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# Social as much as environmental: the drivers of tree biomass in smallholder forest landscape restoration programmes

Geoff J. Wells<sup>1</sup>, Janet Fisher<sup>2</sup>, Rohit Jindal<sup>3</sup>, Casey Ryan<sup>2</sup>

<sup>1</sup> Stockholm Resilience Centre, Stockholm University

<sup>2</sup> School of GeoSciences, University of Edinburgh

<sup>3</sup> Department of Decision Sciences, MacEwan University

Corresponding author: [geoff.wells@su.se](mailto:geoff.wells@su.se)

**Data availability:** the data of the study are available upon request to the authors.

## Abstract

A major challenge for forest landscape restoration initiatives is the lack of quantitative evidence on how social factors drive environmental outcomes. Here we conduct a transdisciplinary quantitative analysis of the environmental and social drivers of tree biomass accumulation across 639 smallholder farms restoring native tree species in Mexico, Uganda and Mozambique. We use environmental and social data to assess the relative effects of key hypothesised drivers on aboveground biomass accumulation at the farm-level over ten years. We supplement this with a qualitative analysis of perspectives from local farmers and agroforestry technicians on the potential causal mechanisms of the observed social effects. We find that the material wellbeing of farmers (e.g. assets) and access to agroforestry knowledge explain as much variation in biomass as water availability. Local perspectives suggest that this is caused by the higher adaptive capacity of some farmers and their associated ability to respond to social-ecological shocks and stresses. Additionally, the variation in biomass between farms increased over time. Local perspectives suggested that this was caused by emergent exogenous and stochastic influences which cannot be reliably predicted in technical analyses and guidance. To deal with this persistent uncertainty, local perspectives emphasised the need for flexible and adaptive processes at the farm- and village-levels. The consistency of these findings across three countries suggests these findings are relevant to similar forest restoration interventions. Our findings provide novel quantitative evidence of a social-ecological pathway where the adaptive capacity of local land users can improve ecological processes. Our findings emphasize the need for forest restoration programmes to prioritise investment in the capabilities of local land users, and to ensure that rules support, rather than hinder, adaptive management.

## 33 Introduction

34 Forest landscape restoration (FLR) initiatives are at the forefront of efforts to reverse  
35 environmental degradation in terrestrial ecosystems (Chazdon et al., 2017). The success of  
36 FLR initiatives, however, has so far has been mixed (J. Aronson & Alexander, 2013;  
37 Mansourian et al., 2017).

38 A major challenge for restoration and other land management schemes is the difficulty of  
39 predicting, controlling and managing the outcomes of interventions in what are often highly  
40 complex and variable social-ecological systems (Messier et al., 2015). There is ongoing  
41 debate on the drivers of FLR outcomes, with different perspectives giving varying levels of  
42 emphasis to environmental and social factors. Some emphasise biophysical aspects and the  
43 need to build and support the integrity of ecological communities—there may be social  
44 benefits, but objectives can be primarily ecological, knowledge is technical, and minimising  
45 human intervention is seen as key (J. C. Aronson et al., 2018; Brudvig et al., 2017; Higgs et  
46 al., 2018; Suding et al., 2015; Temperton et al., 2019). Others emphasise the importance of  
47 institutional and social contexts that support good governance and adaptive management for  
48 sustainable and socially beneficial restoration (Mansourian, 2016; Van Oosten, 2013b). This  
49 divergence of perspectives on the drivers of environmental outcomes also extends to the  
50 related fields of conservation and payments for ecosystem services (Ezzine-de-Blas et al.,  
51 2016; Naeem et al., 2015; Pascual et al., 2014; Soule, 2013), and to the fields of land  
52 system science where existing models and approaches continue to struggle to integrate  
53 local-level social factors and context (Stephanson and Mascia, 2014; Iwamura et al., 2018).  
54 Effective interdisciplinary approaches to FLR and similar interventions remain rare (Huber-  
55 Stearns et al., 2017; Mansourian et al., 2017).

56 One of the key gaps in interdisciplinary FLR remains the quantification of how local (e.g.  
57 household-level) social factors drive biophysical outcomes, and clear knowledge on their  
58 causality (Chazdon et al., 2017; Wortley et al., 2013). While the field of restoration ecology  
59 has generated a wealth of quantitative empirical research on how environmental aspects  
60 drive outcomes (Perring et al., 2015), due to the difficulty of measuring social phenomena,  
61 ex-post quantitative field studies testing the effects of social drivers have remained rare  
62 (Geist & Galatowitsch, 1999; Kibler et al., 2018; Le et al., 2012; Miller & Hobbs, 2007;  
63 Sapkota et al., 2018).

64 In the land systems, forest transition and FLR literature, existing ex-post field studies that do  
65 cover the social drivers of biophysical outcomes have mainly focused on showing how socio-  
66 economic factors influence land users to join a scheme (e.g. Baynes et al., 2017; Mullan and  
67 Kontoleon, 2012; Yin et al., 2010). While useful for targeting initial tree planting, there  
68 remains a dearth of field studies quantitatively assessing how social drivers effect  
69 biophysical outcomes (e.g. tree growth) at the local level. The few field studies that do  
70 assess biophysical outcomes have mainly focused on broad assessments of project-level  
71 factors such as institutional design and economic incentives, and have found that social  
72 drivers are secondary to environmental drivers (Le et al., 2014; Yackulic et al., 2011).  
73 However, such project-level assessment likely miss the great social diversity at sub-project  
74 (e.g. household) levels which likely has great effect on land management and tree care  
75 (Nahuelhual et al., 2018; Pritchard et al., 2018; Tiltonell et al., 2005).

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2  
3 76 A consequence of the lack of fine-grained social analyses, is that models and guidance for  
4 77 predicting and managing FLR outcomes are often focused on technical, largely  
5 78 environmental, factors (Wortley et al., 2013). On the other hand, in implementation, land  
6 79 management schemes are challenged to contend with a much broader array of both social  
7 80 and environmental factors (Van Oosten, 2013). Generating quantitative evidence on the  
8 81 relative importance and causal mechanisms of social factors remains a research frontier for  
9 82 FLR and other land management interventions (Chazdon et al., 2017).

12  
13 83 Here we begin to address this gap through an novel ex-post, field-based interdisciplinary  
14 84 quantitative analysis of environmental and social drivers of tree biomass accumulation  
15 85 across 639 smallholder agroforestry farms restoring native tree species in projects in  
16 86 Mexico, Uganda and Mozambique. To our knowledge this is the first such quantitative  
17 87 analysis of its kind. Additionally, as we will elaborate, the consistency of our results across  
18 88 three countries strengthens the generalisability of our findings to similar land management  
19 89 interventions.

22  
23 90 Agroforestry with native species is increasingly advocated as a key method of FLR, where  
24 91 farmers can increase native tree cover while maintaining crop production in agricultural  
25 92 landscapes (Erdmann, 2005; Robiglio & Reyes, 2016; Schroth et al., 2011). Smallholders  
26 93 are estimated to manage approximately 75% of the world's agricultural land (Lowder et al.,  
27 94 2016), and to make up most of the world's poor (Morton, 2007). Thus, many FLR initiatives,  
28 95 and particularly those in developing countries, will engage smallholders—and native-species  
29 96 agroforestry offers a key way to do this.

31  
32 97 We focus on five key environmental and social factors theorised (by both experts and local  
33 98 land users) to drive biomass outcomes in such interventions: water availability; soil quality;  
34 99 existing tree cover at time of planting; household wealth and living standards (henceforth  
35 100 'material wellbeing'; White, 2010); and household access to agroforestry knowledge. The  
36 101 environmental variables cover the key ecological considerations in designing agroforestry  
37 102 systems: sufficient water and soil nutrients are fundamental for tree growth, while tree cover  
38 103 at the time of planting serves as a proxy for inter-plant competition (Ashton & Montagnini,  
39 104 1999; Corona-Núñez et al., 2018).

42  
43 105 For social drivers, dimensions of household material wellbeing have been shown to be key  
44 106 factors in determining smallholder land management and resource use—people with  
45 107 different levels of deprivation have different capacities to manage land, and rely on different  
46 108 resources (Nahuelhual et al., 2018; Pritchard et al., 2018; Tittonell et al., 2005). For access  
47 109 to agroforestry knowledge, both vertical (expert to farmer) and horizontal (farmer to farmer)  
48 110 extension services (Altieri & Toledo, 2011) have been associated with the successful uptake  
49 111 of new land management techniques amongst smallholders (Baird et al., 2016; Clark et al.,  
50 112 2011).

53  
54 113 More broadly, access to assets and knowledge are theorised to be central to the adaptive  
55 114 capacity, and associated resilience, of actors in natural resource management—a key factor  
56 115 underpinning the achievement of land management objectives despite emergent shocks and  
57 116 stressors (Thiault et al., 2019). For FLR, social factors, extension services and associated  
58 117 adaptive capacity are postulated to be key enabling factors for successful outcomes  
59 118 (Chazdon et al., 2017; Yin et al., 2013).

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3 119 Our research questions are: which of the hypothesised environmental and social drivers  
4 120 have had the greatest effect on the AGB of trees established on agroforestry restoration  
5 121 farms? What are the causal mechanisms of the social effects? What are the implications for  
6 122 smallholder agroforestry, and other, FLR projects?  
7  
8

## 9 123 **Methods**

### 10 124 *Study design*

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13 125 We use tree inventories, social surveys, spatiotemporal biophysical datasets, biomass  
14 126 modelling and mixed effects models to assess the relative effects of a set of hypothesised  
15 127 environmental and social drivers on the accumulation of aboveground biomass (AGB) at the  
16 128 farm-level across all three projects. We focus on AGB as a key metric for understanding  
17 129 changes in forest landscapes (Goetz et al., 2015), acknowledging that the benefits of trees in  
18 130 these landscapes go far beyond biomass. We identified the hypothesised drivers with  
19 131 reference to both the literature and interviews with local farmers and agroforestry technicians  
20 132 (details below). We also used these interviews to supplement the quantitative analysis with  
21 133 local perspectives on the potential causal mechanisms of the observed social effects.  
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### 25 134 *Study areas*

26  
27 135 Our study sites cover farms participating in three smallholder agroforestry schemes:  
28 136 Scole'te in Chiapas State in southern Mexico; Trees for Global Benefits in the districts of  
29 137 Rubrizi, Mitooma, Kasese, Hoima and Masindi in western Uganda; and the Sofala  
30 138 Community Carbon Programme in Sofala Province in central Mozambique (Figure 1). The  
31 139 farms in Mexico occur across a 240 km section of the highlands in Chiapas, along an  
32 140 ecological gradient from montane tropical rainforests to subtropical pine-oak rainforests (De  
33 141 Jong et al., 1995, p. 99). Farmers are from a diverse range of villages, spanning five  
34 142 culturally distinct *Maya* linguistic groups, and *mestizo* farmers of mixed descent (Ruiz-De-  
35 143 Oña-Plaza et al., 2011). In Uganda, sites occur along a 330 km section of the Albertine Rift  
36 144 characterised by crater lakes and tropical high forests. Farmers are members of a range of  
37 145 different *Bantu* linguistic groups (ECOTRUST, 2018). In Mozambique, sites are spread  
38 146 across a 30 km area of tropical open miombo woodland (sometimes classified as savannah)  
39 147 bordering the Gorongosa National Park (Ryan et al., 2011; Woollen et al., 2012). Farmers  
40 148 generally share *Sena* as their local language and are comprised of both long term residents  
41 149 and refugees who have settled in the 1990s following the Mozambican civil war (Hegde et  
42 150 al., 2015).  
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152 **Figure 1. Maps of the regions covered in the study.**



153

154 Each project implemented its own types of agroforestry with different species and  
 155 management protocols, designed for different existing land uses and bioclimatic zones  
 156 (Table 1). The different existing land uses and species likely imply different natural growth  
 157 rates, and different levels of tree management and care. To enable an analysis across  
 158 agroforestry types and bioclimatic zones, we use a relative measure of biomass  
 159 accumulation which controls for different land uses, species and management (see  
 160 Methods). Each village in the project relied on its own nursery for tree saplings. Assuming  
 161 sapling quality varies with nursery, to control for variation in sapling quality we nested our  
 162 analysis at the village level.

163 While socio-ecologically diverse, all regions share similar levels of variance on the key  
 164 variables in our analysis (Table 2, in bold). Additionally, all can be categorised as remote  
 165 areas dominated by subsistence agriculture and/or livestock systems, with high levels of  
 166 poverty by global and national standards (OPHI, 2015, 2018a, 2018b). Additionally, all three  
 167 schemes are funded by a mix of donor funds and carbon credits generated under the Plan  
 168 Vivo Carbon Certification system (Plan Vivo, 2013). They thus have similar organisational  
 169 processes and land management objectives, where a local organisation employs local  
 170 technicians to help farmers to restore native tree species, and to monitor tree growth for 10  
 171 years after planting. These project processes are integrated with existing village institutions  
 172 to varying degrees.

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173 **Table 1. Summary of agroforestry types and land uses**

| Agroforestry type       | Description   |
|-------------------------|---|
| Live fence, Mexico      | Planting of <i>Cedrela odorata</i> around the edge of existing arable fields or areas of pasture. Initial minimum tree spacing of 3m (a stocking density of 133 stems around a one ha. field).                |
| Intercropping, Mexico   | Establishment of forestry plantations of <i>C. odorata</i> and <i>Swietenia macrophylla</i> alongside existing annual agricultural crops. Initial minimum stocking density of 333 stems per ha.               |
| Coffee, Mexico          | Enrichment planting of <i>C. odorata</i> to provide shade in coffee plantations. Initial minimum stocking density of 180 stems per ha.  |
| Improved fallow, Mexico | Planting of <i>Pinus oocarpa</i> and <i>Quercus spp.</i> on long term fallows or areas unsuited for agriculture. Initial minimum stocking density of 475 stems per ha.  |
| Live fence, Mozambique  | Planting of native hard wood tree species (typical of miombo woodland) around the edge of existing arable fields. Initial minimum tree spacing of 4m (a stocking density of 84 stems around a one ha. field). |
| Intercropping, Uganda   | Establishment of forestry plantations of <i>Maesopsis emini</i> alongside existing annual agricultural crops. Initial minimum stocking density of 333 stems per ha.   |

174 **Sampling**

175 We analysed 639 randomly-selected households and their associated agroforestry farms  
 176 (259 in Mexico, 321 in Uganda and 59 in Mozambique). In Mexico and Mozambique, we  
 177 excluded farms for which we had insufficient social variables. Assessments of missing  
 178 values showed no structure to the missingness, implying values were missing at random—  
 179 and thus that our overall sample can continue to be considered random (Kowarik & Templ,  
 180 2016). Our sampling frame covers populations of farmers who opted to participate in FLR in  
 181 three different countries. We therefore interpret our results as case studies having relevance  
 182 to similar interventions (Yin 2014).

183 **Data: relative aboveground biomass**

184 To generate farm-level estimates of AGB per hectare, we used farm-level tree inventories,  
 185 the pantropical allometric models provided by Chave et al. (2009, 2014); and the BIOMASS  
 186 package in R (Rejou-Mechain et al., 2018). Tree inventories were census-style surveys,  
 187 measuring all planted trees on the farms and recording species, tree diameter-at-breast-  
 188 height (DBH; approx. 1.3m), tree height, wood density and plot location. Height was  
 189 recorded for all trees (including saplings), while DBH was measured for all trees with DBH  
 190  $\geq 5$ cm. The BIOMASS packages in R package accounts for variation in allometry by



191 bioclimatic zone based on the expected location of the plot. We used Monte Carlo simulation  
192 to generate 95% credibility intervals (CI) of AGB on each farm.

193 Each project implemented different styles of agroforestry (Table 1), with different tree  
194 communities for different bioclimatic zones, and so different expected rates of biomass  
195 accumulation. To enable comparisons of performance between agroforestry styles and  
196 bioclimatic zones, and plots of different ages we calculated a measure of relative  
197 aboveground biomass (RAGB). First, we used chronosequences (Walker et al., 2010) and  
198 least square log-linear regressions (Paine et al., 2012) to find the expected 'average' AGB  
199 per hectare for a particular year (up to 10 years since planting) for a given agroforestry style.  
200 We then extracted for each farm the adjusted standardised pearson residuals (i.e. the  
201 deviation of the farm AGB from the expected AGB, in standard error units; similar to a z-  
202 score) as an indicator of relative performance (Sorice et al. 2014; Kastenholz et al. 2007;  
203 Maschinski et al. 1997). We used the conservative RAGB value for each farm (the lower  
204 95% CI RAGB for farms with mean RAGB > 0, and the upper 95% RAGB for farms with  
205 mean RAGB < 0, where RAGB = 0 indicates average performance).

#### 206 *Data: environmental explanatory variables*

207 For water availability, we modelled the mean annual climatic water deficit (CWD; potential  
208 evapotranspiration minus actual evapotranspiration) since planting on each farm (for a  
209 similar approach see Poorter et al. 2016) using farm location data, global spatio-temporal  
210 records of temperature and rainfall since tree planting (data from Willmot et al. 2014; digital-  
211 elevation-model assisted interpolation from weather station records to 0.5 degree  
212 resolution), digital elevation models (INEGI, 2018; USGS, 2006; 30m resolution) and the  
213 CWD R function from Redmond (2015). For soil quality, we used estimates of cation  
214 exchange capacity (CEC) from the ISRIC SoilGrids global spatial datasets (Hengl et al.  
215 2017; from soil field measurements extrapolated using 158 remote-sensing-based soil  
216 covariates at 250m resolution). For existing tree cover, we used farm locations and  
217 assessments of tree cover from spectral Landsat and MODIS remote sensing data (Sexton  
218 et al., 2013; 30m resolution) to estimate the proportion of tree cover on the plot in the year of  
219 planting. We also included the initial stocking density of tree on each plot as a  
220 supplementary measure of competition., and the size of the farm to check for bias from farm  
221 size (e.g. the overestimation of biomass on smaller farms).

222 Data on CWD, CEC and initial tree cover are at a coarser resolution than all other variables,  
223 which all operate at the farm-level or similar scales. The spatial mismatch between CWD  
224 and CEC and our outcome measurements increases the likelihood of random error in the  
225 modelling, which would weaken their effects in the regression analysis. Nonetheless, we  
226 include these variables to assess whether broad variation in these soil and climate  
227 variables have an overwhelmingly large effect on biomass accumulation that renders social  
228 factors obsolete.

#### 229 *Data: social explanatory variables*

230 For material wellbeing, we constructed an index of multi-dimensional material wellbeing  
231 using similar indicators and the same 'counting' approach as the widely-used global  
232 multidimensional poverty indicator (MPI; see Alkire & Jahan, 2018). Data were sourced from  
233 household surveys conducted with the randomly selected farmers in each country. All

234 **Table 2. Descriptive statistics of variables.** Variables in bold are included in the main model.

| Variable  | Mexico     |  | Mozambique |  | Uganda     |                                      |
|---|------------|--|------------|--|------------|--------------------------------------|
|   | n          | Mean $\pm$ SD<br>(% for binary)        | n          | Mean $\pm$ SD<br>(% for binary)        | n          | Mean $\pm$ SD<br>(% for binary)      |
| Travel time to city (mins)                                | 259        | 154.45 $\pm$ 84.18                     | 59         | 225.42 $\pm$ 16.75                     | 321        | 71.01 $\pm$ 23.68                    |
| Amount land (ha)  | 259        | 9.38 $\pm$ 6.74                        | 59         | 1.51 $\pm$ 1.45                        | 321        | 10.76 $\pm$ 14.67                    |
| Literacy  | 259        | 93%                                    | 59         | 44%                                    | 321        | 74%                                  |
| Valuable assets (2nd model only)                          | 259        | 52%                                    | 59         | 12%                                    | 83         | 29%                                  |
| Above primary schooling 2nd model only)                   | 259        | 53%                                    | 59         | 17%                                    | 60         | 25%                                  |
| Employment contract (2nd model only)                      | 106        | 8%                                     | 59         | 15%                                    | 85         | 11%                                  |
| Formal land tenure  | 259        | 80%                                    | 59         | 51%                                    | 321        | 24%                                  |
| People in household                                       | 259        | 4.27 $\pm$ 1.4                         | 59         | 6.22 $\pm$ 1.92                        | 321        | 8.71 $\pm$ 0.88                      |
| <b>Wellbeing index (main model: simpler, full sample)</b> | <b>259</b> | <b>3.93 <math>\pm</math> 1.91</b>      | <b>59</b>  | <b>2.29 <math>\pm</math> 0.89</b>      | <b>321</b> | <b>1.99 <math>\pm</math> 1.01</b>    |
| Wellbeing index (2nd model only: broader, partial sample) | 106        | 5.06 $\pm$ 2.13                        | 59         | 2.73 $\pm$ 1.16                        | 60         | 1.68 $\pm$ 1.13                      |
| Village AF experience (years)                             | 259        | 4.61 $\pm$ 2.8                         | 59         | 2.54 $\pm$ 2.28                        | 321        | 2.5 $\pm$ 2.3                        |
| Technician in village                                     | 259        | 85%                                    | 59         | 36%                                    | 321        | 70%                                  |
| <b>Extension services index</b>                           | <b>259</b> | <b>1.27 <math>\pm</math> 0.47</b>      | <b>59</b>  | <b>0.59 <math>\pm</math> 0.56</b>      | <b>321</b> | <b>0.93 <math>\pm</math> 0.55</b>    |
| <b>Tree cover at planting (%/ha)</b>                      | <b>259</b> | <b>42.59 <math>\pm</math> 13.06</b>    | <b>59</b>  | <b>10.04 <math>\pm</math> 3.18</b>     | <b>321</b> | <b>7.87 <math>\pm</math> 2.36</b>    |
| <b>Cation exchange capacity (cmol+/kg)</b>                | <b>259</b> | <b>25.92 <math>\pm</math> 3.54</b>     | <b>59</b>  | <b>9.38 <math>\pm</math> 0.87</b>      | <b>321</b> | <b>15.79 <math>\pm</math> 3.49</b>   |
| <b>Mean climatic water deficit (mm/yr)</b>                | <b>259</b> | <b>-296.35 <math>\pm</math> 139.11</b> | <b>59</b>  | <b>-399.15 <math>\pm</math> 119.75</b> | <b>321</b> | <b>-294.7 <math>\pm</math> 128.5</b> |
| <b>Initial planting density (stems/ha)</b>                | <b>259</b> | <b>426.85 <math>\pm</math> 242.68</b>  | <b>59</b>  | <b>75 <math>\pm</math> 6.27</b>        | <b>321</b> | <b>365.09 <math>\pm</math> 24.21</b> |
| <b>Farm size (ha)</b>                                     | <b>259</b> | <b>1.01 <math>\pm</math> 0.43</b>      | <b>59</b>  | <b>1.1 <math>\pm</math> 0.94</b>       | <b>321</b> | <b>1.67 <math>\pm</math> 1.31</b>    |
| <b>Relative aboveground biomass</b>                       | <b>259</b> | <b>0.01 <math>\pm</math> 0.74</b>      | <b>59</b>  | <b>0 <math>\pm</math> 0.57</b>         | <b>321</b> | <b>0.01 <math>\pm</math> 0.79</b>    |

235

236 surveys were conducted face-to-face with the person responsible for managing the farm (i.e.  
237 usually the farm owner). Interviews were conducted with the help of a local translator (see  
238 S1 in the Supplementary Material for further details). We followed a similar approach to  
239 construct an index of access to extension services based indicators identified from local  
240 consultations and the existing literature (Altieri & Toledo, 2011; Birner et al., 2009; Krishna,  
241 2004). All quantitative variables are summarised at Table 2.

#### 242 *Data: local perspectives on causality*

243 To better frame our hypotheses, and to understand how social drivers operate, we  
244 conducted semi-structured interviews with 39 farmers and 23 technicians during field visits to  
245 Mexico, Uganda and Mozambique (29 in Mexico, 13 in Uganda and 20 in Mozambique). We  
246 used a purposive sample to speak to farmers with varying levels of AGB performance and  
247 the main technicians associated with those farms. We conducted these interviews as broad,  
248 semi-structured conversations about the respondent's experience throughout the project,  
249 including open questions on why some farmers have bigger or different trees compared to  
250 others. Interviews were conducted with prior informed consent and anonymity was  
251 maintained throughout. We documented interviews in notes and audio recordings,  
252 sometimes with the assistance of translators fluent in the local languages.

#### 253 *Analysis*

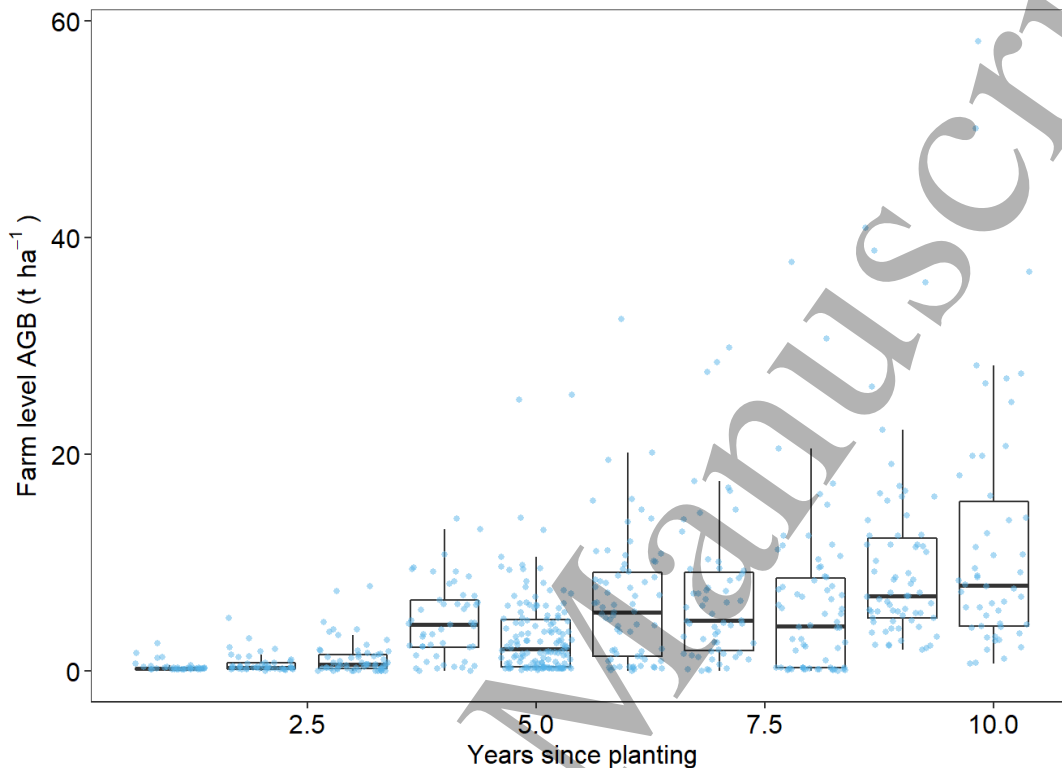
254 For the quantitative analysis, we used linear mixed models with REML estimation, and  
255 village and country as a random effect (minimum of 12 households per village). Diagnostics  
256 indicated a suitable fit with normally distributed residuals with homogenous variance and no  
257 significant collinearity among independent variables (Zuur et al., 2007). We also  
258 subsequently conducted a likelihood ratio test to check the significance of the random effect  
259 of village (Kuznetsova et al., 2017). Given the varying resolution of the variables in our  
260 analyses, we used variograms to assess the spatial dependence of all independent variables  
261 and the dependent variable (RAGB), and global tests of Moran's I and correlograms to  
262 assess spatial autocorrelation in the residuals of the main model. We also plotted model  
263 residuals against farm size to check for bias in biomass estimates from large trees on small  
264 farm sizes. All analyses were performed in R, version 3.5.1 (R Core Team, 2019), and the  
265 model code and diagnostics are in the Supplementary Material, section S3. For the  
266 qualitative analysis, we used a thematic analysis (Ritchie et al. 2013) to frame the  
267 hypotheses around material wellbeing and agroforestry knowledge and, following the  
268 quantitative analysis, to examine in more depth the possible causal mechanisms behind the  
269 observed social effects. We include illustrative (anonymised) quotes from respondents in the  
270 results.

## 271 **Results**

272 Across our sites, farm-level AGB varied greatly, and this variation increased over time  
273 (Figure 2).

274

275 **Figure 2. Boxplots showing variation in aboveground biomass between farms of**  
 276 **different ages.** The boxplots show quantiles, while the points are individual farms  
 277 (horizontally jittered to the width of the boxplot). Tree stocking densities are a main  
 278 determinant of AGB per ha, and target stocking densities varied between the different  
 279 agroforestry styles included in the study. Here we show farm-level AGB for all land uses,  
 280 normalised to a stocking density of 100 stems per ha.



282 Perspectives from farmers and local technicians suggested that this reflects the great and  
 283 inherent social-ecological diversity amongst smallholdings, even across small areas (Box 1).

284 **Box 1. Local perspectives on social-ecological diversity**

285 Every farm is different. The soil changes from one farm to the other. Some are closer to the  
 286 [existing rainforest] so they get more vines and shade. People also want to do different things  
 287 on their farms.

288 *Farmer, Mexico*

289 People are not the same, so having one [agroforestry] plan does not work. You need several  
 290 options with some flexibility. Some people like different trees because of the fruit or  
 291 medicines. Also some trees grow better in some places but we don't really understand why.  
 292 Even the [forest ecologists] don't know.

293 *Agroforestry technician, Uganda*

294 Local actors also suggested that following the establishment (tree planting) phase, land  
 295 managers will lose control over outcomes as emergent social-ecological factors outside of  
 296 their influence come to bear (Box 2).

297 **Box 2. Local perspectives on a loss of control over emergent social-ecological factors**

298 There have been big social and environmental changes since the beginning of the project. In  
 299 some places there were floods, and in other years there were small fires. Other years it was  
 300 ok. Also there are now more people and less land. [The project processes] had to change but  
 301 you can't control everything.

302 *Agroforestry technician, Mexico*

303 It was easy [to grow trees] at first, but then some [farms] do better than others. We had a dry  
 304 year, so people that had just then planted now have smaller trees. Some people did a better  
 305 job at watering [the saplings], but even then that didn't always work.

306 *Farmer, Mozambique*

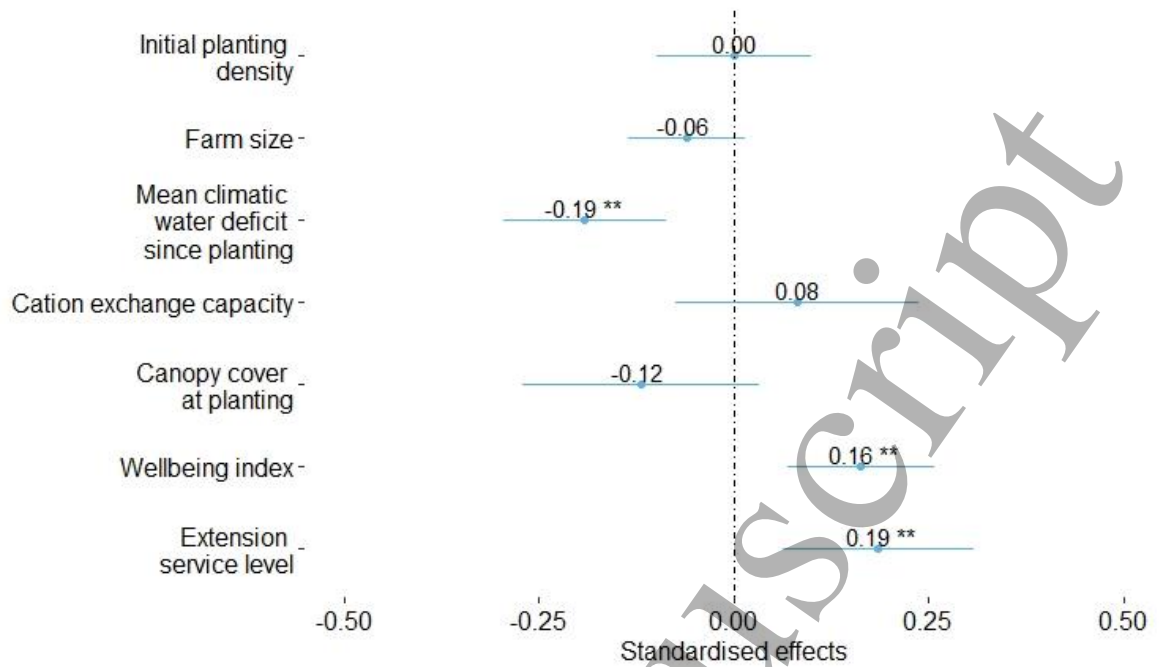
307 In the regression analysis, the social factors of household material wellbeing and access to  
 308 extension services each explained similar amounts of variation in RAGB to that explained by  
 309 climatic water deficit (Figure 3). Cation exchange capacity, tree cover and initial planting  
 310 density had no significant effects. The relative homogeneity of residuals across countries  
 311 (Supplementary Material, Section S3a.i), and supplementary individual regressions for the  
 312 limited sample sizes in each country (Supplementary Material, Section S3b), indicate that  
 313 these results are robust across our sites. Additionally, farm size had no apparent influence  
 314 on the model residuals (S3a.ii), indicating that the results are robust to the influence of large  
 315 trees on small farms.

316 Our results also appear robust to spatial autocorrelation (Supplementary Material, Section  
 317 S3d). While variograms indicate strong spatial dependence of some of our environmental  
 318 independent variables (CWD, CEC and initial tree cover), all other independent variables  
 319 and our dependent variables appear strongly spatially independent. Crucially, correlograms  
 320 of Moran's I of model residuals found no significant spatial dependence at different spatial  
 321 lags in Uganda and Mozambique, and only a very weak dependence at very large spatial  
 322 scales in Mexico (Moran's I = 0.05,  $p < 0.01$ , at distance class midpoint of 1.33 decimal  
 323 degrees; 148km at the equator).

324 Broadly, these results suggest that social factors have a measurable impact on biomass  
 325 accumulation. Given that variability in AGB increases over time and that we only model  
 326 growth in the first ten years since planting, effects are likely to be greater by the time trees  
 327 reach maturity (25 to 40 years). Our conclusions on the relative influence of the  
 328 environmental factors of CWD, CEC and initial tree cover are limited by the coarser  
 329 resolution these variables. However, we view that the lack of significantly larger effects of  
 330 these environmental variables relative to social variables does emphasise that both are  
 331 integral to biomass accumulation in FLR schemes.

332 **Figure 3. Effects of hypothesised drivers on relative aboveground biomass.**

333 Standardised estimates with 95% confidence intervals. \* = significant with 95% confidence



334

335 The inclusion of village as a random effect significantly improved the model fit ( $X^2 = 46.77$ ,  $df = 1$ ,  $N = 639$ ,  $p < 0.01$ ), indicating that farms associated with the same village performed similarly. Conversely, however, there was low spatial auto-correlation of RAGB in Mexico (Moran's  $I = 0.23$ ,  $p < 0.01$ ) and Uganda (Moran's  $I = 0.14$ ,  $p = 0.02$ ) (Mozambique had an insufficient sample for a robust assessment). These results combine to indicate that there are additional drivers operating at the village level and that they are not strongly spatial.

341 These statistical associations correspond with the consistent perspective amongst farmers and technicians that farmers with greater individual capabilities, and more supportive village institutions, were better able to innovate and adapt their land management in response to changing social and environmental conditions. Essentially, farmers with sufficient capabilities appear more able to overcome environmental barriers to tree growth by having more time, labor and knowledge to allocate to the care of their trees (Box 3)

### 347 **Box 3. Local perspectives linking social factors, adaptive capacity and tree growth**

348 It is easier for richer people, or people with a bigger group to help, because they have more  
349 labour ... and money is also important. When things happen, you can use the money to deal  
350 with it.

351 *Farmer, Mexico*

352 It was difficult because it was hard to do something new. Some of the trees didn't work  
353 because of the drought, then my husband got sick and it was difficult to fix things

354 *Farmer, Mozambique*

355 It was always harder when there is no one else doing agroforestry in the village. Farmers  
356 need to learn what works and this is always easier in a group, or when someone has done it  
357 already.

359

360

358

*Agroforestry technicians, Uganda*

359

I lived next door to the house where the [agroforestry technicians] would stay. It helped to have them next door. They would always come and give advice which helped the trees.

360

361

*Farmer, Mozambique*

362

More broadly, while our modelling showed some significant effects, most of the variation in AGB remained unexplained, despite the fact that we had accounted for (to the best of our ability) the major drivers suggested by local stakeholders and the technical literature. While our use of a relative measure of biomass accumulation, and the nesting of our analysis at village level, controls for broad differences in species, sapling quality and land management, residual variation is likely explained by other ecological (e.g. disturbance; species interactions; micro-climates) and social factors (e.g. the nuances of household participation in resource governance institutions; within-household interactions) not covered in our analysis. Combined with local perspectives on the inherent variability and dynamism of the social-ecological system (Box 1), this suggests that there are no simple explanations for variation in land management outcomes in our systems – drivers are likely diverse and very hard to measure and predict. In this context of continued uncertainty, local perspectives emphasised the importance of adaptive learning at the project, village and farm levels. As an agroforestry technician in Uganda told us: “New things arrive in the project that you cannot anticipate. So we need to be flexible if we can, while still caring for the trees and forest. When changes come, we all change as one.”

378

## Discussion

379

In this study, we find strong quantitative evidence that the material wellbeing and knowledge of farmers are key drivers of biomass accumulation in smallholder agroforestry FLR interventions. To the best of our knowledge, this phenomenon has not previously been demonstrated quantitatively using ex-post field data linking directly to biophysical outcomes. Additionally, the quantitative evidence suggests that these factors operate at both the village and household levels.

385

Local perspectives emphasised that the broad causal mechanism for these social effects was that farmers with more resources and knowledge, and better support from village institutions, were better able to adapt their land use to emergent social-ecological shocks and stresses. This reaffirms existing theories on the importance of individual adaptive capacity and adaptive cogovernance for land management programmes (Thiault et al., 2019).

391

Our findings apply across sites in three countries. Given the need for FLR and other restoration programmes to engage rural smallholders in developing countries, we contend that our results are of relevance to the broader restoration field, and other land management interventions such as conservation and payments for ecosystem service schemes. Below we highlight two key contributions.

396

*Social resilience and adaptive capacity drive restoration outcomes*

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2  
3 397 A part of the restoration literature continues to view social factors and objectives as  
4 398 secondary (albeit admirable) considerations for restoration initiatives, relative to more  
5 399 important biophysical considerations (Aronson & Alexander, 2013; Higgs et al., 2018; Suding  
6 400 et al., 2015; Temperton et al., 2019). This view is also prominent in part of the associated  
7 401 conservation and payments for ecosystem services literatures, where social objectives are  
8 402 sometimes seen as aspirational but not integral (and sometimes as a distraction) to technical  
9 403 and biophysical factors (Ezzine-de-Blas et al., 2016; Naeem et al., 2015; Soule, 2013).

12  
13 404 Our results provide robust empirical evidence demonstrating that the social situation of local  
14 405 resource users has a significant, tangible effect on biophysical restoration outcomes. This  
15 406 accords with existing literature on the importance of social factors supporting good  
16 407 governance (Mansourian, 2016; Van Oosten, 2013; Baynes et al. 2013), and extends this to  
17 408 emphasise the importance of supporting the adaptive capacity of individual participants. It  
18 409 also contrasts with coarser (e.g. project-level) analyses which have found no effect from  
19 410 social factors on biomass accumulation in FLR project (Le et al., 2014). By analysing at the  
20 411 household-level we have uncovered novel evidence on how social diversity drives biomass  
21 412 outcomes.

24  
25 413 While improvements in ecological processes are often theorised to benefit humans (Díaz et  
26 414 al., 2018; Chazdon and Brancalion, 2019), here we have clear evidence of a reciprocal  
27 415 pathway: in certain contexts improvements to human capabilities can benefit ecological  
28 416 processes. Essentially, the effectiveness of a land management intervention may only be as  
29 417 good as the social-economic resilience and adaptive capacity of its local participants.  
30 418 Restoration, and related conservation and payments for ecosystem services projects, should  
31 419 thus put such factors on par with biophysical and other technical considerations.

34 420 One interpretation of this finding could be that restoration and similar programmes should  
35 421 avoid engaging poorer people with low capabilities. However, where interventions are aiming  
36 422 for a socially beneficial and landscape-level transformation, excluding more vulnerable  
37 423 people is likely not an option. On the social side, interventions would need to consider the  
38 424 social impacts of excluding already vulnerable and marginalised people from natural  
39 425 resource management programmes, and the related risk of elite capture (Persha &  
40 426 Andersson, 2014). Excluding particular actors could also have knock on effects on  
41 427 community support for the project, and associated local perceptions of project legitimacy  
42 428 (Pascual et al., 2014). Regarding landscape-level transformation, excluding particular actors  
43 429 could restrict interventions to site-level rather than landscape-level interventions, which  
44 430 would likely not achieve the changes that many hope for (Chazdon et al., 2016; Lamb et al.,  
45 431 2005). It could also drive 'leakage' where conservation of one place in the landscape just  
46 432 moves degradation elsewhere (Bode et al., 2015). Programmes seeking socially beneficial,  
47 433 landscape-level change will thus likely need to engage many actors, including vulnerable  
48 434 people. Allocating resources and designing institutions to supporting the adaptive capacity  
49 435 and capabilities of local resource users will be key. This will be particularly important for  
50 436 engaging smallholders, who are often poorer and control much of the world's land (Lowder  
51 437 et al., 2016; Morton, 2007).

56  
57 438 *Accepting uncertainty and supporting adaptive management*  
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3 439 A second key finding of our study is that great variability in land management outcomes may  
4 440 be the norm rather than the exception in smallholder FLR and similar projects, even amongst  
5 441 sites in similar areas with similar land use objectives. Further, this variability likely increases  
6 442 over time. Local perspectives suggest that, rather than technical staff and FLR  
7 443 administrators progressively refining their knowledge and management of the system to  
8 444 reduce variability in outcomes, such actors may in fact begin to lose influence over land  
9 445 management outcomes after the initial establishment of the system. After this, exogenous  
10 446 and stochastic influences may come to dominate, and early differences in the quality of tree  
11 447 planting are exacerbated, pushing the system beyond the predictive and managerial control  
12 448 of land analysts and users.

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16 449 Alongside our findings about local adaptive capacity, this emphasises the need to moderate  
17 450 expectations of being able to accurately design and predict interventions and outcomes  
18 451 (Brudvig et al., 2017). Instead our evidence supports calls to invest in flexible rules and  
19 452 institutions that support rather than hinder adaptive management in restoration and related  
20 453 initiatives (Mansourian et al., 2017; Murray & Marmorek, 2003). Adaptive management is  
21 454 increasingly argued to be key for dealing with uncertainty and complexity in social-ecological  
22 455 systems (Schultz et al., 2015), and our quantitative and qualitative findings support such an  
23 456 approach. This speaks to an ongoing tension in the restoration and conservation literature  
24 457 between those who wish to standardise ‘best practice’ approaches, and those who wish to  
25 458 maintain flexibility (Aronson et al., 2018; Higgs et al., 2018; Wunder et al., 2018). Our  
26 459 findings support adaptive management as one of the core principles of FLR (Besseau et al.,  
27 460 2018). We contend that all initial designs and predictions of restoration and other land  
28 461 management projects are likely to turn out to be at least a little inaccurate in practice—  
29 462 investing in adaptive project processes to adjust and correct interventions over time will  
30 463 therefore be key.

## 31 464 **Conclusion**

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37 465 Our work offers novel evidence on the importance of social factors in driving outcomes in  
38 466 FLR and similar initiatives. We have shown across several hundred farms in three countries  
39 467 that the capability and knowledge of land users can drive outcomes alongside environmental  
40 468 factors—and that this is likely tied to the capacity of land users to respond and adapt to  
41 469 social-ecological shocks and stresses. While there are no doubt many other drivers of  
42 470 outcomes in our sites, and while the magnitude of the effects will likely vary across contexts,  
43 471 we argue that the consistency of our findings across three sites strengthens their relevance  
44 472 for other sites and programmes.

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48 473 Broadly, we contend that restoration initiatives and similar land management programmes  
49 474 must build and maintain the adaptive capacity of smallholders and other local actors through  
50 475 both material and institutional support. Additionally, project designs, funding and rules must  
51 476 be flexible enough to support adaptive management in the context of continued uncertainty.  
52 477 Overall, we suggest that the field of ‘restoration ecology’ must become ‘adaptive restoration  
53 478 social-ecology’ if it is to succeed.

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