Forest regeneration can positively contribute to local hydrological ecosystem services: implications for forest landscape restoration

van Meerveld, Ilja; Jones, J.P.G.; Ghimire, Chandra P. ; Zwartendijk, B. W.; Lahitiana, Jaona ; Ravelona, Maafaka ; Mulligan , Mark

Journal of Applied Ecology

DOI:
https://doi.org/10.1111/1365-2664.13836

Published: 01/04/2021

Publisher's PDF, also known as Version of record

Received: 14 July 2020 | Accepted: 14 September 2020
DOI: 10.1111/1365-2664.13836

RESEARCH ARTICLE

Journal of Applied Ecology | BRITISH ECOLOGICAL SOCIETY

Forest regeneration can positively contribute to local hydrological ecosystem services: Implications for forest landscape restoration

H. J. (Ilja) van Meerveld[1] | Julia P. G. Jones[2] | Chandra P. Ghimire[3] | Bob W. Zwartendijk[1,4] | Jaona Lahitiana[5] | Maafaka Ravelona[5] | Mark Mulligan[6]

[1]Department of Geography, University of Zurich, Zurich, Switzerland; [2]School of Natural Science, Bangor University, Bangor, UK; [3]AgResearch, Lincoln Research Centre, Christchurch, New Zealand; [4]Inholland University of Applied Sciences, Alkmaar, The Netherlands; [5]Laboratoire des Radio-Isotopes, University of Antananarivo, Antananarivo, Madagascar and [6]Department of Geography, King's College London, London, UK

Correspondence
Julia P. G. Jones
julia.jones@bangor.ac.uk

Funding information
Natural Environment Research Council, Grant/Award Number: NE/K010220/1 and NE/K010417/1

Handling Editor: Luke Flory

Abstract

1. Governments are increasingly committing to significant forest restoration. While carbon sequestration is a major objective, the case for restoration often includes benefits to local communities. However, the impacts of forest restoration on local hydrological services (e.g. flood and erosion risk, stream flow during dry periods) are surprisingly poorly understood. Particularly limited information is available on the impacts of passive tropical forest restoration following shifting cultivation.
2. The outcome depends on the trade-off between the improved soil infiltration capacity (reducing overland flow and increasing soil and groundwater recharge) and greater evapotranspiration (diminishing local water availability).
3. Using measurements from highly instrumented plots under three vegetation types in the shifting cultivation cycle in Madagascar's eastern rainforests (forest, tree fallow and degraded abandoned agricultural land), and infiltration measurements for the same vegetation types across the landscape, we explore the impacts of forest regeneration on the ecohydrological processes that underpin locally important ecosystem services.
4. Overland flow was minimal for the tree fallow (similar to the forest) and much lower than for the degraded land, likely leading to a lower risk of erosion and flooding compared to the degraded land. Conversely, evapotranspiration losses were lower for the tree fallow than the forest, leading to a higher net recharge, likely resulting in more streamflow between rainfall events.
5. These results demonstrate that young regenerating tropical forest vegetation can positively contribute to locally important hydrological ecosystem services. Allowing tree fallows to recover further is unlikely to further reduce the risk of overland flow but may, at least temporarily, result in less streamflow.

6. *Synthesis and applications*. Encouraging natural regeneration is increasingly seen as a cost-effective way to deliver forest landscape restoration. Our data suggest that increasing the abundance of young secondary forest in the tropics, by increasing fallow lengths in the shifting cultivation cycle, could make a positive contribution to locally important hydrological ecosystem services (specifically reducing overland flow and therefore erosion and flooding, while maintaining streamflows). Such empirical understanding is needed to inform the models used for planning forest landscape restoration to maximize benefits to local communities.

KEYWORDS

forest and landscape restoration, forest hydrology, forest restoration, Madagascar, rain forest, reforestation, secondary forest, slash-and-burn

1 | INTRODUCTION

There is enormous global interest in forest restoration, with governments around the world making high profile and ambitious commitments (Fagan et al., 2020). Carbon sequestration is an important driver of this policy interest, but it is widely recognized that forest restoration needs to be considered as part of a landscape approach which aims to improve both ecological functioning and the livelihoods of local people (Chazdon et al., 2017). Passive restoration, through encouraging natural regeneration, can be a cost-effective and successful mechanism for forest landscape restoration (Chazdon & Guariguata, 2016; Crouzeilles et al., 2017; Lamb et al., 2005; Molin et al., 2018). In the large areas of the tropics where shifting cultivation is still an important driver of forest loss (Curtis et al., 2018), lengthening fallow periods or even phasing out this system in favour of more productive agriculture on a smaller land area could greatly increase tree cover. Ecologists have shown that tropical forest regeneration following abandonment of shifting cultivation can make a substantial contribution to carbon sequestration and biodiversity conservation (Mukul et al., 2016; Rozendaal et al., 2019). However, remarkably little is known about the likely impacts on the ecohydrological processes underpinning locally important hydrological ecosystem services. Such understanding is critical to ensuring that forest landscape restoration benefits local people.

Hydrological ecosystem services are the benefits to people that accrue due to the impacts of terrestrial ecosystems on freshwater (Brauman et al., 2007). Forests can play a role in large-scale water cycling, ultimately contributing to precipitation in areas downwind from large forests (Ellison et al., 2017). However, our focus in this paper is on local hydrological ecosystem services, such as flood mitigation and the maintenance of streamflow during dry periods (known as baseflow).

Ecology has a strong influence on hydrology and therefore on hydrological ecosystem services. The risk of local flooding and erosion is strongly influenced by infiltration and overland flow which are influenced by leaf litter decomposition which enhances soil structure, and soil faunal activity and root channels that form pathways for water to move quickly into the subsoil (Lozano-Baez et al., 2019; Zimmermann et al., 2006). Forest clearance can reduce infiltration and increase overland flow (Brookhuis & Hein, 2016; Peña et al., 2016; Recha et al., 2012) while vegetation recovery can reverse these impacts (Germer et al., 2010; Zimmermann et al., 2006). However, empirical evidence on the knock-on impacts on flooding is mixed (Calder & Aylward, 2006; van Dijk et al., 2009) and flood risk depends on much more than hillslope hydrology.

Because forests intercept and transpire more water than other vegetation, all other things being equal, forest regeneration will tend to decrease total water yield (Farley et al., 2005; Liu et al., 2016). However, the effect of increasing forest cover on baseflow (the river flow in drier periods) will depend on whether the loss from increased evapotranspiration is greater or less than the associated increase in soil and groundwater recharge due to improved infiltration of precipitation. This is known as the 'infiltration trade-off' hypothesis (Bruijnzeel, 1989). In a systematic review, a third of the 53 included studies suggested that reforestation increased baseflows, although the evidence for the tropics was extremely limited (Filoso et al., 2017).

Some studies have started to explore the ecohydrological effects of tropical reforestation using streamflow data and hydrological models (Krishnaswamy et al., 2018; Lacombe et al., 2016; Ribolzi et al., 2018) but empirical evidence on how this trade-off plays out in practice is very limited because the data are difficult to collect. Field studies exploring the effects of reforestation in terms of both overland flow and evapotranspiration are rare, and very few studies have quantified the net effect of reforestation on net recharge (i.e. the amount of water that infiltrates into the soil and is not returned to the atmosphere by evapotranspiration but rather flows underground towards the streams). Most studies focus on either the effects of forest regeneration on infiltration and overland flow (Germer et al., 2010; Litt et al., 2020) or on the effects on evapotranspiration (Sommer et al., 2002; Wolf et al., 2011). The result is that despite the importance of empirical data exploring how regeneration of tropical rainforests will influence local hydrological ecosystem services, the evidence base remains very limited.

Madagascar has committed to reforest 4 million hectares under the Bonn Challenge and reforestation forms part of the country's Individual Nationally Determined Contribution to the Paris Climate Agreement. Since taking office, the new president has underlined restoration of forest ecosystems as a significant policy goal (Jones et al., 2019). More than 75% of Malagasy live in extreme poverty (The World Bank, 2018), and irrigated rice is very important to the rural economy. As such, it is vital to understand the impact of forest restoration on the local hydrological ecosystem services that affect rice production. These services are the maintenance of continuous flow in streams that ensures water is available for irrigation between rainfall events (for which net recharge is an indicator), and the mitigation of streamflow peaks (for which overland flow can be an indicator) that could damage the irrigation systems associated with rice cultivation.

We present one of the first empirical studies of the link between vegetation and overland flow, evapotranspiration and net recharge for tropical forest vegetation in the shifting cultivation cycle. We combine detailed plot-scale measurements for a whole year for a semi-mature forest, tree fallow and degraded abandoned agricultural land (Ghimire et al., 2020), and support our inferences with measurements of infiltration rates and maximum infiltration depths across the same spectrum of vegetation types across the landscape (Zwartendijk et al., 2020).

2 | MATERIALS AND METHODS

2.1 | Case study and approach to data collection

Over the last 60 years, Madagascar has lost nearly 45% of its forest cover (Vieilledent et al., 2018). While large-scale forestry operations and commercial agriculture played a role (Scales, 2014), a major driver has been small-scale shifting cultivation. Much of the remaining eastern rainforest are a mosaic of forest patches and regenerating vegetation (Styger et al., 2007). Our study region was the Corridor Ankeniheny Zahamena, a new IUCN category VI protected area in eastern Madagascar (Figure 1).

The area has a humid tropical climate; average annual precipitation varies between 1,500 and 3,500 mm/year, with approximately three quarters falling between November and April (see Figures S1 and S2). The soils are mainly highly weathered Ferralsols on highly weathered metamorphic and igneous basement rock (Figure S3).

The majority of the 60,000 people living in the 450 peripheral villages carry out a mixture of shifting cultivation on the hillslopes and irrigated rice in small valley bottoms (Poudyal et al., 2018). Both a lack of water at the start of the wet season (November–December), and flooding (especially when rice is ready to harvest towards the end of the wet season) limit rice production (Figure S4).

We took detailed plot-scale measurements for three vegetation types from the shifting cultivation cycle (forest, tree fallow and degraded abandoned agricultural land). The aim was to construct a water budget including overland flow (relevant to land use impacts on local flood risk and erosion) and evapotranspiration, and use this to estimate land use impacts on net recharge (relevant to baseflows). Due to the highly heterogeneous land cover in the area, it was not possible to identify catchments each with a single vegetation type for which to compare streamflow dynamics. It was logistically (and financially) impossible to replicate the detailed measurements at the instrumented plots at more locations. However, to assess the representativeness of the measurements, we determined infiltration rates for the same vegetation types across the landscape in three study areas (Figure 1). The sites were selected based on the presence of indicator species (Styger et al., 2007) and interviews regarding land use history. In total, we took infiltration measurements at 12 forest sites, 15 tree fallow sites and 10 degraded sites (Figure 1; Table S1). See Figure S5 for the field work context and Supporting Information for justification of this space-for-time approach and additional details on site selection.

2.2 | Detailed hydrological measurements at instrumented plots

The three 0.25-ha plots (one representing each vegetation type; Table 1) were chosen based on representativeness of the vegetation in the region, accessibility and the presence of a local organization who could provide the daily monitoring of equipment (Supporting Information). The forest plot was a semi-mature secondary forest that had not been cleared for agriculture in living memory, but had experienced selective manual logging until 1995. The tree fallow plot had a long history of shifting cultivation and was last cleared in approximately 1990. In 2000, it had some enrichment planting as part of a reforestation project but due to a lack of weeding, the planted saplings died. The degraded plot had been used in many shifting cultivation cycles until it was abandoned around the year 2000. Regeneration has been poor, as is typical in sites that have been degraded by repeated cultivation with short fallow durations (Styger et al., 2007).

We determined the net recharge (i.e. the amount of water that flows via vertical and lateral subsurface flow pathways to the stream) based on the water budget for the three plots. We did this for the 1-year study period (1 October 2014–30 September 2015), and also the wettest month of the study period (February 2015, with ~500 mm of precipitation):

$$P - OF - ET - \Delta S = R, \qquad (1)$$

where P is the total precipitation (mm), OF is the amount of overland flow (mm), ET is the evapotranspiration loss (mm), which consists of the interception loss, transpiration from the overstorey and understorey, and litter and soil evaporation, ΔS is the change in storage in the rooting zone (mm) and R is the net recharge (mm). All terms of the water budget were measured separately, except for R which was computed as the residual term.

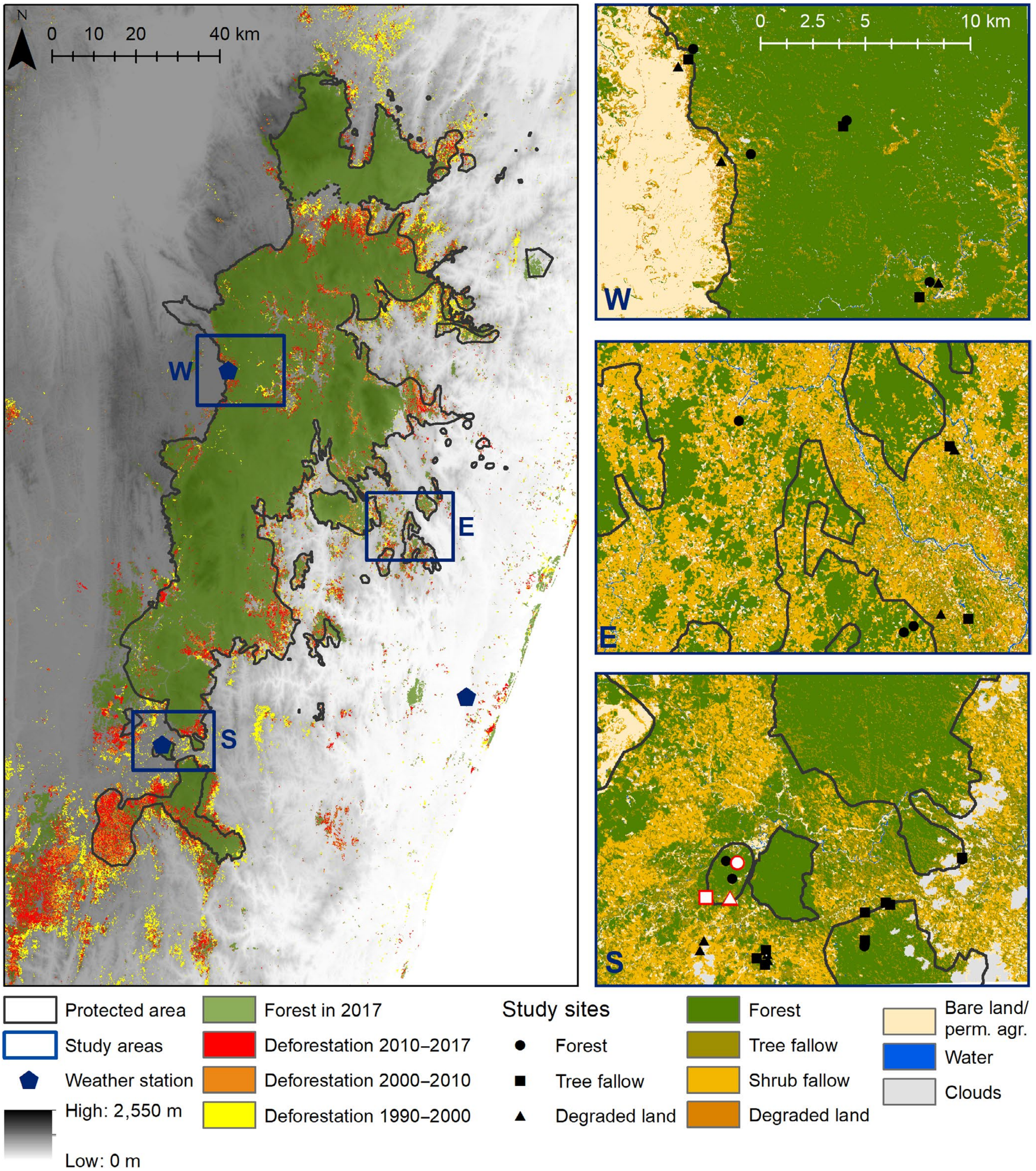

FIGURE 1 Map of the study region showing the Coridor Ankeniheny Zahamena and associated protected areas, the current forest cover, areas of recent deforestation (from: Vieilledent et al., 2018; left) and the three study areas (west, east and south). The study areas are expanded to show the mosaic of vegetation (from Horning & Hewson, 2017), the location of the three highly instrumented plots (in red outlined symbols) and the sites for the infiltration measurements across the landscape

Although the instrumented plots were within 2.5 km from each other (Figure 1), we installed a weather station at each plot to obtain precipitation and other climate data (Figure S6). Overland flow *OF* was measured at 3 × 10 m bounded runoff plots within each instrumented plot and collected in large metal troughs that drained into large drums that were emptied daily. Two runoff plots were installed in the forest and tree fallow and three in the degraded land plot (values were averaged).

TABLE 1 Detailed information on the three highly instrumented plots. Average values (±*SD*). See Supporting Information for the methods used to determine the soil characteristics and Leaf Area Index (LAI)

	Forest	Tree fallow	Degraded land
Lat, Long	18.932S, 48.412E	18.947S, 48.395E	18.946S, 48.4073E
Slope (°)	18	16	17
Aspect	NE	NW	NE
Clay (%)	39	50	45
Silt (%)	26	27	18
Sand (%)	35	23	37
Bulk density (g/cm^3)	1.19 (±0.17)	1.14 (±0.20)	1.25 (±0.03)
Porosity (%)	53 (±7)	51 (±4)	51 (±2)
Moisture content at field capacity (%)	49 (±5)	46 (±4)	48 (±2)
LAI	3.11 to 3.59	1.75 to 2.14	–
Average (±*SD*) DBH (cm)	9 (±4.0)	6.1 (±1.3)	–
Stem density (trees/ha)	5,233	2,133	–
Average (±*SD*) height of dominant vegetation (m)	19 (±8.0)	5 (±0.3)	~1
Vegetation	Diverse; 72 species of tree and shrub; *Abarahamia ditimena*, *Brachylaena ramiflora*, *Cryptocaria* sp., *Ocotea samosa*, *Eugenia* spp. and *Leptolaena* together comprised 35% of the stems	Relatively low richness of tree and shrub. *Psiadia altissima* trees (95% of all stems), *Cassinopsis madagascariensis*, *Harungana madagascariensis*. Dense understorey dominated by *Rubus molluccanus*, *Lantana camara* and *Clidemia hirta*	Dominated by grasses: *Imperata cylindrica* and *Hyparrhenia rufa*. *Helichrysum* sp., *Lantana camara*, *Clidemia hirta* and a few small *Harungana madagascariensis*

The interception loss was calculated from the difference between the precipitation and throughfall plus stemflow. For the forest and tree fallow plots, we measured throughfall for the entire measurement period using 66 funnel gauges that were emptied daily, as well as three V-shaped troughs connected to a tipping bucket. Stemflow was measured on 10 trees in the forest plot and five trees on the tree fallow plot using stemflow collars that drained into large containers that were also emptied daily. See Ghimire et al., (2017) and Supporting Information for more details. Tree transpiration was measured using thermal dissipation probes on 21 trees in the forest plot and 12 in the tree fallow plot and scaled by multiplying the average sap flux density by the total sapwood area (see Ghimire et al., 2018 and Supporting Information for details). Litter evaporation was based on the measured water-holding capacity of the litter and model simulations. For the degraded plot, the interception loss, and transpiration and soil evaporation were based on model simulations (see Supporting Information).

Soil moisture was measured at four different depths (5, 15, 40 and 75 cm). The change in root zone soil moisture storage ΔS for the 1-year study period was calculated from the difference in the amount of soil moisture stored in the upper 75 cm of the soil at the beginning and the end of the study period. The exact depth of the rooting zone is not known, but few roots were observed below 75 cm. Changes in soil water storage below 75 cm and groundwater storage are assumed to be negligible at the annual time-scale.

The net recharge R was calculated from the water budget. Because it is the residual from all other fluxes (Equation 1), it also includes all measurement errors. Differences in R among the instrumented plots thus need to be interpreted with care. Net recharge R represents the amount of water that leaves the plots via lateral subsurface flow and vertical drainage to groundwater and thus ultimately flows towards the streams. Some of it may reach the streams quickly during high rainfall events via shallow subsurface flow pathways and thus contribute to flooding (particularly during large events) instead of baseflow. However, we assume that the majority of net recharge that leaves the plots via subsurface pathways can be used for irrigated agriculture because it feeds the local groundwater bodies beneath foot-slopes and the valley bottoms, where irrigated rice production is concentrated. We thus consider it an ecosystem service to local communities (see Supporting Information for further justification of this assumption). In contrast, we assume that overland flow leads to erosion and affects flooding and that most of this water is not useful for local irrigated rice production because of its quick and short response during precipitation events. We thus consider it a dis-service for local communities but acknowledge that some of the overland flow may re-infiltrate into the soil at lower hillslope positions.

2.3 | Infiltration measurements across the landscape

The measurements from the highly instrumented plots were complemented by infiltration measurements at 37 sites across the wider landscape (Figure 1; Table S1). At each site, we measured the saturated hydraulic conductivity (K_{sat}) at the soil surface using a double ring infiltrometer and at 20–30 cm below the surface using a constant head permeameter to assess the likelihood of overland flow generation and deep infiltration. The measurements were taken at five locations along an upslope to downslope transect; the median value for these five measurements is considered to be representative for each site. To determine the statistical significance of the differences in the median K_{sat} values per vegetation type, we used the Kruskal–Wallis with Dunn post hoc test ($p < 0.05$). For a subset of the sites (Table S1), we investigated preferential flow pathways and the maximum infiltration depth by spraying brilliant blue dye on the soil surface (see Supporting Information and Zwartendijk et al., 2017).

3 | RESULTS

3.1 | Water budget for the three vegetation types from the plot measurements

The amount of overland flow was similar for the forest and tree fallow, but much higher at the degraded land plot. Overland flow was only 2% of the annual precipitation for the forest and tree fallow plots but 11% for the degraded plot (Figure 2a). For the wettest month during the study period, the average overland flow ratio was much higher for the degraded land plot (22% of total precipitation; Figure 2b).

Total evapotranspiration was greatest for the forest (65% of the precipitation compared to 42% for the tree fallow and 28% for the degraded land; Figure 2a). The difference was mainly caused by differences in the interception and transpiration losses (Table S2). Litter interception and evaporation was a relatively minor component of total evapotranspiration (<6% of precipitation).

The change in shallow soil moisture between the start and end of the 1-year study period was small (−1% of annual precipitation for the forest and tree fallow plots, and 2% for the degraded plot).

The calculated net recharge was smallest for the forest (34% of annual precipitation) and similar for the tree fallow and degraded land plots (56% and 63% respectively; Figure 2a). However, for the wettest month, net recharge was highest for the tree fallow and lowest for the degraded land plot due to the much greater overland flow losses for the degraded plot (Figure 2b).

3.2 | Infiltration measurements across the landscape

The results from the infiltration measurements at the three study areas corroborate the findings of the instrumented plots that overland flow is unlikely in the forest and likely in the degraded land. The median values of saturated hydraulic conductivity (K_{sat}) at the soil surface were higher than the 95th percentile of the 5-min precipitation intensity measured at the instrumented plots, except for one tree fallow site and one degraded land site (Figure 3a). This means that even during the most intense events, precipitation will infiltrate into the soil, regardless of vegetation type. However, at 20–30 cm depth, the K_{sat} was two orders of magnitude lower than at the surface and less than the median 5-min precipitation intensity for all but one degraded land site and many fallow sites (Figure 3b; Table S3). This means that for common precipitation intensities, infiltration below 20–30 cm depth is slower than the precipitation rate and saturation will occur above this layer. If the events are large enough to saturate the entire soil profile above this layer, then overland flow will occur.

Visual inspection of the blue dye tracer experiments suggested that the patterns of infiltration differed between the vegetation types (Figure 4). At the forest and tree fallow sites, most of the dye moved more than 15 cm into the soil via preferential flow pathways but for most of the degraded land sites, the dye remained largely in the top 15 cm of the soil. However, there was no significant difference between the maximum infiltration depth between the vegetation types; although for two degraded land sites and one tree fallow site, no water penetrated into the clay rich layer at 30 cm depth (Figure S7).

4 | DISCUSSION

4.1 | The impacts of tropical forest regeneration on local hydrological ecosystem services

Our findings, from the vegetation mosaic that dominates the eastern rainforest region of Madagascar, suggest that from the perspective of minimizing overland flow and maximizing net recharge, tree fallows perform well. Although more mature forest has better capacity than tree fallow to store carbon (Andriamananjara et al., 2016), and likely supports more biodiversity (Lennox et al., 2018; Rozendaal et al., 2019), our results show that additional vegetation growth may not limit overland flow further, and may come at a cost of increased evapotranspiration and reduced net recharge. The results support

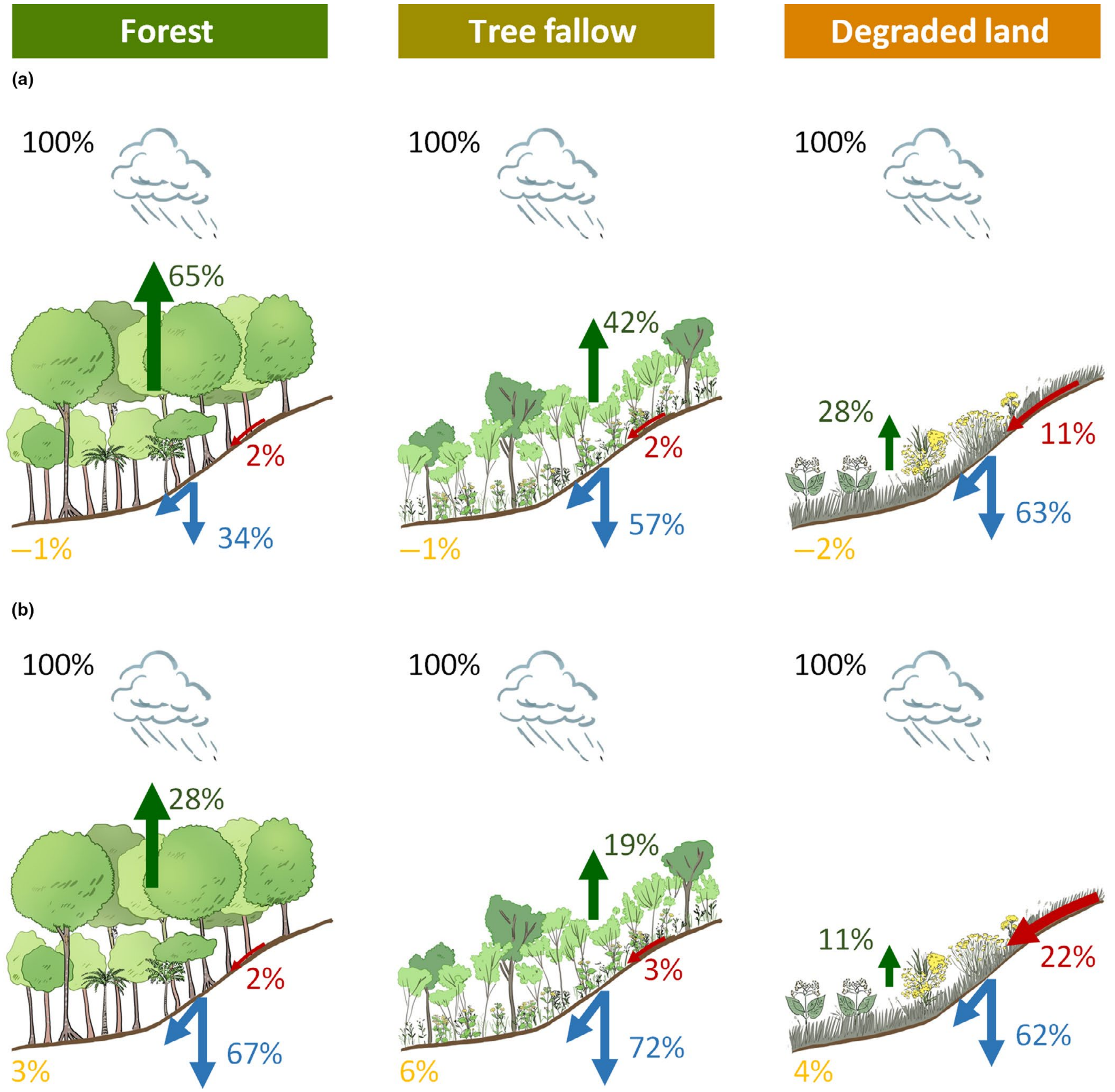

FIGURE 2 Water budget in percentage of incoming precipitation: evapotranspiration *ET* in green, overland flow *OF* in red, change in soil moisture storage Δ*S* in yellow (no arrow) and net recharge (i.e. both lateral flow and vertical recharge) *R* in blue. The water budget is shown for the three instrumented plots in % of total precipitation for (a) the whole year and (b) the wettest month (February)

the infiltration trade-off hypothesis (Bruijnzeel, 1989): trees (both tree fallow and forest) increase infiltration resulting in less overland flow, but transpiration and interception losses are greater for the forest than the tree fallow and degraded land. This is a similar finding (with the same underlying mechanism) to that reported by Ilstedt et al., (2016), who found that intermediate densities of mature trees (in a spectrum of tree densities in a woodland system in semi-arid West Africa) are optimal for groundwater recharge.

We note that our instrumented forest plot was a semi-mature forest with relatively many young trees. Transpiration rates may decrease as the forest further matures (cf. Giambelluca, 2002). However, the evidence base for such a reduction is fairly limited. For the majority of the 43 (mostly temperate) catchments studied by Bentley and Coomes (2020), the decreases in annual streamflow after reforestation were permanent, suggesting no such decline in evapotranspiration as forests mature.

An important caveat is that the results provide only a partial understanding of the effects of forest regeneration on flood mitigation and baseflow. To fully understand the effects of reforestation on the amount of water in streams and rivers, more information on the

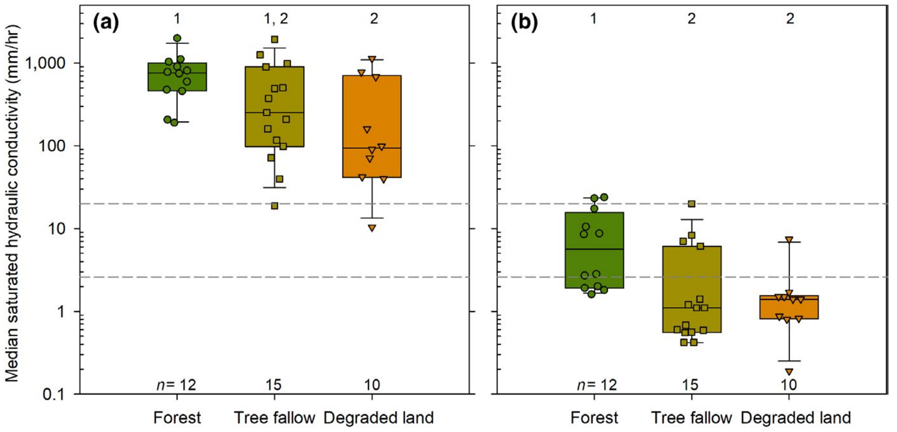

FIGURE 3 Box plots of the median saturated hydraulic conductivity (K_{sat}) per site for (a) the surface and (b) at 20–30 cm below the soil surface. Symbols represent the median values for the five measurements per study site. Different numbers (1, 2) indicate statistically significant differences. The dashed horizontal lines represent the median and 95th percentile of the 5-min precipitation intensity measured at the highly instrumented plots

FIGURE 4 Example pictures of the blue dye profiles showing preferential flow for three nearby sites in the western study area. Each block on the black and white scale bar represents 10 cm

local hydrogeological setting, for example, the storage provided by riparian aquifers, and the partitioning of the net recharge into fast lateral subsurface flow and vertical recharge would be needed. We also note that small differences in non-land use factors (soil texture, aspect, climate between the plots) may impact the fluxes.

4.2 | What about other hydrological ecosystem services?

Of course, forest regeneration may impact hydrological ecosystem services beyond those addressed in this paper. For example, it may have benefits for water quality in terms of sediment and contaminants, particularly where regenerating forests replace agricultural land (Herrera et al., 2017). The effects of reforestation on hydrological ecosystem services further downstream (rather than the small valleys which were the focus of this paper) may be very different due to the increased importance of reservoirs and the local hydrogeological setting on the flow regimes. Overland flow may provide water for users further downstream because of the downstream attenuation of the flood peak, particularly where there are reservoirs to capture the water during high peak flows. To assess the realized ecosystem services, the number, type and downstream distribution of users is also important (van Soesbergen & Mulligan, 2018). When assessing the hydrological effects of large-scale forest restoration, variations in the local climate (exposure to rainfall and solar radiation or fog) will also be important. Very large-scale restoration could, at least in theory, positively impact precipitation (Ellison et al., 2017) though the evidence surrounding this is equivocal as even restoration of 70,000 km^2 in China did not change regional precipitation (Zhou et al., 2010).

4.3 | Lesson for forest restoration in Madagascar

Forest policy in Madagascar (as elsewhere; Swanson et al., 2011) has so far tended to focus on the value of forest vegetation, underplaying the potential ecosystem services contributed by earlier stages of succession. Our results show that regenerating tree fallows increase infiltration and minimize overland flow just as well as older forest stands, at least under normal rainfall conditions. Decreasing overland flow would tend to reduce flooding and erosion (an important threat to irrigated rice farming), while increasing net recharge would improve baseflows (especially important near the start of the rice farming season because planting is often water limited). Therefore, lengthening the shifting cultivation cycles and increasing the area covered by tree fallows could positively affect these locally important ecosystem services. Given the high cost, and mixed success, of active reforestation (Busch et al., 2012), encouraging natural regeneration of land in the shifting cultivation cycle could be a positive way to deliver Madagascar's forest landscape restoration targets.

It is important to understand how forest restoration can contribute positively to locally valued ecosystem services, as local acceptability is critical to successful forest restoration interventions (Mansourian et al., 2016). Because the poorest are often most dependent on shifting cultivation, efforts to reduce this low input agricultural system will tend to negatively impact their livelihoods (Poudyal et al., 2018). Conservation and restoration policies more generally need to do better at minimizing local costs, maximizing local benefits and ensuring global benefits are more equitably shared locally (Gardner et al., 2013). This requires knowledge on all impacts of these policies, including the hydrological impacts.

4.4 | Lessons for the global expansion in forest landscape restoration initiatives

There is real interest in the potential of forest landscape restoration for delivering local benefits, including local hydrological ecosystem services. Therefore, understanding the impact of forest regeneration on ecohydrological processes is very important. Hydrological modelling has been used in some cases to inform the planning for forest landscape restoration initiatives (e.g. Sun et al., 2006; Trabucco et al., 2008). However these studies generally only considered the effect on evapotranspiration which will tend to increase after restoration (Farley et al., 2005), and have largely ignored the possible positive effects of increased tree cover on soil hydrological functioning (i.e. infiltration). A recent modelling study that took both effects (i.e. the trade-off between increased evapotranspiration and infiltration) into account (Peña-Arancibia et al., 2019) showed that the net effect of restoration on streamflow differed spatially across the tropics due to the interplay between precipitation amount and seasonality, evaporative demand, as well as soil type and land surface condition. Models can only be as good as the mechanistic understanding that underpins them and the data used to parameterize them. So far, these data are lacking for many regions that are targeted for forest landscape restoration.

This works adds much needed empirical evidence of the effects of regenerating tropical forest vegetation on ecohydrological processes. While mature tropical forests provide greater storage of carbon and support much greater biodiversity, young vegetation can already reduce overland flow and thus soil erosion and local flood risk, while also ensuring reasonable recharge that can maintain baseflow. They will accrue carbon and biodiversity as they age. The results from this study suggest that efforts to increase the abundance of young secondary forest in the degraded and deforested regions of the world, by increasing fallow lengths, would make a positive contribution in terms of hydrological ecosystem service delivery. This empirical understanding can contribute to the planning of forest landscape restoration initiatives throughout the tropics and help inform models that are used for the planning of these initiatives.

ACKNOWLEDGEMENTS

The authors thank Association Mitsinjo and the authorities for permission and practical help, M.W. Lubczynski and L.A. Bruijnzeel for valuable support and comments, and the wider p4ges project team. We thank the artist Eric Andriantsialonina for the drawings in Figure 2. See Supporting Information for extended acknowledgements. This work was funded by the ecosystem services for poverty alleviation program NE/K010220-1 and NE/K010417/1.

AUTHORS' CONTRIBUTIONS

H.J.v.M., C.P.G., B.W.Z., M.M. and J.P.G.J. conceived the study and designed methodology; J.L. and M.R. particularly contributed to data collection; H.J.v.M. and J.P.G.J. led the writing. All the authors contributed critically to the drafts and gave final approval.

DATA AVAILABILITY STATEMENT

The data from the instrumented plots are available via https://doi.org/10.5285/5d080fef-613a-4f24-a613-b249ccdd12bf (Ghimire et al., 2020); the saturated hydraulic conductivity measurements across the landscape https://doi.org/10.5285/7987c6d4-973d-436d-a13b-c52997d0bce5 (Zwartendijk et al., 2020); the sapflow data for the transpiration values are available via https://doi.org/10.5281/zenodo.3971689 (Poyatos et al., 2020).

ORCID

H. J. (Ilja) van Meerveld https://orcid.org/0000-0002-7547-3270
Julia P. G. Jones https://orcid.org/0000-0002-5199-3335
Chandra P. Ghimire https://orcid.org/0000-0002-3715-6311
Bob W. Zwartendijk https://orcid.org/0000-0002-0581-7330
Mark Mulligan https://orcid.org/0000-0002-0132-0888

REFERENCES

Andriamananjara, A., Hewson, J., Razakamanarivo, H., Andrisoa, R. H., Ranaivoson, N., Ramboatiana, N., Razafindrakoto, M., Ramifehiarivo, N., Razafimanantsoa, M.-P., Rabeharisoa, L., Ramananantoandro, T., Rasolohery, A., Rabetokotany, N., & Razafimbelo, T. (2016). Land cover impacts on aboveground and soil carbon stocks in Malagasy rainforest. *Agriculture, Ecosystems & Environment*, *233*, 1–15. https://doi.org/10.1016/j.agee.2016.08.030

Bentley, L., & Coomes, D. A. (2020). Partial river flow recovery with forest age is rare in the decades following establishment. *Global Change Biology*, *26*(3), 1458–1473. https://doi.org/10.1111/gcb.14954

Brauman, K. A., Daily, G. C., Duarte, T. K., & Mooney, H. A. (2007). The nature and value of ecosystem services: An overview highlighting hydrologic services. *Annual Review of Environment and Resources*, *32*(1), 67–98. https://doi.org/10.1146/annurev.energy.32.031306.102758

Brookhuis, B. J., & Hein, L. G. (2016). The value of the flood control service of tropical forests: A case study for Trinidad. *Forest Policy and Economics*, *62*, 118–124. https://doi.org/10.1016/J.FORPOL.2015.10.002

Bruijnzeel, L. A. (1989). De(forestation) and dry season flow in the tropics: A closer look. *Journal of Tropical Forest Science*, *1*, 229–243.

Busch, J., Dave, R., Hannah, L., Cameron, A., Rasolohery, A., Roehrdanz, P., & Schatz, G. (2012). Climate change and the cost of conserving species in Madagascar. *Conservation Biology*, *26*(3), 408–419. https://doi.org/10.1111/j.1523-1739.2012.01838.x

Calder, I. R., & Aylward, B. (2006). Forest and floods. *Water International*, *31*(1), 87–99. https://doi.org/10.1080/02508060608691918

Chazdon, R. L., Brancalion, P. H. S., Lamb, D., Laestadius, L., Calmon, M., & Kumar, C. (2017). A policy-driven knowledge agenda for global forest and landscape restoration. *Conservation Letters*, *10*(1), 125–132. https://doi.org/10.1111/conl.12220

Chazdon, R. L., & Guariguata, M. R. (2016). Natural regeneration as a tool for large-scale forest restoration in the tropics: Prospects and challenges. *Biotropica*, *48*(6), 716–730. https://doi.org/10.1111/btp.12381

Crouzeilles, R., Ferreira, M. S., Chazdon, R. L., Lindenmayer, D. B., Sansevero, J. B. B., Monteiro, L., Iribarrem, A., Latawiec, A. E., & Strassburg, B. B. N. (2017). Ecological restoration success is higher for natural regeneration than for active restoration in tropical forests. *Science Advances*, *3*(11), e1701345. https://doi.org/10.1126/sciadv.1701345

Curtis, P. G., Slay, C. M., Harris, N. L., Tyukavina, A., & Hansen, M. C. (2018). Classifying drivers of global forest loss. *Science*, *361*(6407), 1108–1111. https://doi.org/10.1126/science.aau3445

Ellison, D., Morris, C. E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., Noordwijk, M. V., Creed, I. F., Pokorny, J., Gaveau, D., Spracklen, D. V., Tobella, A. B., Ilstedt, U., Teuling, A. J., Gebrehiwot, S. G., Sands, D. C., Muys, B., Verbist, B., … Sullivan, C. A. (2017). Trees, forests and water: Cool insights for a hot world. *Global Environmental Change*, *43*, 51–61. https://doi.org/10.1016/J.GLOENVCHA.2017.01.002

Fagan, M. E., Reid, J. L., Holland, M. B., Drew, J. G., & Zahawi, R. A. (2020). How feasible are global forest restoration commitments? *Conservation Letters*, *13*(3), https://doi.org/10.1111/conl.12700

Farley, K. A., Jobbagy, E. G., & Jackson, R. B. (2005). Effects of afforestation on water yield: A global synthesis with implications for policy. *Global Change Biology*, *11*(10), 1565–1576. https://doi.org/10.1111/j.1365-2486.2005.01011.x

Filoso, S., Bezerra, M. O., Weiss, K. C. B., & Palmer, M. A. (2017). Impacts of forest restoration on water yield: A systematic review. *PLoS ONE*, *12*(8), e0183210. https://doi.org/10.1371/journal.pone.0183210

Gardner, C. J., Nicoll, M. E., Mbohoahy, T., Oleson, K. L. L., Ratsifandrihamanana, A. N., Ratsirarson, J., René de Roland, L.-A., Virah-Sawmy, M., Zafindrasilivonona, B., & Davies, Z. G. (2013). Protected areas for conservation and poverty alleviation: Experiences from Madagascar. *Journal of Applied Ecology*, *50*(6), 1289–1294. https://doi.org/10.1111/1365-2664.12164

Germer, S., Neill, C., Krusche, A. V., & Elsenbeer, H. (2010). Influence of land-use change on near-surface hydrological processes: Undisturbed forest to pasture. *Journal of Hydrology*, *380*(3–4), 473–480. https://doi.org/10.1016/j.jhydrol.2009.11.022

Ghimire, C. P., Adrian Bruijnzeel, L., Lubczynski, M. W., Ravelona, M., Zwartendijk, B. W., & van Meerveld, H. J. (2017). Measurement and modeling of rainfall interception by two differently aged secondary forests in upland eastern Madagascar. *Journal of Hydrology*, *545*, 212–225. https://doi.org/10.1016/J.JHYDROL.2016.10.032

Ghimire, C. P., Bruijnzeel, L. A., Lubczynski, M. W., Zwartendijk, B. W., Odongo, V. O., Ravelona, M., & van Meerveld, H. J. (2018). Transpiration and stomatal conductance in a young secondary tropical montane forest: Contrasts between native trees and invasive understorey shrubs. *Tree Physiology*, *38*(7), 1053–1070. https://doi.org/10.1093/treephys/tpy004

Ghimire, C. P., Zwartendijk, B. W., Ravelona, M., Lahitiana, J., & van Meerveld, H. J. (2020). Hydrological and meteorological data for three plots with different vegetation near Andasibe, Madagascar, 2014–2015. *NERC Environmental Information Data Centre*, https://doi.org/10.5285/5d080fef-613a-4f24-a613-b249ccdd12bf

Giambelluca, T. W. (2002). Hydrology of altered tropical forest. *Hydrological Processes*, *16*(8), 1665–1669. https://doi.org/10.1002/hyp.5021

Herrera, D., Ellis, A., Fisher, B., Golden, C. D., Johnson, K., Mulligan, M., Pfaff, A., Treuer, T., & Ricketts, T. H. (2017). Upstream watershed condition predicts rural children's health across 35 developing countries. *Nature Communications*, *8*(1), 811. https://doi.org/10.1038/s41467-017-00775-2

Horning, N., & Hewson, J. (2017). *Very high resolution derived land cover/use classifications for the Corridor Ankeniheny-Zahamena (CAZ), Madagascar*. https://doi.org/10.5285/ce535cef-842e-4875-ad80-26760900cec0

Ilstedt, U., Bargués Tobella, A., Bazié, H. R., Bayala, J., Verbeeten, E., Nyberg, G., Sanou, J., Benegas, L., Murdiyarso, D., Laudon, H., Sheil, D., & Malmer, A. (2016). Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics. *Scientific Reports*, *6*(1), 21930. https://doi.org/10.1038/srep21930

Jones, J. P. G., Ratsimbazafy, J., Ratsifandrihamanana, A. N., Watson, J. E. M., Andrianandrasana, H. T., Cabeza, M., Cinner, J. E., Goodman, S. M., Hawkins, F., Mittermeier, R. A., Rabearisoa, A. L., Rakotonarivo, O. S., Razafimanahaka, J. H., Razafimpahanana, A. R., Wilmé, L., & Wright, P. C. (2019). Last chance for Madagascar's biodiversity. *Nature Sustainability*, *2*(5). https://doi.org/10.1038/s41893-019-0288-0

Krishnaswamy, J., Kelkar, N., & Birkel, C. (2018). Positive and neutral effects of forest cover on dry-season stream flow in Costa Rica identified from Bayesian regression models with informative prior distributions. *Hydrological Processes*, *32*(24), 3604–3614. https://doi.org/10.1002/hyp.13288

Lacombe, G., Ribolzi, O., de Rouw, A., Pierret, A., Latsachak, K., Silvera, N., Pham, D. R., Orange, D., Janeau, J. L., Soulileuth, B., Robain, H., Taccoen, A., Sengphaathith, P., Mouche, E., Sengtaheuanghoung, O., Toan, T. D., & Valentin, C. (2016). Contradictory hydrological impacts of afforestation in the humid tropics evidenced by long-term field monitoring and simulation modelling. *Hydrology and Earth System Sciences*, *20*(7), 2691–2704. https://doi.org/10.5194/hess-20-2691-2016

Lamb, D., Erskine, P. D., & Parrotta, J. A. (2005). Restoration of degraded tropical forest landscapes. *Science*, *310*(5754), 1628–1632. https://doi.org/10.1126/science.1111773

Lennox, G. D., Gardner, T. A., Thomson, J. R., Ferreira, J., Berenguer, E., Lees, A. C., Mac Nally, R., Aragão, L. E. O. C., Ferraz, S. F. B., Louzada, J., Moura, N. G., Oliveira, V. H. F., Pardini, R., Solar, R. R. C., Vaz-de Mello, F. Z., Vieira, I. C. G., & Barlow, J. (2018). Second rate or a second chance? Assessing biomass and biodiversity recovery in regenerating Amazonian forests. *Global Change Biology*, *24*(12), 5680–5694. https://doi.org/10.1111/gcb.14443

Litt, G. F., Ogden, F. L., Mojica, A., Hendrickx, J. M. H., Kempema, E. W., Gardner, C. B., Bretfeld, M., Regina, J. A., Harrison, J. B. J., Cheng, Y., & Lyons, W. B. (2020). Land cover effects on soil infiltration capacity measured using plot scale rainfall simulation in steep tropical lowlands of Central Panama. *Hydrological Processes*, *34*(4), 878–897. https://doi.org/10.1002/hyp.13605

Liu, Y., Xiao, J., Ju, W., Xu, K., Zhou, Y., & Zhao, Y. (2016). Recent trends in vegetation greenness in China significantly altered annual evapotranspiration and water yield. *Environmental Research Letters*, *11*(9), 094010. https://doi.org/10.1088/1748-9326/11/9/094010

Lozano-Baez, S. E., Cooper, M., Meli, P., Ferraz, S. F. B., Rodrigues, R. R., & Sauer, T. J. (2019). Land restoration by tree planting in the tropics and subtropics improves soil infiltration, but some critical gaps still hinder conclusive results. *Forest Ecology and Management*, *444*, 89–95. https://doi.org/10.1016/J.FORECO.2019.04.046

Mansourian, S., Razafimahatratra, A., Ranjatson, P., & Rambeloarisao, G. (2016). Novel governance for forest landscape restoration in Fandriana Marolambo, Madagascar. *World Development Perspectives*, *3*, 28–31. https://doi.org/10.1016/J.WDP.2016.11.009

Molin, P. G., Chazdon, R., de Barros, F., Ferraz, S., & Brancalion, P. H. S. (2018). A landscape approach for cost-effective large-scale forest restoration. *Journal of Applied Ecology*, *55*(6), 2767–2778. https://doi.org/10.1111/1365-2664.13263

Mukul, S. A., Herbohn, J., & Firn, J. (2016). Co-benefits of biodiversity and carbon sequestration from regenerating secondary forests in the Philippine uplands: Implications for forest landscape restoration. *Biotropica*, *48*(6), 882–889. https://doi.org/10.1111/btp.12389

Peña, L. E., Barrios, M., & Francés, F. (2016). Flood quantiles scaling with upper soil hydraulic properties for different land uses at catchment scale. *Journal of Hydrology*, *541*, 1258–1272. https://doi.org/10.1016/J.JHYDROL.2016.08.031

Peña-Arancibia, J. L., Bruijnzeel, L. A., Mulligan, M., & van Dijk, A. I. J. M. (2019). Forests as 'sponges' and 'pumps': Assessing the impact of deforestation on dry-season flows across the tropics. *Journal of Hydrology*, *574*, 946–963. https://doi.org/10.1016/J.JHYDROL.2019.04.064

Poudyal, M., Jones, J. P. G., Rakotonarivo, O. S., Hockley, N., Gibbons, J. M., Mandimbiniaina, R., Rasoamanana, A., Andrianantenaina, N. S., & Ramamonjisoa, B. S. (2018). Who bears the cost of forest conservation? *PeerJ*, *6*, e5106. https://doi.org/10.7717/peerj.5106

Poyatos, R., Granda, V., Flo, V., Molowny-Horas, R., Steppe, K., Mencuccini, M., & Martínez-Vilalta, J. (2020). SAPFLUXNET: A global database of sap flow measurements. *Zenodo*, https://doi.org/10.5281/zenodo.3971689

Recha, J. W., Lehmann, J., Walter, M. T., Pell, A., Verchot, L., Johnson, M., & Johnson, M. (2012). Stream discharge in tropical headwater catchments as a result of forest clearing and soil degradation. *Earth Interactions*, *16*(13), 1–18. https://doi.org/10.1175/2012EI000439.1

Ribolzi, O., Lacombe, G., Pierret, A., Robain, H., Sounyafong, P., de Rouw, A., Soulileuth, B., Mouche, E., Huon, S., Silvera, N., Latxachak, K. O., Sengtaheuanghoung, O., & Valentin, C. (2018). Interacting land use and soil surface dynamics control groundwater outflow in a montane catchment of the lower Mekong basin. *Agriculture, Ecosystems & Environment*, *268*, 90–102. https://doi.org/10.1016/J.AGEE.2018.09.005

Rozendaal, D. M. A., Bongers, F., Aide, T. M., Alvarez-Dávila, E., Ascarrunz, N., Balvanera, P., Becknell, J. M., Bentos, T. V., Brancalion, P. H. S., Cabral, G. A. L., Calvo-Rodriguez, S., Chave, J., César, R. G., Chazdon, R. L., Condit, R., Dallinga, J. S., de Almeida-Cortez, J. S., de Jong, B., de Oliveira, A., … Poorter, L. (2019). Biodiversity recovery of Neotropical secondary forests. *Science Advances*, *5*(3), eaau3114. https://doi.org/10.1126/sciadv.aau3114

Scales, I. R. (2014). The drivers of deforestation and the complexity of land use in Madagascar. In I. R. Scales (Ed.), *Conservation and environmental management in Madagascar* (pp. 105–125). Routlege.

Sommer, R., Sá, T. D. D. A., Vielhauer, K., De Araújo, A. C., Fölster, H., & Vlek, P. L. G. (2002). Transpiration and canopy conductance of secondary vegetation in the eastern Amazon. *Agricultural and Forest Meteorology*, *112*(2), 103–121. https://doi.org/10.1016/S0168-1923(02)00044-8

Styger, E., Rakotondramasy, H. M., Pfeffer, M. J., Fernandes, E. C. M., & Bates, D. M. (2007). Influence of slash-and-burn farming practices on fallow succession and land degradation in the rainforest region of Madagascar. *Agriculture, Ecosystems & Environment*, *119*(3–4), 257–269. https://doi.org/10.1016/j.agee.2006.07.012

Sun, G., Zhou, G., Zhang, Z., Wei, X., McNulty, S. G., & Vose, J. M. (2006). Potential water yield reduction due to forestation across China. *Journal of Hydrology*, *328*(3–4), 548–558. https://doi.org/10.1016/J.JHYDROL.2005.12.013

Swanson, M. E., Franklin, J. F., Beschta, R. L., Crisafulli, C. M., DellaSala, D. A., Hutto, R. L., Lindenmayer, D. B., & Swanson, F. J. (2011). The forgotten stage of forest succession: Early-successional ecosystems on forest sites. *Frontiers in Ecology and the Environment*, *9*(2), 117–125. https://doi.org/10.1890/090157

The World Bank. (2018). *Poverty and shared prosperity: Piecing together the poverty puzzle*, . The World Bank. https://doi.org/10.1596/978-1-4648-1330-6

Trabucco, A., Zomer, R. J., Bossio, D. A., van Straaten, O., & Verchot, L. V. (2008). Climate change mitigation through afforestation/reforestation: A global analysis of hydrologic impacts with four case studies. *Agriculture, Ecosystems & Environment*, *126*(1–2), 81–97. https://doi.org/10.1016/J.AGEE.2008.01.015

van Dijk, A. I. J. M., van Noordwijk, M., Calder, I. R., Bruijnzeel, S. L. A., Schellekens, J., & Chappell, N. A. (2009). Forest-flood relation still tenuous - comment on 'Global evidence that deforestation amplifies flood risk and severity in the developing world' by C. J. A. Bradshaw, N.S. Sodi, K. S.-H. Peh and B.W. Brook. *Global Change Biology*, *15*(1), 110–115. https://doi.org/10.1111/j.1365-2486.2008.01708.x

van Soesbergen, A., & Mulligan, M. (2018). Uncertainty in data for hydrological ecosystem services modelling: Potential implications for estimating services and beneficiaries for the CAZ Madagascar. *Ecosystem Services*, *33*, 175–186. https://doi.org/10.1016/j.ecoser.2018.08.005

Vieilledent, G., Grinand, C., Rakotomalala, F. A., Ranaivosoa, R., Rakotoarijaona, J.-R., Allnutt, T. F., & Achard, F. (2018). Combining global tree cover loss data with historical national forest cover maps to look at six decades of deforestation and forest fragmentation in Madagascar. *Biological Conservation*, *222*, 189–197. https://doi.org/10.1016/j.biocon.2018.04.008

Wolf, S., Eugster, W., Majorek, S., & Buchmann, N. (2011). Afforestation of tropical pasture only marginally affects ecosystem-scale evapotranspiration. *Ecosystems*, *14*(8), 1264–1275. https://doi.org/10.1007/s10021-011-9478-y

Zhou, G., Wei, X., Luo, Y., Zhang, M., Li, Y., Qiao, Y., Liu, H., & Wang, C. (2010). Forest recovery and river discharge at the regional scale of Guangdong Province, China. *Water Resources Research*, *46*(9). https://doi.org/10.1029/2009WR008829

Zimmermann, B., Elsenbeer, H., & De Moraes, J. M. (2006). The influence of land-use changes on soil hydraulic properties: Implications for runoff generation. *Forest Ecology and Management*, *222*(1–3), 29–38. https://doi.org/10.1016/J.FORECO.2005.10.070

Zwartendijk, B. W., Ghimire, C. P., Ravelona, M., Lahitiana, J., & van Meerveld, H. J. (2020). Soil hydrological characteristics for three areas in the Corridor Ankeniheny-Zahamena (CAZ), Madagascar. *NERC Environmental Information Data Centre*. https://doi.org/10.5285/7987c6d4-973d-436d-a13b-c52997d0bce5

Zwartendijk, B. W., van Meerveld, H. J., Ghimire, C. P., Bruijnzeel, L. A., Ravelona, M., & Jones, J. P. G. (2017). Rebuilding soil hydrological functioning after swidden agriculture in eastern Madagascar. *Agriculture, Ecosystems & Environment*, *239*, 101–111. https://doi.org/10.1016/j.agee.2017.01.002

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: van Meerveld HJ(I.), Jones JPG, Ghimire CP, et al. Forest regeneration can positively contribute to local hydrological ecosystem services: Implications for forest landscape restoration. *J Appl Ecol*. 2021;00:1–11. https://doi.org/10.1111/1365-2664.13836