High sedimentary oxygen consumption indicates that sewage input from small islands drives benthic community shifts on overfished reefs

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SUMMARY

Small-island coral reef ecosystems are usually closely coupled to the activities of human inhabitants. Ahus Island (Papua New Guinea) is an isolated Pacific island with a rapidly growing population, heavy reliance on marine resources and limited infrastructure. We hypothesized that untreated sewage was driving distinct benthic assemblages around Ahus and neighbouring uninhabited Onetah. At sites with varying proximities to beach toilets, fore-reef herbivorous fish biomass and benthic composition were measured alongside reef-flat sedimentary oxygen consumption (SOC); a high SOC rate reflects high organic input into coastal waters, thus serving as a potential indicator of sewage input. Fish biomass was low (17.1–20.1 g m^{-2}), but consistent between sites. However, cyanobacteria dominated the fore-reef closest to toilets (62 ± 3%) with highest reef-flat SOC, whereas hard corals dominated furthest away (63 ± 1%), where SOC was lowest. To our knowledge, this is the first study that used SOC to detect local differences in sewage pollution. The results indicate that whilst corals can maintain their dominance on overfished reefs, additional sewage stress may drive pronounced benthic shifts, highlighting the urgency to improve small-island waste management.

Keywords: phase shifts, sewage, sedimentary oxygen consumption, herbivorous fish, cyanobacteria, waste management, small-island communities, coral reefs, overfishing

INTRODUCTION

Island communities, such as those in the Pacific, have a particularly strong reliance on coral reef ecosystem services such as food, livelihoods and coastal protection. Often the high dependence on these services is coupled with a very low capacity to adapt to their loss (Burke *et al.* 2011), rendering these communities highly vulnerable to reef degradation. Modern influences and coastal population growth on Pacific islands have led to surges of non-traditional fishing methods (Hamilton *et al.* 2012), declining water quality and land-use change (Zann 1994), which are threatening coral reef integrity. An amalgamation of climate change and local stressors often results in the replacement of hard corals with alternative benthic organisms, which frequently leads to a decline of structural complexity with associated reductions of ecosystem services (Pratchett *et al.* 2014). Small-island ecosystems are uniquely fragile to disturbance due to their close coupling with the effects of human inhabitants.

Knowing where to focus management depends on determining and extracting information on relevant key drivers of degradation at different localities. Whilst relatively simple methods for measuring herbivorous fish communities are well established, assessing nutrient and organic matter (OM) input remains challenging in areas with limited infrastructure due to difficulties regarding sample storage, processing and measurements. Studies have proposed suitable indicators of changes in water quality (Cooper *et al.* 2009; Fabricius *et al.* 2012), but measurements are often static (e.g. macroalgal abundance, coral tissue thickness), and generally require laboratory facilities at some point (e.g. stable isotope analyses, exogenous sediment analyses – see Risk *et al.* 2001). Furthermore, despite sewage-based OM input having been recognized as a key problem for reefs worldwide for many decades (e.g. Barnes 1973), there remains a distinct lack of *in situ* studies that investigate its impacts (Wear & Thurber 2015). Rapidly growing populations and limited infrastructure make sewage treatment a critical issue on small islands.

To interpret ecosystem responses and trajectories that can provide important quantitative metrics for setting specific conservation goals, simple *in situ* indicators are required. The current study extended existing *in situ* methods for determining local pollution by exploring the potential for sedimentary oxygen consumption (SOC) incubations to assess

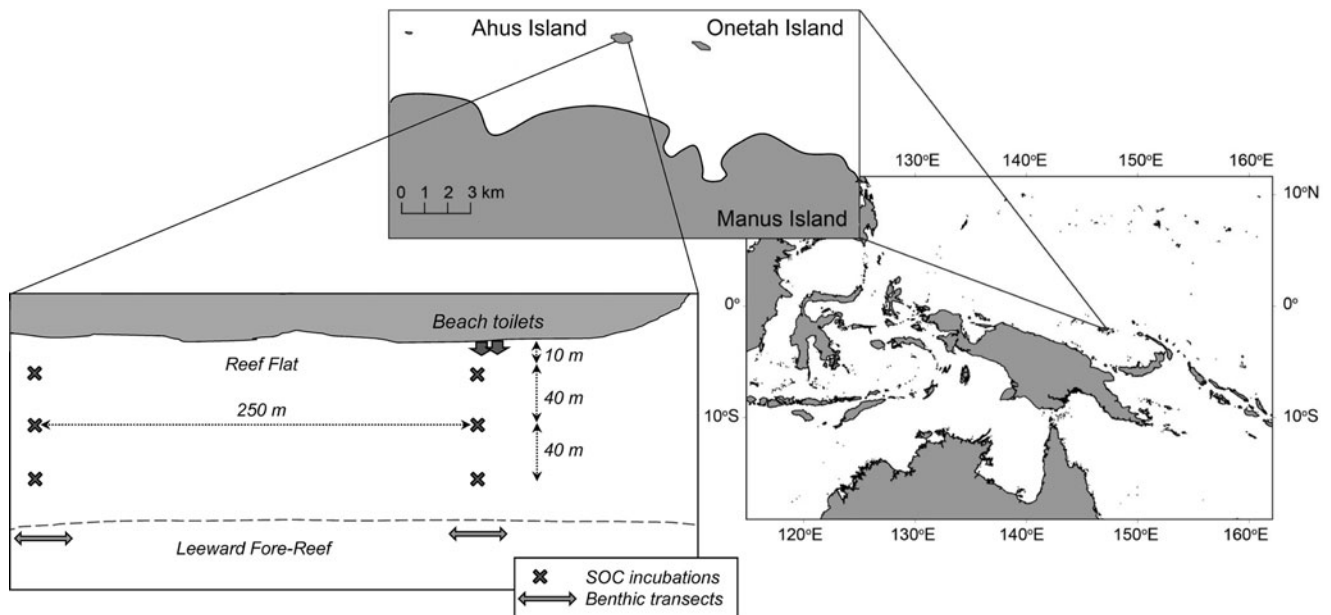*Correspondence: Amanda K. Ford e-mail: amanda.ford@leibniz-zmt.de

Figure 1 Map of study sites on the north coast of Manus Island, Papua New Guinea, including schematic diagram (bottom-left box) showing locations for SOC incubations and fore-reef benthic transects for the sites Ahus BT (right) and Ahus non BT (left). SOC = sedimentary oxygen consumption.

local anthropogenic OM input promptly in the field. In shallow-water reef environments with primary benthic cover by permeable sediments, intense benthic–pelagic coupling causes sediments to integrate OM concentration changes in the overlying water (Wild *et al.* 2005). As key organic components of sewage are rapidly recycled in surface sediments (Wild *et al.* 2008), elevated SOC rates should directly reflect recent sewage (OM) input. Sedimentary OM is less subject to short-term fluctuations than water column OM, implying that SOC indicates long-term processes more reliably than assessments of water parameters. If found to distinguish differences in local OM input, then SOC measurements have strong applicability to future studies in remote environments with limited infrastructure due to their simplicity and immediate results, thus offering a potential tool for island monitoring and research.

By measuring SOC alongside benthic and fish community assessments, this study aimed to investigate the roles of both overfishing and anthropogenic OM input in driving distinct benthic community assemblages of reefs fringing two small neighbouring barrier islands – Ahus and Onetah – in Papua New Guinea (PNG; Fig. 1). Ahus Island is densely populated (*c*. 700 people, which equates to *c*. 2500 people km^{-2}) with a heavy dependency on marine resources; 77% of households rate fishing as their primary income (Cinner 2005), compared to the regional coastal community average of 29.5% (Pinca *et al.* 2010). This dependency has resulted in high pressure on local reef fish populations, to such an extent that Ahus' fish biomass is now among the most degraded worldwide (MacNeil *et al.* 2015). Additionally, Ahus lacks

sewage treatment facilities, with raw sewage directly reaching the reef-flat at specific points (originating from around ten beach toilets on the island's shoreline, located over the water at *ca*. 5 m from the shore), thus providing an ideal opportunity to investigate the *in situ* impacts of anthropogenic OM input. Ahus' human population has increased rapidly over recent decades: the local district's population grew by 36% between 2000 and 2011 (National Statistical Office 2014), and consequently relative sewage input and fishing pressure will have increased significantly. By contrast, Onetah (3 km east) is uninhabited, although its reefs also fall under Ahus' customary marine tenure as a fishing ground.

These study sites provided a unique opportunity to explore two islands within the same tenure system that exhibit different anthropogenic influences regarding sewage pollution. We hypothesized that (i) benthic assemblages are significantly different between Ahus and Onetah, but (ii) because of the customary marine tenure and accessibility, herbivorous fish communities are comparable. We thus further hypothesized that (iii) benthic community differences are significantly linked to proximity to beach toilets, and (iv) SOC rates will reflect higher OM degradation closer to beach toilets.

MATERIALS AND METHODS

The two islands that were studied are located just north of Manus Island, northern PNG (Fig. 1). Two sites were selected on the leeward side of Ahus (147° 6′ E, 1° 56′ S) directly adjacent to beach toilets ('Ahus BT'), and along the shore

at 250 m from beach toilet influence ('Ahus non BT'). A third site was selected on the leeward side of uninhabited Onetah ('Onetah Control': 147° 8′ E, 1° 57′ S). Sites were consistent regarding exposure, orientation, bathymetry and distance from mainland. All fieldwork was carried out during May and June 2014.

To determine benthic community composition at the leeward fore-reef, 25-m transects ($n = 3$ site^{-1}) were deployed at 3-m depths parallel to, and at 120–150 m distance from the shore. Cover type was recorded every 25 cm (n = 100 transect^{-1}) using the point-intercept method. Where cyanobacterial mats were observed, they were distinguished between growing over dead substrate or sand ('cyanobacteria') and growing over live *Halimeda* spp. ('cyanobacteria on macroalgae'). Juvenile corals (<3 cm) were counted within 0.25-m^2 quadrats (n = 10 transect^{-1}) using a GOBE Nightsea UV lamp for fluorescence detection (Piniak *et al.* 2005). Herbivorous fish biomass was quantified using the distance sampling underwater visual census method (Labrosse *et al.* 2002); two divers recorded abundances and fork lengths of all observed fish along 50-m transects (n = 6 site^{-1}) at each island's leeward fore-reef. Length and spacing of transects as well as movement patterns and extensive home ranges of some species precluded comparisons between the two Ahus sites. Data were converted to biomass using established species-specific length–weight relationships (Froese & Pauly 2013). Herbivorous fishes were classified into four key functional groups that exhibit distinct roles of algal removal: browsers, grazers and detritivores, scrapers and small excavators, and large excavators and bioeroders (Green & Bellwood 2009).

Due to the proximity to OM input and the homogeneous shallow environment, and in order to document any potential changes from the shore towards the fore-reef, SOC measurements were carried out on the reef-flat at 10, 50 and 90 m from the shore (n = 8–10 distance^{-1} site^{-1}). Cut 50-mL syringes were used to collect 10-mL surface sediment cores (1 cm depth), which were placed into 160-mL glass vials and filled with water from the overlying water column. O$_2$ concentration was recorded prior to vials being sealed airtight, ensuring no air bubbles remained, and these were incubated *in situ* inside opaque bags for *ca.* 2 hours (Onset HOBO® pendant temperature and light loggers confirmed that light was excluded), following which O$_2$ was re-measured. O$_2$ concentrations were measured using an O$_2$ optode sensor with a conductivity probe (MultiLine® IDS 3430, WTW GmbH, Weilheim, Germany; accuracy: ±0.5% of measured value) 1 cm above the sediment after the water was stirred. Temperature and salinity were monitored throughout in order to confirm consistency. O$_2$ consumption in control chambers containing only water from the overlying water column (n = 5–6 distance^{-1} site^{-1}) was averaged and subtracted from SOC rates. After accounting for incubation time, vial volume and control measurements, SOC values were calculated to hourly rates per volume of surface sediment: μg O$_2$ cm^{-3} sediment h^{-1}.

To evaluate statistical differences between sites, benthic community transect data were entered into a principal components analysis (PCA) using the R *prcomp* (R base package version 3.1.1; R Development Core Team 2013) and *ggbiplot* (ggplot2 package; Wickham 2009) functions. Fish biomass data were tested by PERMANOVA using the Bray–Curtis similarity coefficient in PRIMER v.6 and PERMANOVA+ (PRIMER-E, Plymouth, UK), with 'island' as the fixed factor, using type 3 sums of squares and unrestricted permutation of raw data. Juvenile coral data were compared between sites by negative binomial regression using the R *MASS* package (Venables & Ripley 2002), which amended previous overdispersion. SOC data were tested for independent and combined effects of 'site' and 'distance from shore' using two-way ANOVA hypothesis testing through the R *aov* function (R base package version 3.1.1). Lastly, dominant benthic groups of hard corals and cyanobacteria (including cyanobacteria on macroalgae) were compared between sites using one-way ANOVA. Shapiro–Wilk normality tests confirmed normality ($p > 0.05$) of SOC rates, hard coral and log (+1)-transformed cyanobacteria data. *Post hoc* Tukey honest significant difference tests explored significant differences between groups.

RESULTS

Benthic assemblages differed significantly between the leeward fore-reefs of all sites (Fig. 2(a)). A PCA of the benthic communities emphasized these differences by distinguishing three distinct clusters according to site (Fig. 2(b)), with the first two components explaining 62.6% of the variation. The dominant benthic organisms – hard coral and cyanobacteria – were strongly associated to site (one-way ANOVA: hard coral – $F_{(2,6)} = 50.03$, $p < 0.001$; cyanobacteria – $F_{(2,6)} = 59.37$, $p < 0.001$), with hard coral decreasing and cyanobacteria increasing as sites increased in proximity to beach toilets. Directly in front of the beach toilets (Ahus BT), cyanobacteria dominated ($62 \pm 3\%$; mean $\pm$ SE), growing either on solid substrates ($17 \pm 2\%$) or on macroalgae ($44 \pm 2\%$). Hard coral cover ($12 \pm 0.1\%$) and juvenile coral abundances (1.3 ± 0.5 juveniles m^{-2}) were both low. Further from direct OM input (Ahus non BT), the reef was characterized by significantly lower cyanobacteria ($14 \pm 6\%$) and higher hard coral cover ($30 \pm 4\%$), though juvenile corals were still rare (1.3 ± 0.4 juveniles m^{-2}). At the furthest point from OM input (Onetah Control), coral cover was high ($63 \pm 1\%$) and cyanobacteria were negligible (<2%), and juvenile corals (4.0 ± 0.5 juveniles m^{-2}) were significantly more abundant than at the other sites ($z = 2.3$, $p = 0.02$).

Distinct differences in benthic communities were not reflected in herbivorous fish populations; biomass was neither significantly different within functional groups nor in total between islands (PERMANOVA; $F_{(1,10)} = 0.32$, $p > 0.05$; Fig. 3). However, SOC rates were greater at sites closer to beach toilets (two-way ANOVA; $F_{(2,77)} = 24.83$, $p < 0.001$; Fig. 4), indicating higher OM degradation. Distance from
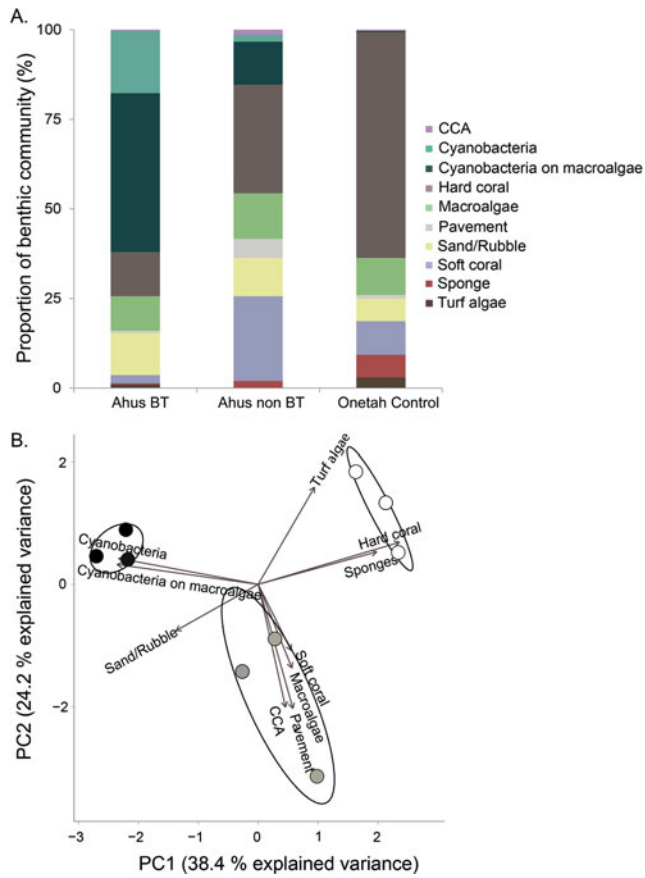
Figure 2 (a) Benthic community composition across the three sites. (b) Principal components analysis clusters the sites (Ahus BT = black circles; Ahus non BT = grey circles; Onetah Control = white circles) into distinct groups according to benthic composition of each transect (n = 3 site^{-1}). The first (PC1) and second (PC2) principal components combined explain 62.6% of the variance. CCA = crustose coralline algae.
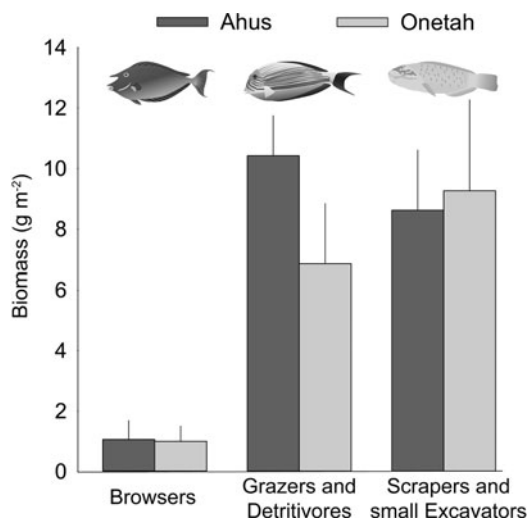

Figure 3 Biomass values of herbivorous fish functional groups – browsers, grazers and detritivores, and scrapers and small excavators – for each island. Larlgge excavators and bioeroders were not observed, and thus are not included in the graph.
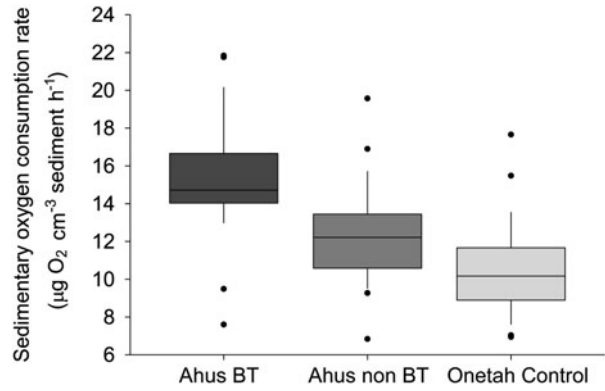

Figure 4 Sedimentary oxygen consumption rates for each site.

shore did not affect SOC rates ($F_{(2,74)} = 0.04$, $p = 0.96$), and this did not vary among sites ($F_{(4,74)} = 2.30$, $p = 0.066$; Supplementary Figure S1, available online), indicating the potential of land-derived OM to affect adjacent reefs even when separated by a reef-flat of at least 90 m.

DISCUSSION

The results underline the strong potential effects of small-island sewage-based OM input on the reef environment. Coral reef assemblages differed significantly between sites, with reefs closest to and furthest from the beach toilets being dominated by cyanobacterial mats and hard corals, respectively. While herbivorous fish biomass was not different between the islands, SOC rates were greater at sites closer to beach toilets. As both islands show equal herbivorous fish biomass, it is not possible to ascertain the specific contribution of herbivory relative to OM input on reef condition. However, the results suggest that anthropogenic OM input from sewage has a significant role in structuring benthic communities when herbivory remains consistent and low between sites.

Overfishing of herbivorous fish

The dependency of Ahus fishers on reef fish, coupled with the rapidly growing human population, promotes increasing use of non-traditional methods (e.g. night-time spearfishing) to maximize catches, thus intensifying pressure on already depleted resources. Total herbivorous fish biomass was consistently low (Onetah 17.1 ± 3.0 g m^{-2}, Ahus 20.1 ± 3.4 g m^{-2}), implying that Onetah's reefs are fished to the same extent as Ahus'. Herbivore biomass values are actually below notably overexploited Pacific islands such as the Main Hawaiian Islands (>30 g m^{-2}; Friedlander & DeMartini 2002). Ahus' fish stocks are projected to require 59 years to recover if fishing were stopped (MacNeil *et al.* 2015), and our results imply that recovery times will be similar at Onetah. Herbivorous fish communities play a central role in reef function and dynamics, and are important in maintaining reef resilience (Hughes *et al.* 2007). Therefore, it is likely that

these fished reefs are less able to resist and recover from other stressors (e.g. declining water quality), adding complexity to the interpretation of our findings.

Factors driving local benthic communities

The islands depict a common picture of overexploited fish communities and low water quality. We suggest that the results allow for the following two interpretations: (i) even when herbivorous fish populations are heavily exploited, healthy hard coral-dominated systems can be maintained when water quality is high, but (ii) under such reduced levels of herbivorous fish, OM input can have severe consequences for reef health.

Significant differences in both cyanobacteria abundance and reef-flat SOC rates among sites (highest closest to beach toilets) indicate that OM input is driving cyanobacterial mat proliferation. In the Caribbean, a region that is also characterized by chronically low levels of herbivores (Roff & Mumby 2012), OM degradation facilitates the release of sedimentary iron and phosphate, promoting mat development (Brocke et al. 2015a). Similarly, organic carbon, phosphorous and iron input stimulated mat growth in Australia (Albert et al. 2005). Once established, cyanobacterial mats release up to 79% of the total reef community's dissolved organic carbon (DOC) (Brocke et al. 2015b), thus promoting further bacterial proliferation, which can indirectly result in declining reef health through mechanisms such as increasing coral disease prevalence (Kline et al. 2006). Furthermore, cyanobacteria reduce coral recruitment (Kuffner & Paul 2004), supporting the observed juvenile coral densities, and they exhibit some of the highest reef nitrogen fixation rates (Cardini et al. 2014), which may further favour reef degradation.

SOC incubations as a simple and cost-effective monitoring tool

Elevated SOC rates indicate higher OM degradation at sites closer to beach toilets, demonstrating the ability of this method to identify sedimentary signals of localized sewage input on coral reef sediments. Interestingly, the lack of differences in SOC rates among different distances from the shore implies that OM homogeneously affects sediments up to at least 90 m from the source, perhaps due to tidal mixing across the reef-flat (being almost dry at lowest tide). Nonetheless, the capacity to distinguish significant differences at larger distance intervals (≥ 250 m) from sewage input demonstrates the potential for rapidly comparing local pollution *in situ* in remote (island) situations where infrastructure and equipment are limiting. While this measurement in itself provides a useful proxy for comparing OM input at a local scale within a coastal zone, combining it with other measurements could allow for further interpretations. For example, subsequent analyses of sedimentary lipids such as coprostanol (O'Leary et al. 1999), stable isotopes of nitrogen, bacterial communities and/or exogenous (anthropogenically derived) sediment contribution

would enable identification of the pollution source (Risk et al. 2001, 2009).

Ecological perspective and management implications

OM-driven proliferation of benthic cyanobacterial mats may stimulate a positively reinforcing cycle whereby limiting nutrients become readily available (phosphate from sedimentary OM degradation, DOC and bioavailable nitrogen release from mats) and further promote reef degradation. As few organisms feed on cyanobacteria due to poor nutritional quality and chemical defences (Nagle & Paul 1998), and mats inhibit key processes (e.g. coral recruitment; Kuffner & Paul 2004), this cycle may become increasingly challenging to reverse. Considering that most reefs are overfished and projected recovery times are extensive (35 years on average; MacNeil et al. 2015), it is critical to manage water quality in order to provide reefs with the best chance to maintain coral cover and to facilitate recruitment, especially in small-island environments, which are particularly sensitive to anthropogenic impacts.

Management of fisheries and water quality should be accompanied by support of alternative livelihoods and food sources for island communities in a holistic management approach. A limitation of small coral islands is the scarcity of arable land (Catala 1957) and infrastructure. One potential management tool that considers these needs and limitations is the installation of composting toilets, after due consideration of local culture. This could improve future food security of vulnerable communities by (i) improving production of land-based resources and (ii) promoting the recovery of fish stocks by both decreasing reliance on marine resources and reducing nutrient and OM levels that are detrimental to reef health. Such holistic management approaches are likely to meet with more success than strict limitations on fishing efforts that do not address the needs of island communities in terms of food security and livelihoods.

warm hospitality and permission to carry out research on their land.

Supplementary material

To view supplementary material for this article, please visit https://doi.org/10.1017/S0376892917000054

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