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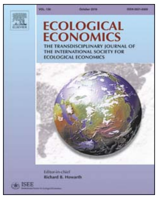

Analysis

Human Appropriation of Net Primary Productivity and Rural Livelihoods: Findings From Six Villages in Zimbabwe

Rose Pritchard[a,*], Casey M. Ryan[a], Isla Grundy[b], Dan van der Horst[a]

[a] *School of Geosciences, University of Edinburgh, Crew Building, Alexander Crum Brown Road, Edinburgh EH9 3FF, Scotland*
[b] *Department of Biological Sciences, University of Zimbabwe, P.O. Box MP167, Mount Pleasant, Harare, Zimbabwe*

ABSTRACT

The African land system is undergoing rapid change, and novel approaches are needed to understand the drivers and consequences of land use intensification. Human Appropriation of Net Primary Productivity (HANPP) is a powerful indicator of land use intensity, but has rarely been calculated at high spatial resolutions. Based on data from six villages in Zimbabwe, we present a novel method of calculating HANPP at community and household scales, and explore to what extent household wealth is related to NPP appropriation. HANPP at the village scale was higher than expected from previous studies, ranging from 48% to 113% of potential NPP. Loss of NPP through land use change accounted for the greater proportion of HANPP in four of the six villages, but NPP embodied in livestock feed, firewood and construction materials also contributed significantly to total appropriation. Increasing household wealth was associated with increasing appropriation of NPP in harvested resources, but not with loss of potential NPP through land use change. Our results indicate that land use intensity is currently underestimated in smallholder farming areas of southern Africa. High-resolution HANPP calculations based on field data offer an effective new approach to improving understanding of land use intensification in complex socioecological systems.

1. Introduction

Human activity is having unprecedented influence within the global land system. Over 80% of ice-free land has been altered by human impact (Sanderson et al., 2002), changing atmospheric composition, climate dynamics, nutrient cycling, biodiversity and ecosystem services (Chapin et al., 2000; Millennium Ecosystem Assessment, 2005; Foley et al., 2005). This 'human domination of the earth's ecosystems' (Vitousek et al., 1997) has led to reconceptualisation of humans as integral components and engineers of the global biosphere (Ellis and Ramankutty, 2008) and the recognition of a need for novel integrated approaches, breaking down the historic barriers between natural and social science, to better understand the drivers and consequences of land use change (Kates et al., 2001; Turner et al., 2007; Hackman et al., 2014).

Human Appropriation of Net Primary Productivity (HANPP), the proportion of annual plant biomass production co-opted by human activity, was first suggested as a measure of land use intensity by Vitousek et al. (1986). Land use intensity is a complex and multidimensional concept (Erb et al., 2013), and the advantage of HANPP compared to simpler metrics such as fertiliser inputs (Potter et al., 2010) or crop output (Monfreda et al., 2008) is that it is intrinsically socioecological, encompassing the interactions between human livelihoods and an ecological energy flux. Early studies quantified the annual extraction of NPP embodied in resources such as crops, livestock feed and timber as between 20 and 40% of annual global NPP (Vitousek et al., 1986; Rojstaczer et al., 2001; Imhoff et al., 2004), before Haberl et al. (2007) developed the HANPP concept further by expressing HANPP as a proportion of the potential NPP in a system undisturbed by human influence, thereby including resource extraction but also losses or gains in NPP caused by human land use change (such as deforestation or intensive agriculture). Using the latter approach, HANPP was calculated as 23.8% of potential global terrestrial NPP in the year 2000 (Haberl et al., 2007).

Land use intensification is a subject of particular research interest in sub-Saharan Africa for several reasons. Firstly, HANPP has increased more steeply in Africa over the last century than on any other continent (Krausmann et al., 2013), but yields of staple crops remain far below potential levels (Licker et al., 2010; Sanchez, 2010). Secondly, Africa has been identified as a hotspot of potential new agricultural land (Ramankutty et al., 2002; Deininger et al., 2011; Lambin and Meyfroidt, 2011; although see Young, 1999; Chamberlin et al., 2014), but

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* Corresponding author.
E-mail address: r.c.pritchard@sms.ed.ac.uk (R. Pritchard).

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Fig. 1. Location of Wedza District in Mashonaland East Province, Zimbabwe, relative to major urban centres. Wedza Mountain is located in the central part of Wedza District (18°46'28S, 31°32'41E).

agricultural expansion involves numerous conflicts – both social, such as poor recognition of land rights resulting in displacement of rural communities (Cotula et al., 2009), and ecological, such as the situation of much potential agricultural land in highly biodiverse regions (Gibbs et al., 2010). Thirdly, and at a more local scale, rural subsistence livelihoods in Africa are often centred on crop production, livestock rearing, and collection of wild-sourced resources such as firewood and wild foods (Angelsen et al., 2014) and as such are directly linked and highly sensitive to changes in ecosystem properties. Whether approached from 'bottom-up' livelihoods and development perspectives or from 'top-down' global change and conservation perspectives, understanding the processes and impacts of land use intensification in sub-Saharan Africa is therefore a research priority.

To date there has been little use of HANPP as a land use intensity measure in sub-Saharan Africa. HANPP has been quantified at continental (Fetzel et al., 2016) and regional scales (Abdi et al., 2014), but most national case studies have been carried out in Europe (e.g. Schwarzlmuller, 2009; Musel, 2009; Kolheb and Kraussman, 2009) and Asia (Prasad and Badarinth, 2004; Kastner, 2009; Chen et al., 2015), with the only national HANPP case study in Africa focused on South Africa (Niedertscheider et al., 2012). One recent study (Bartels et al., 2017) adapted the HANPP framework to the village scale in Tanzania and calculated village-level HANPP to be between 34 and 38% of annual potential NPP, but without further case studies it is impossible to determine whether this is a representative example. The lack of fine scale HANPP research in Africa may be a consequence of data availability, with commonly used data sets such as FAOSTAT (FAO, 2015a) and the Global Forest Resources Assessment (FAO, 2015b) having well-recognised weaknesses in the African context (Mather, 2005; Fetzel et al., 2016). Previous studies may also have underestimated HANPP in rural Africa due to lack of recognition of the importance of wild-sourced resources such as firewood and construction material in rural livelihoods – a recent global analysis found that around 30% of household income in rural Africa is derived from such wild-sourced resources (Angelsen et al., 2014), but only a minority of studies have attempted to include domestic fuelwood consumption (Niedertscheider et al., 2012; Fetzel et al., 2016; Bartels et al., 2017), and resources such as construction poles have been largely omitted from existing analyses. Additionally, the low resolution and simplifying assumptions of published studies have potentially obscured important heterogeneity in parameters such as forest structure and population distribution. Drawing linkages between HANPP and ecosystem goods and services such as biodiversity demands a finer resolution of analysis (an approach adopted by Haberl et al., 2004).

Analysis of NPP appropriation patterns at the household scale also has the potential to improve understanding of the social and environmental consequences of changing rural livelihoods. Many studies have documented the income portfolios of rural African households (e.g. Cavendish, 2000; Mamo et al., 2007; Kamanga et al., 2009), but fewer have considered how livelihood strategies and socio-economic characteristics influence household-scale environmental or NPP footprints. Further, past studies indicate that wealthier households have higher absolute environmental income (Cavendish, 2000; Mamo et al., 2007), partly driven by ability to obtain a higher share of the most lucrative environmental resources (Ambrose-Oji, 2003; De Merode et al., 2004), but no research has assessed whether this pattern of 'elite capture' of environmental goods is replicated in NPP appropriation, or whether the greater capability of wealthy households to access resources or displace NPP demand during periods of scarcity results in exacerbation of rural NPP appropriation inequalities during land use intensification.

Reflecting the research gaps described above, the first objective of this study is to develop a novel method of quantifying HANPP at the community scale and to calculate HANPP in six villages in central Zimbabwe. Avoiding the inaccuracies associated with the use of national statistics, we instead base our analysis on detailed field data describing woodland structure and rural livelihoods. Our second objective is to adapt this method to the household scale, in order to assess the extent to which household wealth and income may be associated with household NPP appropriation and to discuss the potential ramifications of land use change for inequalities in NPP appropriation.

2. Methods

Our methods consist of field data collection in rural Zimbabwe and the development of a new method quantifying HANPP at village and household levels. We begin by describing the study site and field data collection methods. We then detail our village-level HANPP calculations, and finish by describing how we investigated the relationship between household wealth and appropriated NPP.

2.1. Study Site

The study was conducted in the Communal Area on and around Wedza Mountain, in the Mashonaland East province of Zimbabwe (Fig. 1). Due to traditional sacred values and past legal restrictions (Gumbo, 1988), Wedza Mountain has maintained high biomass woodland while the surrounding lowlands have become mainly deforested (Hansen et al., 2013). Woodland in the study area is of the dry miombo type, characterised by *Brachystegia spiciformis*, *B. boehmii* and *J. globiflora*. Wedza Mountain is in agroecological region 2b of Zimbabwe, with estimated rainfall of 750–1000 mm yr^{-1} (Vincent and Thomas, 1960).

Three pairs of villages were selected for inclusion in the study: Makumbe and Pfende in the mainly deforested lowlands with households 3 and 5 km west of the mountain woodland; Mapfanya and Betera on the western fringes of the mountain woodland; and Charambira and Mbizi on the more remote eastern side of the mountain. Livelihoods in the area are centred on subsistence agriculture, livestock husbandry (primarily cattle, goats and chickens), and casual day labour.

2.2. Field Data Collection

2.2.1. Land Cover Maps

Two participatory mapping group discussions and four transect walks were carried out in May 2014 in each of the six villages, and these resulted in six locally understood land cover categories (Table 1). These locally derived mapping data were combined with Google Earth satellite imagery in QGIS (QGIS, 2016) to create village land cover maps (Supporting information Fig. 1; SI Table 1). The extent of cover by high biomass mountain woodland was cross-checked using maps developed by Hansen et al. (2013).

Ecological survey plots were established in the three land cover categories with greatest spatial extent. Five plot locations were randomly generated in QGIS in each of three land cover categories (mountain woodlands, lowland woodland and croplands) in each of the six villages, giving a total of 30 plots each for lowland woodlands and croplands and 20 plots for mountain woodland (the villages of Makumbe and Pfende have no mountain woodland area). Plots were inventoried between February and April 2015, using circular plots of 20 m radius. In each plot, diameter at breast height (DBH: measured at 1.3 m) and local vernacular name were recorded for all stems with DBH ≥ 3 cm. Where possible, names in the local Shona language were translated to scientific names in the field using Mullin (2006) or Hyde et al. (2016), and identification checked using Coates Palgrave (2002). Specimens of species unknown to research assistants and Shona ethnospecies without a previously recorded scientific translation were taken for identification at the National Herbarium of Zimbabwe in Harare.

2.2.2. Household Survey

To understand household livelihood strategies, a household survey was undertaken using stratified random sampling. Household lists were generated during participatory mapping exercises, and in each village the households were selected proportional to sample size, selection stratified into three categories of household size (1–2 residents, 3–5 residents and 6 + residents) and three categories of household head (male-headed, widow-headed, and de facto female-headed with husbands working away; categories follow Cavendish, 2000) to give a total sample size of 104 households. High population mobility in Zimbabwe due to economic instability resulted in high survey attrition compared to similar studies, resulting in a final sample size of 91 households. Village size ranged from 10 to 53 permanently inhabited households (mean of 33 households) and sampling intensity ranged from 37 to 80% (mean of 52%).

The questionnaire was adapted from the CIFOR-PEN prototype questionnaire (CIFOR-PEN, 2008) and used to collect detailed data on use of wild-sourced resources (such as firewood and wild fruits) in the month preceding the questionnaire. Data were also collected on household assets and all other income sources, including crops, livestock, informal labour and remittances. The questionnaire was used three times to capture seasonal variation in livelihood strategies (June/July 2014, February/March 2015 and October/November 2015).

2.3. Quantifying HANPP

Following Haberl et al. (2007) and Haberl et al. (2014), we define HANPP as:

$$HANPP = HANPP_{luc} + HANPP_{harv}$$

where $HANPP_{luc}$ is the loss of potential NPP due to land use change and $HANPP_{harv}$ is NPP harvested by humans. $HANPP_{harv}$ is further subdivided into used extraction (consumed by humans) and unused NPP, meaning NPP influenced by human activity but not extracted from the ecosystem such as unrecovered crop residues.

$HANPP_{luc}$ is calculated as:

$$HANPP_{luc} = NPP_{pot} - NPP_{act}$$

where NPP_{pot} is the potential NPP in a hypothetical undisturbed system, and NPP_{act} is the actual NPP of the prevailing human-altered system. Reflecting the greater uncertainty associated with calculating below-ground NPP, we follow a number of previous studies by focusing solely on aboveground HANPP (Prasad and Badarinth, 2004; Kolheb

Table 1
Overarching land cover categories derived from locally perceived land cover types in rural Zimbabwe. Mountain woodland, lowland woodland and wet grasslands are all common property resources available for use by all village residents, whereas croplands and gardens are privately managed.

Land cover category	Definition
Mountain woodland	Comparatively undisturbed miombo woodland found on Wedza Mountain
Lowland woodland	More disturbed lowland woodlands, found in village grazing areas and on riverbanks/kopjes. Also long-term abandoned fields with significant tree regrowth.
Wet grasslands	Seasonally dry (locally termed **bani**) and non-seasonal (**dofonya**) wetlands
Croplands	Active and recently fallowed fields
Gardens	Small fields, usually found in wetlands or along riverbanks, used for growing vegetables.
Residual area	Areas without vegetation cover, such as roads, household yards and borrow pits left following road construction.

and Kraussman, 2009; Vačkář and Orlitova, 2010), hereafter aHANPP. All results are presented in tonnes of dry matter.

2.3.1. Potential Aboveground NPP (aNPP$_{pot}$)

It is assumed that areas currently covered by woodland (both mountain and lowland), fields and residual area would, in the absence of human activity, be covered by undisturbed miombo woodlands. aNPP of undisturbed savanna woodland is the sum of annual woody growth, leaf production and understorey grass production. The area cover of all land cover types in each village is provided in the supporting information (SI Table 1).

Ten mountain woodland plots with minimal evidence of disturbance were used as proxies for undisturbed woodlands. Current plot stem biomass in undisturbed plots was determined using stem biomass allometric equations derived from similar dry miombo ecosystems (Grundy, 1995; Chidumayo, 1997; Ryan et al., 2011). Three different sets of annual woody increment estimates (Chidumayo, 1988; Frost, 1996; Flack, 2013) were used to project DBH one year in the future, and annual woody production determined by calculating plot biomass from the projected DBH values and deducting current standing biomass. Leaf production estimates were calculated using two leaf production equations (Chidumayo, 1997; Frost, 1996). The non-contiguous canopy in savanna woodlands also allows persistence of a grass understorey (Parr et al., 2014). As this was not measured directly in the field, expected annual grass production per hectare in relation to tree basal area was identified using Frost (1996; p26). Full details of all allometric equations, woody growth increments and annual grass production estimates can be found in the supporting information (SI Table 2).

There is comparatively little data on annual increments and leaf production in dry miombo systems, so all six possible combinations of increment and leaf production equation were calculated to give upper and lower aNPP$_{pot}$ estimates. Mean woody and leaf production in tonnes of dry matter ha^{-1} yr^{-1} were calculated for the ten reference plots to give the aNPP$_{pot}$ of undisturbed woodlands, and this was multiplied by the number of hectares of woodland, fields and residual area in each village (identified from village land cover maps) to give aNPP$_{pot}$ of undisturbed woodland per village.

All study villages also contain areas of wet grassland which would have low tree cover even in an undisturbed state, and total village aNPP$_{pot}$ is therefore the sum of woodland aNPP$_{pot}$ and grassland aNPP$_{pot}$. aNPP$_{pot}$ of wet grassland was assumed to be equal to peak annual grass biomass. Mean peak grass biomass was estimated from five studies in Zimbabwean and Zambian wet grassland (Scoones, 1991; Hoffa et al., 1999; Jeanes & Baars, 1991 *in* Scholes et al., 1996; Shea et al., 1996; Nyamadzawo et al., 2014; see SI Table 3) and gave a mean value of 4.2 ± 0.6SE t DM ha^{-1} yr^{-1}. This aNPP$_{pot}$ was multiplied by the number of hectares of wet grassland and gardens in each study village, and added to the aNPP$_{pot}$ of the woodland area to give total village aNPP$_{pot}$.

2.3.2. Actual Aboveground NPP (aNPP$_{act}$)

The aNPP$_{act}$ for woodland area was calculated by applying the method described above to the ten plots in each land cover type in each pair of adjacent study villages, giving separate annual NPP estimates for mountain woodland, lowland woodland, and trees on agricultural land in each village pair. These woodland aNPP$_{act}$ values were multiplied by the area cover in hectares of the relevant land cover type in each village. Reflecting poor data availability on NPP in disturbed vs. undisturbed wet grasslands, wet grassland NPP$_{act}$ was assumed to be the same as it would be in the altered landscape, so the same aNPP value of 4.2 ± 0.6 t DM ha^{-1} was applied to wetland areas.

NPP$_{act}$ of crop production was determined by calculating village production of eight key crops (maize, millet, sorghum, rice, sugar beans, cowpeas, sunflower and leafy green vegetables). Groundnuts and sweet potatoes are also grown in the study area, but were excluded from the analysis as the majority of biomass production is belowground. Mean per capita production of each of the crops over the last three harvest seasons was calculated for study households in each village and used to scale crop production to the village level using village household composition lists. As survey households within each village represent a broad range of socioeconomic and agroecological conditions, we believe these village level production estimates to be robust. Locally reported units were converted to kilograms using USDA (1992) and adjusted to dry matter using appropriate moisture content estimates (Gebhardt and Thomas, 2002; OMAFRA, 2016). Associated crop residues and pre-harvest crop losses were calculated from crop yield data using harvest factors from Haberl et al. (2007) (SI Table 4).

Grass production in agricultural land is focused on contour ridges; raised boundaries between fields intended to prevent soil erosion which are also an important source of livestock feed (Scoones, 1995). However, reflecting the small area coverage of contour ridges (< 2 ha per village) and the lack of data on contour ridge NPP, contour ridge grass production was not included in the analysis.

2.3.3. Harvested NPP (aHANPP$_{harv}$)

aHANPP$_{harv}$ was calculated as the sum of crop production and recovered residues, material grazed by livestock, and consumption of three wild-sourced resources accounting for the highest proportion of extracted biomass (firewood, construction poles and thatching grass).

For crops, aHANPP$_{harv}$ was assumed to be equal to aNPP$_{act}$. The proportion of crop residues recovered for use was calculated using conversion factors in Haberl et al. (2007).

Size of the village livestock herd was calculated by estimating ownership of the main livestock species (cattle, goats, chickens, turkeys and guinea fowl) in the village from the household survey. The proportion of livestock feed derived from the environment (the feed gap) was calculated by estimating annual feed demand using daily food intake estimates from Haberl et al. (2007) and deducting dry matter mass of feed crops, purchased concentrate, and the proportion of crop residues used as livestock feed (estimated as 41% in sub-Saharan Africa by Haberl et al., 2007).

Annual firewood consumption was estimated from the three months incorporated in the household questionnaire, including both firewood used domestically and for commercial purposes such as beer brewing and tobacco curing. Firewood consumption was recorded in local units, and following a review of the literature (see SI Table 5) and conversion to dry matter weight using moisture content estimates from Abbott and Lowore (1999) (SI Table 6), headloads were assigned a weight of 11 kg DM, wheelbarrows 20 kg DM, and cartloads 158 kg DM.

Volume of wood required annually for construction and maintenance of household structures (wooden huts, fences and cattle kraals) was calculated using volumes reported in Grundy et al. (1993) and converted to dry matter weight using published wood density values for the most prevalent local construction species (Goldsmith and Carter, 1981; Malimbwi et al., 1994; Abbott and Lowore, 1999; Williams et al., 2008; Chave et al., 2009). Firewood used for brick burning to construct household structures was not included, as the lifespan of brick buildings means that firewood demand is very low when expressed on an annual basis.

Annual thatching grass consumption was estimated from the household survey. Following Grundy et al. (2000), we assume thatching grass bundles to weigh 5 kg (fresh weight). Thatching grass is mainly collected in the early dry season, when grass moisture content is estimated to be 55% (Woollen et al., 2016). Consumption of firewood, construction materials and thatching grass was calculated on a mean per capita basis for study households in each village and then scaled to the non-surveyed households in the village.

A key consideration in calculating aHANPP is that estimates of aNPP$_{pot}$, aNPP$_{act}$ and aHANPP$_{harv}$ all apply to the same spatially bounded area, in this case the village. Village boundaries were determined during participatory mapping groups and confirmed during four GPS-tracked transect walks with key informants in each village.

Use of village land cover maps and village household survey data meant that $aNPP_{pot}$, $aNPP_{act}$ and $aHANPP_{harv}$ embodied in crops could all be reliably calculated within village boundaries, while data collected during the household survey on the source location of wild-sourced resources meant that estimates of $aHANPP_{harv}$ of firewood and construction materials could be restricted to reflect only aNPP appropriated within the village area. There is however some uncertainty over the proportion of cattle graze sourced within village boundaries. Cattle are herded during the farming season from October to May and stay primarily within the village area, while following the harvest from May to July field crop residues are a main food source, giving cattle little motivation to roam. The only season when cattle roam further is the later dry season from July to September when food becomes scarcer; however, Scoones (1995) found that cattle roaming distance is related to distance to permanent water source. As all study villages have permanent water sources, and as roaming distance is limited by the return of all cattle to the homestead each night due to fears of theft or predation by hyenas, we have assumed for this analysis that all environmental livestock feed is derived from within the village area. The limitations of this assumption are considered in the discussion.

Unrecovered crop residues and pre-harvest crop losses were included in $aHANPP_{harv}$ but reported as unused extraction. Although human-caused veld fires were common in the study area, there are no accurate data available at sufficiently high resolution; we therefore follow Niedertscheider et al. (2012) in omitting biomass changes caused by human-induced fires from the analysis.

2.4. Household Wealth and aNPP Appropriation

Twelve interviews were carried out, two in each village, to identify features that indicated whether households were very poor, less poor, or wealthy by local standards. Interview respondents were purposively sampled: one high income and one low income household identified from the household survey in each village to obtain a broad range of perspectives, and including only long-term village residents with a good knowledge of all other households in the village.

Wealth indicator interview responses were combined to give a wealth index with seven categories (Table 2). Indicators which were locally important but which were linked directly to NPP consumption such as cattle ownership were not included in the index. Surveyed households were assigned a wealth index between 0 and 7.

Household level $aHANPP_{luc}$ was calculated by deducting household crop production and aNPP of trees in fields from the $aNPP_{pot}$ of the land area belonging to the household. Respondents could not provide reliable estimates of the area in hectares of household land holdings and so were instead asked for the number of fields owned. Number of fields was then multiplied by 0.4 ha, this being the mean area of 10 fields measured using QGIS and Google Earth imagery. $aHANPP_{harv}$ was calculated as the sum of crop and crop residue production, livestock environmental feed demand, and wild-sourced resource consumption.

Restricting $aHANPP_{harv}$ to only the area owned by the household would seriously underestimate household consumption of NPP embodied in firewood and livestock feed, and the method presented here therefore represents the household 'footprint' of aNPP appropriated within the village area. However, it should be noted that there are no suitable data available to calculate the contributions of individual households to changes in the $aNPP_{act}$ of common property woodlands, which may result in underestimates of household $aHANPP_{luc}$.

Linear regression was used to examine the relationship between aNPP appropriation and three different wealth measures: wealth index, household cash income (calculated from the household survey), and the median of household rank by these two measures (hereafter the combined wealth rank). Households were also split into two groups, those belonging to the three villages with highest land use intensity (Makumbe, Pfende and Mapfanya) and those with the lowest land use intensity (Betera, Charambra and Mbizi). The ratio of total aNPP appropriation by households with a combined wealth rank in the top and bottom 20% of each village set was compared to assess NPP appropriation inequality. The same method was used to calculate inequality in cash income. All analyses were carried out in Excel and R (R Core Team, 2014).

3. Results

3.1. $aNPP_{pot}$ and $aNPP_{act}$ in Miombo Woodland Systems

$aNPP_{pot}$ calculated from undisturbed woodland reference sites ranged from $3.6 \pm 0.2\,\mathrm{t\,DM\,ha^{-1}\,yr^{-1}}$ to $6.0 \pm 0.2\,\mathrm{t\,DM\,ha^{-1}\,yr^{-1+}}$ dependent on the combination of leaf and increment equations used (Fig. 2), with these aNPP estimates being within the range of published studies (SI Table 7).

Annual $aNPP_{act}$ was highest in mountain woodland plots, with the six combinations of increment and leaf equations giving a mean annual aNPP of $4.7 \pm 0.4\,\mathrm{t\,DM\,ha^{-1}\,yr^{-1}}$ in the Charambira/Mbizi village pair and $3.8 \pm 0.3\,\mathrm{t\,DM\,ha^{-1}\,yr^{-1}}$ in Mapfanya/Betera (Fig. 3). Increased grass production only partially compensated for loss of tree productivity in more disturbed lowland woodlands. Tree $aNPP_{act}$ in croplands was almost twice as high in Charambira/Mbizi as in the other two village pairs, but even in these villages amounted to only $0.5 \pm 0.05\,\mathrm{t\,DM\,ha^{-1}\,yr^{-1}}$.

3.2. aHANPP at the Village Scale

aHANPP ranged from 113% in Makumbe village to 48% in Charambira village (Table 3). $aHANPP_{harv}$ and $aHANPP_{luc}$ made an equal contribution to aHANPP in Mapfanya and Makumbe villages, whereas $aHANPP_{luc}$ accounted for a much higher proportion of aHANPP in the other four villages. Although different equation combinations resulted in quite high levels of variation in estimated appropriation of aNPP in tonnes of dry matter, aHANPP expressed as a

Table 2
Wealth Index comprised of locally derived wealth indicators relevant to Wedza District, Zimbabwe, compiled from twelve key informant interviews. Households were assigned a score between 0 and 1 in each indicator category, resulting in a total wealth index score of between 0 and 7.

Category	Very poor (assigned score of 0)	Less poor (assigned score of 0.5)	Locally wealthy (assigned score of 1)
Farming equipment	No large farming equipment	Own two or more of: plough, wheelbarrow, scotch cart	Fulfil 'less poor' criteria, and also own one or more of: harrow, cultivator, planter, tractor
Transport	No form of transport	Bicycle	Car
Household structures	No large bedroom house, only one or two roundhouse kitchens	Main house with 1–3 rooms	Main house with 4 or more rooms
Sanitation	No toilet		Toilet
Household furnishings	No expensive furnishings	Own two or more of the following: Bed (1 only), radio, chairs	Fulfil 'less poor' criteria and also own two more of: TV, beds (2 or more), generator, lounge suite
Domestic help	No domestic worker		Domestic worker employed at any time during study period
Water supply	Use shared water sources such as wells or boreholes		Private well, borehole or water pump

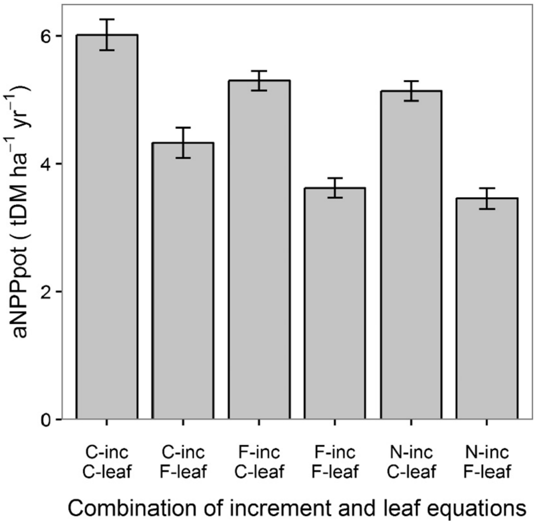

Fig. 2. $aNPP_{pot}$ ha^{-1} yr^{-1} calculated using all combinations of three woody increment ('inc') estimates and two annual leaf ('leaf') production allometric equations, based on data from ten comparatively undisturbed miombo plots on Wedza Mountain, central Zimbabwe. Error bars represent one standard error.

Abbreviations refer to equations derived from the following: C-inc = Chidumayo (1988), F-inc = Frost (1996), N-inc = Flack (2013), C-leaf = Chidumayo (1997), F-leaf = Frost (1996). Full details of all allometric equations and increments can be found in the supporting information.

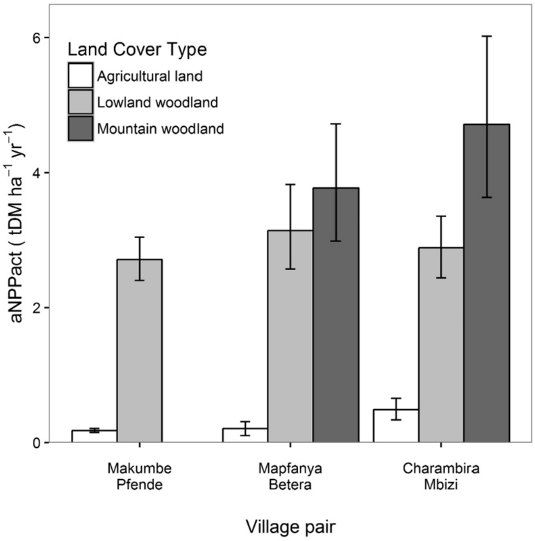

Fig. 3. Annual NPP of tree and grass production in three different land covers in three village pairs in central Zimbabwe. Agricultural land data do not include crop production. Error bars represent range of results calculated using six different combinations of leaf production and woody increment equations.

percentage of $aNPP_{pot}$ was much less sensitive, with a maximum difference of 10% between upper and lower estimates. Although the choice of equation used altered the relative contributions of $aHANPP_{harv}$ and $aHANPP_{luc}$, in four of the study villages there is no overlap in the ranges of the potential percentage contributions of $aHANPP_{luc}$ and $aHANPP_{harv}$. Therefore the conclusion that $aHANPP_{luc}$ is the greater contribution to HANPP in these villages remains robust whichever equation combination is used. Compared to the findings of previous African HANPP studies (Table 4), aHANPP was substantially higher in each of the six villages.

Livestock grazing was the main contributor to $aHANPP_{harv}$, accounting for between 42 and 66% of total $aHANPP_{harv}$ (Fig. 4). Collection of firewood and construction materials accounted for between 21% and 31% of $aHANPP_{harv}$, while crop production accounted for a relatively small proportion, between only 9 and 20%.

3.3. aNPP Appropriation and Household Wealth

There were significant relationships between aNPP appropriation and household wealth index score and combined household ranking, but no correlation with log cash income per capita (Table 5a). There was no apparent relationship between household $aHANPP_{luc}$ and any wealth indicator, whereas there was a significant relationship between $aHANPP_{harv}$ and all wealth indicators. However, the low adjusted R^2 in all cases (Table 5) indicates that there are numerous factors other than wealth influencing variation in aNPP appropriation.

When $aHANPP_{harv}$ was disaggregated by source category there was a significant positive correlation between wealth indicators and appropriation of aNPP embodied in livestock feed and crops, but no apparent relationship between any wealth indicators and appropriation of aNPP embodied in environmental resources (Table 5b). Increasing household wealth was associated with increased ownership of livestock, particularly cattle and poultry, but was not associated with increased field holdings (Table 5c).

In the higher land use intensity villages (Makumbe, Pfende and Mapfanya) the top 20% of households by combined wealth ranking appropriated on average 30.8 ± 4.1 t DM hh^{-1} yr^{-1}, while the poorest 20% of households appropriated on average 18.4 ± 2.9 t DM hh^{-1} yr^{-1}. In the lower land use intensity villages (Betera, Charambira and Mbizi), households in the wealthiest 20% appropriated on average 27.2 ± 4.2 t DM hh^{-1} yr^{-1} while households in the poorest 20% appropriated 13.0 ± 2.5 t DM hh^{-1} yr^{-1}. The ratio of total combined NPP appropriation by the richest 20% of households to that appropriated by the poorest 20% of households was 1.7 in the higher land use intensity villages and 2.1 in lower land use intensity villages, indicating slightly higher inequality in HANPP appropriation in the lower land use intensity villages.

Inequality in HANPP consumption was much lower than inequality in cash income. In the higher land use intensity villages, the ratio of cash income in the wealthiest 20% of households by combined wealth ranking compared to the poorest 20% was 23.3, with the wealthiest 20% earning US\$1912.91 ± 570 per capita yr^{-1} compared to US \$82.09 ± 13 per capita yr^{-1}. Even excluding the wealthiest household, which had cash income per capita six times that of the next wealthiest household, the ratio of cash income in the wealthiest and poorest 20% was still 15.8. In the three lower land use intensity villages the equivalent ratio was only 8.0, with the wealthiest 20% of households earning US\$1079.14 ± 249 per capita yr^{-1} compared to US \$134.82 per capita yr^{-1} in the poorest 20%.

4. Discussion

4.1. aHANPP at the Village Scale

Our findings indicate that aHANPP quantified at the village level is much higher than would be anticipated from previous studies. aHANPP varied from 48% in Charambira up to 113% in Makumbe, whereas previous regional studies reported a range from 12.4 to 23.0% (Imhoff et al., 2004; Haberl et al., 2007; Niedertscheider et al., 2012; Krausmann et al., 2013; Fetzel et al., 2016) and the only previous village scale study estimated aHANPP as between 34 and 38% (Bartels et al., 2017). Even in the higher resolution maps developed by Haberl et al. (2007), the majority of Zimbabwe has HANPP of between 20 and 40%, with few areas exceeding 50%.

There are several potential reasons behind the discrepancy between our results and those of published studies. Partly the high aHANPP is attributable to the choice of study site. The heterogeneity of land use in Africa is well-recognised, with some areas being underutilised while others are densely populated by smallholder farming communities (Tittonell and Giller, 2013; Chamberlin et al., 2014; Jayne et al., 2014).

Table 3
aHANPP in six villages in Wedza District, Zimbabwe, in total and disaggregated as aHANPP$_{luc}$ (aNPP prevented due to land use change), used aHANPP$_{harv}$ (harvested aNPP embodied in resources such as crops and firewood) and unused aHANPP$_{harv}$ (aNPP impacted by human activity but not harvested, such as unrecovered crop residues). Percentages are calculated as the proportion of aNPP$_{pot}$ (the potential NPP in a system undisturbed by human activity). Main figures are the mean of calculations using six combinations of woody increment and leaf production equations. Figures in brackets represent the range of results derived from using these six different combinations of equations.

Village	Village area (ha)	aHANPP (%)	aHANPP (t DM yr^{-1})	aHANPP$_{luc}$ (%)	aHANPP$_{harv}$ (used, %)	aHANPP$_{harv}$ (unused, %)
Makumbe	368	113 (110–118)	1897 (1548–2294)	56 (46–65)	56 (43–68)	1.6 (1.2–1.9)
Pfende	323	84 (80–86)	1253 (915–1623)	59 (48–69)	25 (19–32)	0.5 (0.4–0.6)
Mapfanya	441	72 (68–78)	1461 (1125–1809)	35 (26–41)	36 (27–46)	0.8 (0.6–1.0)
Betera	636	53 (50–55)	1571 (1120–2045)	37 (30–42)	16 (12 – 20)	0.4 (0.3–0,6)
Charambira	249	48 (43–50)	548 (374–726)	31 (22–37)	16 (12–20)	0.2 (0.2–0.3)
Mbizi	268	58 (54–60)	716 (511–929)	39 (30–44)	19 (14–23)	0.4 (0.3–0.5)

Table 4
Previously published HANPP estimates from studies in Africa.

Region	HANPP estimate (%)	Reference
Sub-Saharan Africa	12.4[a]	Imhoff et al. (2004)
Sub-Saharan Africa	18	Haberl et al. (2007)
South Africa	21–25	Niedertscheider et al. (2012)
Africa	20	Krausmann et al. (2013)
Southern Africa	23	Fetzel et al. (2016)
Ololosokwan village, Tanzania	34–38	Bartels et al. (2017)

[a] Imhoff et al. (2004) express HANPP as the used proportion of NPP$_{act}$, while all other studies define HANPP as human appropriation of NPP$_{pot}$.

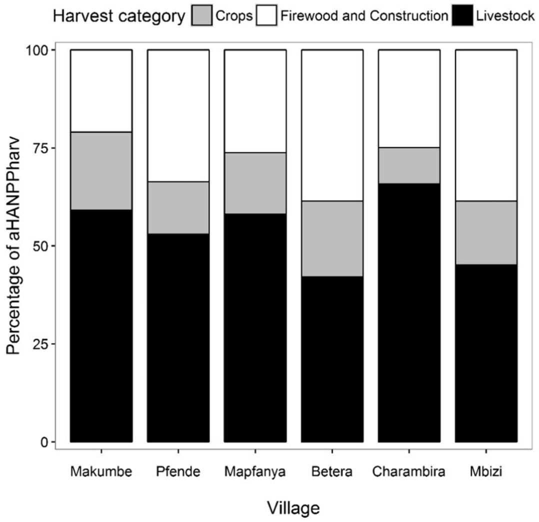

Fig. 4. Used aHANPP$_{harv}$ in six villages in central Zimbabwe separated into three main harvest categories. 'Crops' includes the most important field crops in the area along with associated recovered crop residues. 'Livestock' represents grazed and browsed livestock feed. 'Firewood and construction' encompasses all firewood, construction poles and thatching grass collected by village residents within the village area.

Table 5
Relationships between three indicators of household wealth and (a) total household NPP appropriation, aHANPP$_{harv}$ and aHANPPluc; (b) aHANPP$_{harv}$ disaggregated into the source categories of livestock feed, crops, and firewood/construction material; and (c) household characteristics with potential to mediate the interaction between wealth and aHANPP. Linear regression analysis based on data from 91 households in Wedza Communal Area, Zimbabwe. Combined ranking refers to the median of household positions within the total sample when ranked by cash income and by wealth index.

	Wealth index score	Log cash income per capita	Combined ranking
	Adjusted R^2	Adjusted R^2	Adjusted R^2
(a)			
aHANPP (t DM)	0.21**	0.02	0.12**
aHANPP$_{luc}$ (t DM)	0.0	0.01	0.0
aHANPP$_{harv}$ (used fraction, t DM)	0.34**	0.04*	0.20**
(b)			
aHANPP$_{harv}$ (livestock feed)	0.32**	0.04*	0.21**
aHANPP$_{harv}$ (crops)	0.30**	0.03	0.15**
aHANPP$_{harv}$ (firewood/construction)	0.0	0.0	0.0
(c)			
Agricultural efficiency (crop production t DM field^{-1})	0.006	0.01	0.04*
Household field holdings	0.02	0.0	0.01
Heads of cattle	0.34**	0.04*	0.20**
Heads of poultry	0.14**	0.05*	0.15**
Heads of goats	0.05*	0.01	0.04*

Significance levels:
* $p < 0.05$.
** $p < 0.001$.

In Zimbabwe, these densely populated areas are a legacy of past inequity in land ownership, with many indigenous black farmers restricted to crowded Communal Areas while the best agricultural land was conserved for large commercial white farms (Palmer, 1990). While land reform has resulted in some population re-distribution (Scoones, 2010), the historic land ownership system still shapes the extant landscape. Although focusing on a Communal Area will undoubtedly result in higher aHANPP, there is a strong argument that, as rural populations in more marginal agricultural areas are most sensitive to environmental change (Jones and Thornton, 2009), these areas should be a priority for land use change research.

However, our higher aHANPP is also driven by a number of other factors. Firstly, use of field data rather than national statistics allowed inclusion of resources such as firewood and construction material which are only poorly recorded in national level data. Firewood, construction poles and thatching grass accounted for between 21 and 31% of total aHANPP$_{harv}$, with average per capita extraction totalling 1.1 t DM yr^{-1}. Excluding this resource flow could therefore result in significant underestimates of $aHANPP_{harv}$ particularly in rural areas of developing countries. Use of locally derived woodland survey data also meant that we could account for the contribution of woodland degradation to $aHANPP_{luc}$. The majority of published studies assume $aNPP_{pot}$ and $aNPP_{act}$ to be equal in forest and woodland systems – and in rangeland systems in the case of Bartels et al. (2017) – but our data show human disturbance results in substantial variation in $aNPP_{act}$ over even relatively fine spatial scales. While recognising that the resource intensity of our approach would be challenging if seeking to ascertain HANPP at wider spatial scales, we suggest that detailed field data on forest and woodland structure and on rural livelihood portfolios is key to improving the accuracy of higher resolution aHANPP estimates.

The finding of extremely high aHANPP (113%) in Makumbe village has two potential explanations. The first is that the estimate includes some aNPP appropriated outside the village area due to livestock grazing. As detailed in the methods, observations of local herding patterns suggest the majority of livestock feed to be obtained within the village, but without a more detailed analysis of livestock movement patterns there is uncertainty attached to this assumption. However, even were it very conservatively assumed that only 50% of livestock feed was obtained inside the village area, aHANPP would still be high at 91%. This leads us to suggest that the high aHANPP observed in several villages is also due to harvest of production from previous years embodied in firewood and construction poles. The high environmental pressure and unsustainable use implied by a HANPP estimate of > 100% is supported by the levels of woodland degradation observed in the highest land use intensity villages.

4.2. Uncertainty in aHANPP Estimates

The main source of potential error in the presented method is in the estimation of $aNPP_{pot}$ and $aNPP_{act}$ in miombo woodlands. There have been few longitudinal studies of annual production in miombo woodlands, but our estimates of annual woody $aNPP_{pot}$ of woody production lie within the range of published studies (see SI Table 7). There are few published studies of annual leaf production in miombo woodland, and use of the allometric equations developed in Zambia by Chidumayo (1997) indicate much higher annual leaf production than that predicted by the Zimbabwean equations from Frost (1996). However, the midpoint of the two leaf production calculations used in this study falls within the range of published estimates.

An additional potential source of overestimation is that miombo woodland production is linked to precipitation levels (Frost, 1996), and although all allometric equations used in this study were derived from dry miombo systems, woodlands in Mozambique and Zambia typically receive higher rainfall than Zimbabwean woodlands and may have corresponding differences in growth rate and in proportional relations between DBH and leaf production. As there are no allometric equations developed within the study site, using a range of equations derived from similar systems was the only way to assess the scale of uncertainty introduced by choice of allometric. Furthermore, it could be argued that use of local reference plots may have resulted in overestimation of woodland production as some plots showed signs of minor disturbance. However, given that miombo woodland evolved in a context of disturbance, either by humans or by fire and megaherbivore activity (Mapaure and Moe, 2009), the use of mildly disturbed reference plots is of less substantial concern. We also do not account for the possibility that there could have been areas which were naturally clear of vegetation even in the undisturbed landscape.

Despite these limitations, our village level HANPP estimates appear robust. The different combinations of woody increment and leaf production equations resulted in varying estimates of woodland production in tonnes of dry matter, and altered the relative contributions of $aHANPP_{harv}$ and $aHANPP_{luc}$ to total aHANPP, but in no village did the final HANPP percentage estimate have a range of > 10 percentage points with all equation combinations. This indicates that aHANPP has low sensitivity to equation choice and allows a high level of confidence in the results.

An additional critique of our methods might relate to our focus on aboveground NPP. Miombo woodland soils are an important carbon store (Walker and Desanker, 2004) and changes in belowground production could significantly impact $HANPP_{luc}$, while inclusion of key local crops with primarily belowground production such as groundnuts and sweet potatoes could alter both NPP_{act} and $HANPP_{harv}$. A valuable development on the present study would therefore be to explore methods of integrating belowground production into HANPP estimates.

4.3. aNPP Appropriation and Household Wealth

Household wealth index score was positively associated with aNPP embodied in harvested resources, partially supporting the idea that elite capture of aNPP occurs in rural Zimbabwean communities. Our data do not allow us to isolate the reasons behind the link between household wealth and crop harvests. Wealth may be a direct driver of high crop harvests, reflecting the ability of wealthier households to afford inputs such as synthetic fertiliser and paid labour (Zingore et al., 2007), or alternatively both wealth and crop harvest may co-vary with another factor such as soil fertility in household fields. Higher extraction of livestock fodder by wealthier households reflects the significant correlation of wealth with number of cattle owned. Cattle are an important multifunctional asset in many areas of Africa, used for ploughing fields and pulling carts (and thereby helping perpetuate wealth accumulation), producing manure for fertiliser (improving soil quality of private fields), and acting as a status indicator and savings bank (Dercon, 1998; Hoddinott, 2005).

The lack of a clear link between household wealth and $aHANPP_{luc}$ is interesting. A global study found that national $HANPP_{luc}$ decreases with increasing development, as increasing agricultural yield compensates for loss of NPP_{pot} in undisturbed ecosystems (Krausmann et al., 2013). However, although wealthier households in Wedza obtained higher overall crop production, this appears to be due to increased area cultivated as there was no significant relationship between household wealth and yield. Further, while cropland area cultivated each year by the household may increase with wealth, there was no significant relationship between wealth and the total cropland area owned, suggesting that land ownership in the communal area is also linked to a diversity of other factors such as length of time resident in the community, gender of the household head, and number of times the land has been divided amongst family members. These longer terms factors are important as the lowlands around Wedza Mountain have been largely deforested for over 30 years (Gumbo, 1988). Our data also only permitted calculation of $aHANPP_{luc}$ on household field holdings, and identifying methods of quantifying household contributions to $aHANPP_{luc}$ beyond the boundaries of household property (for example due to woodland degradation through firewood collection) should be a priority for future studies, particularly in areas such as southern Africa where there is high dependence on common property resources.

Also somewhat surprising is the finding that inequality of aNPP appropriation is slightly higher in the combined households from the three lower land use intensity villages than in the three highest land use intensity villages. However, one limit of applying the HANPP paradigm at a small scale is that it only records NPP appropriated within the village area. At the national scale, wealth is associated with an ability to displace demand for natural resources (Krausmann et al., 2009; Weinzettel et al., 2013). Without more detailed household consumption data we cannot calculate the quantity of displaced HANPP, but there is evidence that households in the highest land use intensity villages do displace a portion of their NPP appropriation: 15 out of 36 households in Makumbe and Pfende reported collecting or purchasing firewood outside their home village, as opposed to only one household in total out of the other four study villages. Obtaining firewood outside the study area in many cases requires either a cash payment or the possession of assets such as wooden cart and cattle, both of which are linked to household wealth. A further interesting development on the current analysis would be to determine whether inclusion of NPP embodied in resources obtained outside the study area alters the NPP appropriation inequality findings of the current study.

5. Conclusions

This study deploys a new approach to the assessment of HANPP at the household and village level, yielding new evidence in the study of socio-ecological interdependences and resources inequalities in small scale African farming systems. The findings from this study suggest that the low resolution of previous HANPP studies has resulted in a substantial underestimation of the intensity of land use in smallholder farming areas in southern Africa, masking the ramifications of land use intensification for rural livelihoods and the conservation of biodiversity and natural capital.

Our findings indicate that high-resolution calculations of HANPP based on field data can make a valuable contribution to understanding of patterns of land use intensity, improving the accuracy of HANPP estimates by facilitating inclusion of resources omitted from many studies such as construction materials, and also allowing finer-scale analysis of human impacts on ecosystems such as woodland degradation which may not be apparent from broader scale data sets. We suggest that such high resolution approaches mapping HANPP over larger areas can make a valuable contribution to identification of 'hotspots' of environmental pressure, and that linking HANPP patterns at community and household scales to characteristics of local livelihoods may assist anticipation of environmental externalities associated with livelihood change.

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Appendix A. Supplementary Data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2017.10.003.

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