (14 of 15) sites have $^{18}$O- and $^{2}$H-depleted groundwaters relative to long-term amount-weighted precipitation, implying that recharge/precipitation ratios are higher during intensive rains relative to lighter rains (see schematic diagram). The inset in the top left is a replication of the main figure but extends the ranges shown by the $x$ and $y$ axes. Errors mark average ± one standard deviation of modern groundwater $\delta^{18}$O and $\delta^{2}$H). Two-letter country codes representing each study site are shown.

intensity thresholds (figure 3). At locations across tropical Africa (ML, ET, TZ), Asia (IN, ID, GU), Americas (SV, BO, FR, BR, BB) and Australia (AU$^a$, AU$^b$), groundwater isotope compositions (within 1 standard deviation) can be reconciled to monthly rainfalls exceeding the ~70th percentile intensity (range of >30th to >90th percentile); apparent thresholds for each location are summarized in table 1. Under primarily humid conditions, these potential intensity thresholds correspond to rainfall intensities of ~100–300 mm/month, suggesting that rainfall intensities below these thresholds do not contribute substantially to groundwater recharge. For the one site in an arid location (Alice Springs), the apparent monthly precipitation threshold intensity decile is considerably lower, ~30 mm.

## Discussion

Precipitation thresholds traced by isotopic data for generating recharge are indicative rather than definitive. The comparison is complicated by two key uncertainties. First, the representivity of amassed groundwater isotope measurements at locations where observations are few (e.g. BO, BR, TZ in table 1) is uncertain. Second, our analysis implicitly assumes that all intensive rainfalls under progressively higher decile thresholds contribute equally to groundwater recharge. For example, a value of −5.5‰ for $\delta^{18}$O at Bamako (ML) for >70th percentile rainfalls is calculated from the weighted mean average of all rainfalls

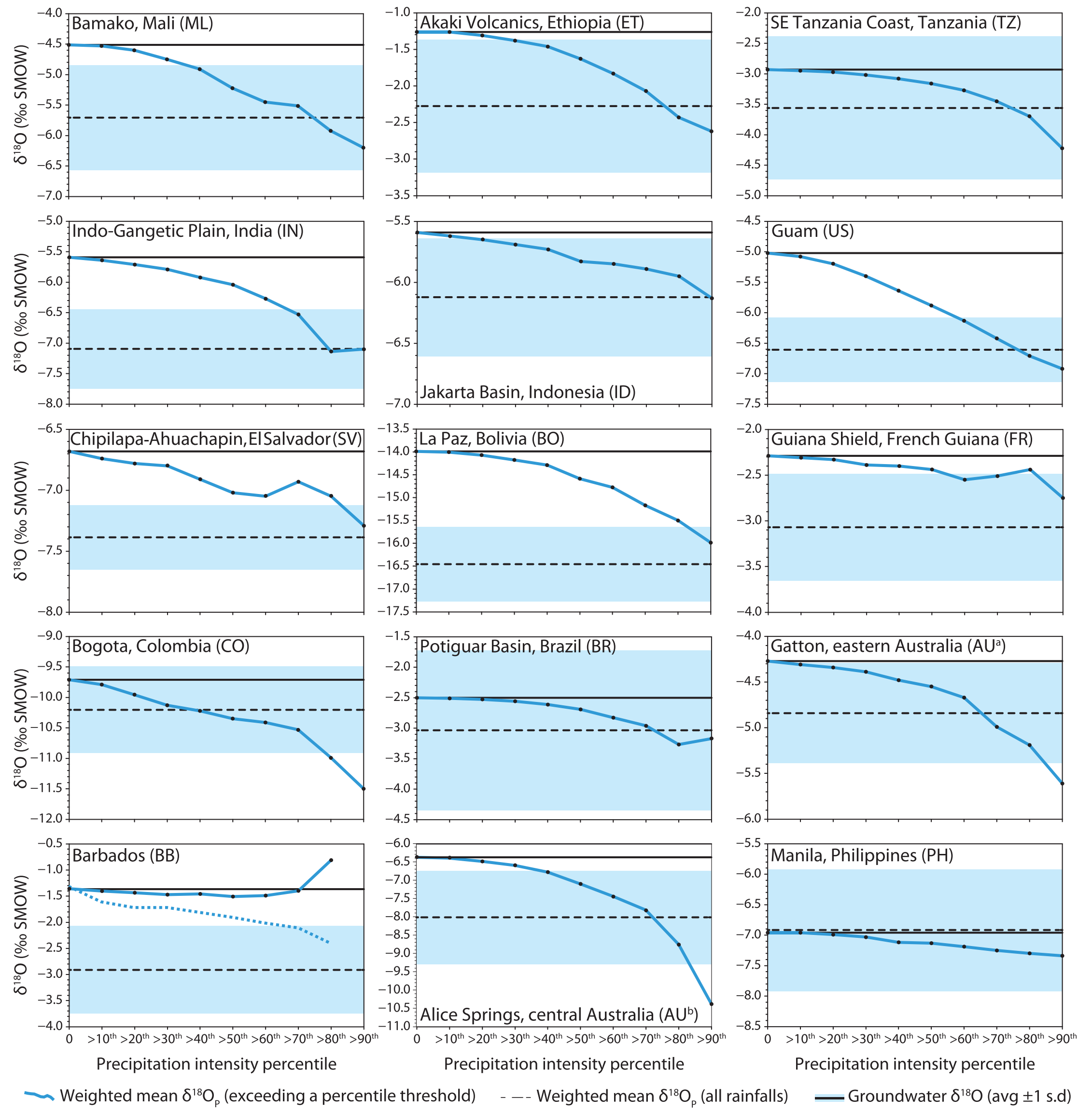


**Figure 3.** Long-term amount-weighted precipitation $\delta^{18}$O using data exceeding precipitation intensity thresholds and local groundwater $\delta^{18}$O values (dashed line and grey shading mark the average ±1 s.d.). The intersection of groundwater $\delta^{18}$O and the amount-weighted precipitation $\delta^{18}$O under varying precipitation intensities provides an approximation of possible precipitation intensity thresholds required to initiate groundwater recharge. Note that for one location (BB: Barbados) an additional dotted line excluding precipitation isotope data exceeding the 90th percentile intensity, is also plotted for comparison (dashed blue line); no explanation is currently available as to why a small number of months (four) are anomalously enriched in the heavy isotope of O and H.

exceeding this percentile. However, limited piezometric data [4] reveal that the proportion of very heavy, statistically extreme rainfalls (e.g. >95th percentile) that is converted to groundwater recharge, can be substantially greater than comparatively less intensive (e.g. 80th percentile) rainfalls (figure S7 in supplementary materials). Further, antecedent moisture can strongly influence the proportion of intensive rainfall that is converted to groundwater recharge [6].

That groundwater in the tropics can be traced to intensive rainfall has two important implications. First, it indicates that soils associated with a range of geological, climatological and land-use conditions are able to transmit intensive rainfall, defined here as monthly rainfall exceeding the median, to shallow aquifers. This finding is consistent with hydrometric evidence from weathered crystalline rock aquifers in Tanzania [4] and Uganda [5] that show rapid water-table rises to intensive rainfall. Neither the isotopic data nor current hydrometric observations reveal, however, the processes by which intensive rainfall is conveyed to groundwater. Whether recharge is diffuse resulting from the direct infiltration of rainfall or focused occurring as leakage from stormflow, isotopic data indicate that recharging waters are not subjected to substantial evaporative enrichment. The rapid transmission of recharge is expected to involve preferential pathways such as soil macropores that bypass soil matrices and whose role in soil hydrology has long been neglected [21]. The existence of macropores and their role in enabling recharge are suggested by rapid increases in the faecal bacterial counts that have been observed in tropical groundwaters following heavy rainfalls [22]. These surface-borne microorganisms act as passive tracers that sample soil macropores. Their observed rapid transmission to underlying groundwater also highlights the vulnerability of groundwater to contamination [22].

The second, key implication of our results is that the continued intensification of precipitation, brought about by global warming and involving a shift toward fewer light and medium intensity precipitation events and a greater number of very heavy precipitation events [4, 5], is expected to favour groundwater recharge in the tropics. Heavy rains are fuelled by atmospheric moisture content that is currently increasing at ~7% per °C [23]. Unlike average annual precipitation fluxes, which have divergent responses to observed climate warming [24], the frequency of extreme precipitation has increased nearly everywhere at a global average of ~6% per °C, with the greatest positive associations in the tropics [25]. Numerous climate simulations predict that continued climate warming will lead to more frequent high-intensity precipitation events [26] but these simulations consistently underestimate increases to precipitation intensity [9], meaning that recharge models [1, 27] applying these data may underestimate future tropical groundwater recharge.

## Conclusions

Stable-isotope ratios of O and H in modern groundwaters at 14 of 15 sites throughout the tropics trace a pan-tropical bias in groundwater recharge to intensive monthly rainfall, often exceeding the 70th decile. Climate change constrains soil moisture and the availability of surface water through the amplification of potential evapotranspiration and the intensification of precipitation [28]. These effects are especially pronounced in the tropics where there is substantial dependence upon rain-fed agriculture and where the majority of the projected global population increase of ~3.7 billion by 2100 is projected to take place [29]. The pan-tropical bias in groundwater recharge to intensive rainfall presented here suggests that groundwater may prove to be a climate-resilient source of freshwater in the tropics, enabling adaptive strategies such as groundwater-fed irrigation and sustaining domestic and industrial water supplies. It should be recognized that our results simply indicate a propensity towards increased groundwater recharge associated with the intensification of precipitation in a warming world. Other influences on groundwater storage including human overuse [2], changes in the total volume of precipitation [24, 28], and land-use change [30] can undermine and overwhelm this resilience of groundwater resources in the tropics to climate change.

## Acknowledgments

Isotope data analyzed in this study are available within the primary literature cited in the supplementary materials. S Jasechko was supported by an NSERC Discovery Grant (No. 5668); R Taylor was supported by NERC Grant No. NE/L001926/1 under the NERC-ESRC-DFID UPGro programme.

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