Droughts, Biodiversity, and Rural Incomes in the Tropics

Frederik Noack, Marie-Catherine Riekhof, Salvatore Di Falco

Abstract: Poverty and biodiversity are concentrated in rural areas of developing countries where incomes fluctuate with seasons and weather extremes. In this paper, we quantify the income stabilizing role of natural biodiversity and forests for rural households in developing countries. We use panel data covering 7,556 households in 23 developing countries, combined with gridded data on droughts, data on natural biodiversity, and data on the timing of the agricultural cycle. We find that droughts during the growing season reduce crop incomes but that these negative shocks are partly offset by increased incomes from forest extraction. We also find that the negative impact of droughts on rural incomes declines with increasing levels of natural biodiversity. An increase in biodiversity by one standard deviation reduces the impact of droughts on rural production to almost zero. These results therefore stress the importance of biodiversity and natural resources for the stability of rural incomes.

JEL Codes: Q54, Q56, Q57

Keywords: biodiversity, forests, droughts, weather shocks, rural incomes, poverty

A LARGE BODY OF LITERATURE in ecology stresses the fundamental role of biodiversity for the stability of natural systems. Biodiversity, that is, the number of species in natural ecosystems,[1] reduces biomass fluctuations (Hooper et al. 2005; Tilman et al.

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[1] We use the term "biodiversity" here in a narrow sense as a measure of the number of species in an ecosystem of a given size. Biodiversity in a wider sense also takes the individual abun-

Received February 1, 2018; Accepted September 7, 2018;

JAERE, volume 6, number 4. 2333-5955/2019/0604-0006$10.00 http://dx.doi.org/10.1086/703487

2006) and the response of biomass production to droughts (Isbell et al. 2015). This stabilizing role of biodiversity has been observed across different ecosystems, and the ecological mechanisms are well understood (Loreau and Mazancourt 2013; Tilman et al. 2014).

Biodiversity also supports the production of goods and services that are crucial for human welfare (Millennium Ecosystem Assessment 2005; Tilman et al. 2005; Liang et al. 2016; Isbell et al. 2017). Despite strong evidence for the importance of natural biodiversity[2] for ecosystem services in agricultural systems in the form of pollinators and natural enemies of pests (Garibaldi et al. 2016; Larsen and Noack 2017) and its stabilizing role for agricultural production (Bartomeus et al. 2013; Brittain et al. 2013; Rogers et al. 2014), the relationship between natural biodiversity and rural incomes is largely unexplored. This paper investigates the impact of natural biodiversity on income fluctuations in rural areas of the developing world. Understanding the welfare-supporting role of biodiversity is particularly important for the rural poor in developing countries, as they are heavily dependent on ecosystem services (Angelsen et al. 2014) and face imperfect insurance and credit markets to smooth consumption (Banerjee and Duflo 2010; Karlan and Morduch 2010).

Our empirical strategy is based on a stylized model of rural production with three income sectors that differ with respect to their dependence on biomass, their vulnerability to droughts, and their reliance on biodiversity to stabilize production. The model predicts that (1) biodiversity reduces the impact of droughts on total income and that (2) biodiversity can either increase or decrease the impact of a drought on sector incomes. The reason for the second result is that input reallocation, once a shock has materialized, amplifies the production losses in sectors with larger factor productivity declines and dampens the shock in sectors with lower productivity declines. If biodiversity stabilizes production in less affected sectors more than in sectors that are more heavily affected by shocks, sector-level income fluctuations increase with biodiversity levels. However, for total incomes, the effects of input reallocation cancel out, which explains the first theoretical result.

To estimate the impact of droughts and biodiversity on rural incomes, we construct a panel of sector-level quarterly income data from 7,556 rural households in 23 tropical countries (Angelsen et al. 2014), gridded plant species diversity data (Kreft and Jetz 2007), and gridded drought data (Beguería et al. 2014). To account for the seasonality of rural incomes and temporal differences in the vulnerability of rural incomes to droughts, we further match our income data to data on the timing of local cropping cycles from Sacks et al. (2010).

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dance, shift of species composition across ecosystems, or the genetic diversity within species into account.

[2] We use "natural biodiversity" to distinguish it from biodiversity influenced by humans, e.g., via crop diversity.

We focus on crop and forest incomes in our analysis, as both sources combined constitute a large share of incomes in our sample and both rely directly on biomass for production. The growth of harvestable biomass such as grains, fruits, vegetables, and timber is affected by weather fluctuation (e.g., Lobell et al. 2011; Anderegg et al. 2015; and Bennett et al. 2015). However, while only the biomass that accumulated during the preceding growing season is harvested in crop production, forestry relies on biomass that has accumulated over years or even decades. Crop production may thus be more vulnerable to droughts than forestry, as individual tree growth fluctuations average out over time.[3] This interpretation is in line with the notion of common pool resources such as unmanaged forests as insurance mechanisms for the rural poor (Baland and Francois 2005; Delacote 2009). Other sources of income such as wage labor can have a similar income-stabilizing role, and we include these sources in our analysis for completeness.

Forest production depends directly on natural plant biodiversity such as trees for timber and a wide range of plant species for non-timber forest products. In contrast, crop production depends only indirectly on natural biodiversity for pollination services and natural enemies of pests. Both services depend heavily on anthropod diversity (e.g., bees for pollination or spiders for natural pest control), which is highly correlated with natural plant biodiversity (Koricheva et al. 2000; Scherber et al. 2010; Borer et al. 2012). We therefore use plant biodiversity as the relevant measure of natural biodiversity.

Households in our panel indicated droughts as the major environmental reason for crop losses. Droughts are water deficits caused by a combination of high temperatures and low precipitation levels with negative impacts on crop production (Lesk et al. 2016) and general economic outcomes (Couttenier and Soubeyran 2014). We measure droughts with the Standardized Precipitation-Evapotranspiration Index (SPEI), which is defined as the difference between precipitation and potential evapotranspiration (Vicente-Serrano et al. 2010). Potential evapotranspiration measures the temperature-dependent evaporation that would occur if sufficient water were available. Positive SPEI values indicate excess water availability for plant growth while negative values indicate water deficits. The advantage of the SPEI index over weather shocks measured by deviations of temperature and precipitation levels or degree days (e.g., Deschenes and Greenstone 2007) is that it captures interactions between both variables such as the effect of temperature on the water demand of plants. This property is important for our study, as we cover a large geographical area with different baseline temperature and precipitation levels.

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[3] For forest biomass, the impact of droughts becomes visible in the size of tree rings, i.e., the annual increment of biomass, but much less through changes in the biomass stock of the entire forest, e.g., through forest fires and other extreme events. No major forest fire occurred in our sample.

We expect that the impact of droughts on income depends on their timing within the growing cycle. For example, additional precipitation can be beneficial for plant-based production during the growing season but may destroy the quality of the crop during the harvesting season. The quarterly income and weather data allow us to estimate the effect of droughts on rural incomes with high temporal resolution. However, growing cycles may differ across countries and across villages within countries. To account for these differences, we match our income data with the planting and harvesting dates at the subnational level from Sacks et al. (2010) and estimate the impact of droughts on crop and forest incomes in the planting, growing, and harvesting season separately.

Our empirical results show that crop incomes and, to a lesser extent, incomes from other sources are highly seasonal, while forest incomes are almost constant or even countercyclical and therefore reduce the seasonal fluctuations of total incomes. We find further that droughts reduce rural incomes, but their impact depends on the timing of their occurrence and on the surrounding natural biodiversity. While a drought of one standard deviation during the growing season reduces crop incomes by 45%, droughts of similar magnitude have no statistically significant impact on crop incomes when they occur during the harvesting season. Unlike crop incomes, forest incomes increase in response to a one standard deviation drought during the growing season by almost 30%. We interpret this result as evidence for input reallocation from crop to forest production.

The impact of droughts on sector incomes is composed of the direct effect of droughts on production and the indirect impact of droughts on sector incomes through input reallocation. In contrast, the response of total harvesting income to droughts reflects only the direct impact of droughts on incomes. We find that droughts during the harvesting season have no significant influence on total income, but that a drought of one standard deviation in the growing season significantly reduces total income by more than 20%.

Biodiversity affects the impact of droughts on rural production. An increase in the natural biodiversity level by one standard deviation compared to the regional mean reduces the impact of droughts significantly. In fact, it reduces the drought's impact on rural incomes to almost zero. This result is robust to controlling for the impact of agricultural suitability, baseline climate, or crop diversity on drought impacts, suggesting that the results are driven by biodiversity directly and not by other related factors. This result therefore suggests that halting the global biodiversity decline may also reduce the vulnerability of rural households to increased weather extremes.

This paper relates to two strands of literature at the intersection of environment and development economics. The first strand is of the literature on the value of biodiversity. It includes studies on the positive impacts of biodiversity on production (Brock and Xepapadeas 2003; Tilman et al. 2005; Chavas and Di Falco 2012; Bellora et al. 2017) and on risk and resilience (Smale et al. 1998; Baumgärtner 2007; Quaas and Baumgärtner 2008; Di Falco and Chavas 2009; Finger and Buchmann 2015; Bellora et al. 2016; Henselek et al. 2017). However, none of these papers address the question of how natural biodiversity affects rural incomes.[4] We fill this gap by making use of a very large global panel data set covering more than 20 different tropical countries.

The second body of literature is on the estimation of the welfare-supporting role of resources in the developing world. There is, indeed, some empirical evidence highlighting the positive contribution of conservation areas in Costa Rica and Thailand to local incomes (Andam et al. 2010; Sims 2010; Ferraro et al. 2015). Our paper uses a much larger panel data set consisting of 7,556 households in 304 villages and 23 countries. Noack et al. (2015) use the same household data in a cross-sectional analysis of the impact of weather and climate on rural incomes. The current study extends their analysis by estimating the income-stabilizing role of biodiversity and by exploring the seasonality of rural incomes and weather impacts using the panel structure of the data.

Our results show that biodiversity conservation can play an important role in poverty alleviation in developing countries. Importantly, it shows that the welfare-supporting role of natural resources is greater in the presence of droughts. Although biodiversity conservation may constrain the production in rural areas of developing countries, our study shows that it increases the resistance of rural incomes to droughts. This insurance effect of natural resources has important welfare consequences for poor rural households that face incomplete credit and insurance markets (Baland and Francois 2005) and adds to the benefits of protected areas for biodiversity conservation and poverty alleviation (Wunder 2001; Sunderlin et al. 2005; Andam et al. 2010; Sims 2010; Ferraro et al. 2015; Sims and Alix-Garcia 2017).

The paper proceeds as follows. In the next section we present our data. We then discuss our theoretical framework and derive our estimation strategy. Finally, we show our results and conclude with a discussion.

1. DATA

The empirical analysis is based on a large panel of quarterly income data from 23 tropical countries combined with gridded data on droughts, biodiversity, and data on the timing of planting and harvesting. We describe the data in the following.

1.1. Income

The study is based on the income data from the Poverty and Environmental Network (PEN) from the Center for International Forestry Research (CIFOR). The PEN survey is the largest survey of rural households that paid special attention to environmental

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[4] To our knowledge, the only exception is Henselek et al. (2017), which studies the impact of bee diversity on almond production in a very restricted geographical area.

incomes, covering 7,556 households from 304 villages in 23 countries across three continents (Latin America, Asia, and Africa). Interviews took place every 3 months within 1 year within an overall survey period ranging from 2005 to 2010. The survey sites were selected (*a*) based on their location in rural areas of tropical or subtropical regions within Asia, Africa, or Latin America (*b*) with at least some access to forests and (*c*) in order to increase the representativeness of the global sample for rural areas of tropical and subtropical countries (Angelsen et al. 2014). Households within villages were randomly selected. The general sampling procedure of the PEN survey is described in appendix A (apps. A–E are available online). The locations of PEN study sites are shown in figure 1, while figure 2 compares the biodiversity distribution within our sample to the general biodiversity distribution within the tropics. Both figures are discussed in more detail below.

We use quarterly net incomes measured in 2005 purchasing power parity (PPP) dollars per adult equivalent (AEU). We follow the definition of AEUs by Angelsen et al. (2014) and assign children below 15 years and adults above 65 years a weight of 0.5 while all other household members are weighted with 1. Incomes are net of production costs but include family labor. The methods for data cleaning and transformations are described in detail in Angelsen et al. (2014). We focus on crop and forest incomes as these income sources directly rely on plant-based production and are most affected by biodiversity and droughts. We only consider crop income—instead of total agricultural income that would also include livestock income—because livestock may serve as a buffer stock (see Noack et al. 2015). The mean crop income share in our sample is 30%. Forest income includes all incomes from forest sources, that is, including lumber, firewood, bush meat, and other non-timber forest products. The mean forest income share in our sample is 19%. We lump all other income sources together as "other income," which includes business income, wages, and livestock incomes, as well as remittances and government transfers. Although intuition suggests that business incomes and wages may be less affected by droughts than agriculture, much wage work is related to agriculture. Local businesses may also directly depend on the agricultural incomes of their customers to generate income. We therefore report the estimates for other incomes only for the sake of completeness.

Table 1 shows the mean, the standard deviation, and the first, fifth, and ninth decile of the sector-level incomes in PPP US$ per adult equivalent unit and year. Appendix B compares the country-level income distributions of the PEN sample to the per capita GDP from the World Bank's World Development Indicators.

1.2. Biodiversity

The data on biodiversity are gridded data of the number of plant species per one degree grid cell from Kreft and Jetz (2007), who use 1,032 species richness accounts to compute the gridded data with three different methods. These accounts are from geographical units larger than 10 km^2, including countries, provinces, and national parks. The data are extrapolated using kriging that depends on spatial auto-correlation, a

Table 1. Summary Statistics of Rural Incomes

	Mean	SD	Q10	Median	Q90
Total income (US$/AEU/year)	1,626	3,837	220	822	3,374
Crop income (US$/AEU/year)]	411	1,303	7	173	857
Crop income share (%)	30	42	1	26	67
Forest income (US$/AEU/year)	317	917	2	77	725
Forest income share (%)	19	22	0	11	52
Other income (US$/AEU/year)	914	3,311	70	365	1,840
Other income share (%)	51	41	16	51	88

Note. The summary statistics provide the mean, the standard deviation (SD), and the 10th (Q10), the 50th (median), and 90th (Q90) quantile of sector-level and total incomes. All values are expressed in PPP US$ per adult equivalent unit (AEU) and year. The total number of households in our sample is 7,556.

regression model that is based on geography, climate, vegetation, and evolutionary history, and a model that uses both the information of kriging and the information from the regression model. We use the gridded data based on the combined model that is also the preferred specification in the original paper but compare our results to estimations based on kriging as a robustness check. Although we use data on plant species richness, they may be representative for natural biodiversity in general as diversity of different taxa is positively correlated (Siemann et al. 1998; Haddad et al. 2001; Qian and Ricklefs 2008). We use linear interpolation to compute the village-level biodiversity levels from the gridded plant species richness data. Figure 1 shows the global distribution of natural plant biodiversity and the location of the PEN study sites.

Figure 2 compares the relative distribution of biodiversity in the tropics (all land areas between the latitudes 23.43691° north and south) to the distribution of biodiversity in our sample. The figure shows that our sample covers areas with intermediate to high biodiversity levels but is less informative for areas with low biodiversity levels such as deserts with low human population densities.

The biodiversity estimates from Kreft and Jetz (2007) measure the original or natural biodiversity level and do not take deviations from this level due to economic activities into account. The advantage of this measure over the actual level of biodiversity is its exogeneity and independence of economic activity.

1.3. Droughts

To measure droughts, we use the Standardized Precipitation Evapotranspiration Index (SPEI) that takes interactions between temperature and precipitation into account and was successfully applied to predict plant growth across different continents (Vicente-Serrano et al. 2012; Isbell et al. 2015; Greenwood et al. 2017). The SPEI is

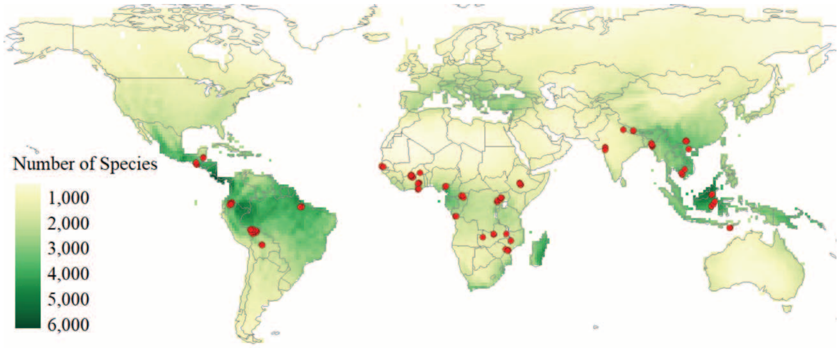

Figure 1. Biodiversity levels (*different shades*) and PEN study sites (*dots*). Biodiversity is measured in the number of plant species per one degree grid cell. Each PEN study site represents several surveyed villages.

defined as the difference between actual precipitation and potential evapotranspiration, that is, the potential evaporation and transpiration of organisms as a function of temperature (Vicente-Serrano et al. 2010). The gridded version of the SPEI is based on the weather data of the Climatic Research Unit of the University of East Anglia, version 3.23, and the Penman-Monteith estimation of potential evapotranspiration (Beguería et al. 2014). Values are expressed in standard deviations from median conditions (the standardization process is described in Vicente-Serrano et al. [2010]). Based on the SPEI, our shock variable is geographically defined at the village level but differs across households within one village, depending on the timing of their inter-

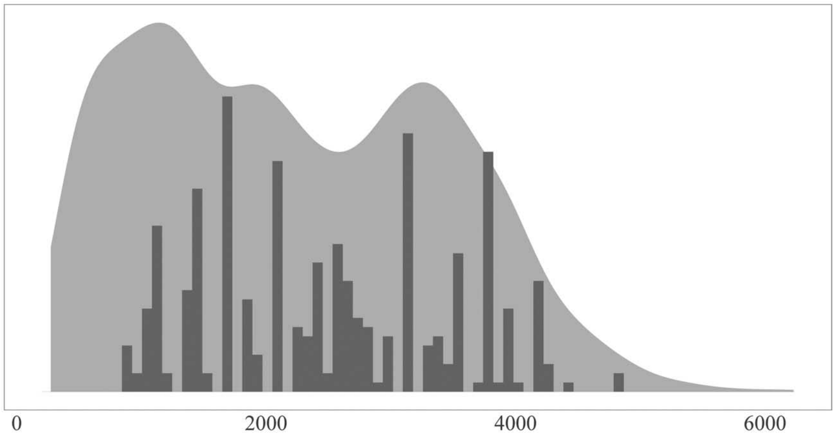

Figure 2. Distribution of biodiversity in the tropics (*shaded area*) compared to the biodiversity distribution in our sample (*bars*). Color version available as an online enhancement.

views. Figure 3 depicts the distribution of the SPEI index in our sample and compares it with the long-term distribution of the index in the same locations. Positive values indicate droughts or water deficits, as we reversed the scale of the index. About 34% of the observations in our sample deviate from normal conditions by more than one standard deviation, while only less than 5% of the sample deviate from normal conditions by more than two standard deviations.

We sum water balances over the 3 months of each income quarter. We therefore neglect interperiod water balance dynamics as well as water deficits or excess water at the beginning of each income period. As plant growth depends largely on the available water in the soil that accumulates over time, we are more concerned about water deficits that enter our income quarters. In fact, Vicente-Serrano et al. (2013) find large effects of water balances of three or more months on global plant growth. We therefore include additional lagged SPEI values in our regression specification.

1.4. Seasons

Planting and harvesting seasons differ between villages in our sample. Further, many villages have several planting and harvesting seasons per year, and the timing of the seasons differs between crops. To allow the impact of droughts and biodiversity on rural incomes to differ across seasons we match our household data with subnational data on the timing of planting and harvesting seasons from Sacks et al. (2010). To classify the 3 months from the survey in which incomes are generated into either planting, growing, or harvesting season, we proceed in three steps. First, we match our sample villages with

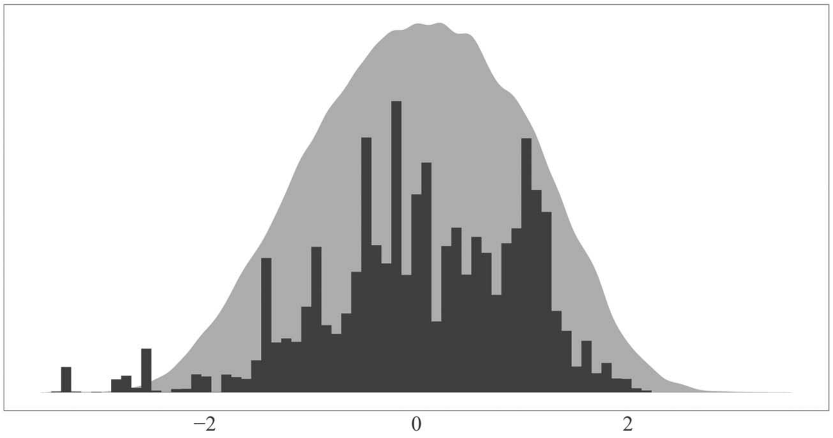

Figure 3. Distribution of the SPEI index in our sample (*bars*) compared to the 50-year distribution of the index in the same locations (*shaded area*). The scale is reversed, such that positive values indicate water deficits and negative values wet conditions. Color version available as an online enhancement.

the data on the timing of planting, growing, and harvesting seasons in the nearest geographical unit from Sacks et al. (2010). Second, we classify each day of a year in the villages as being part of the planting, growing, or harvesting season. As a consequence of multiple crops with only partially overlapping growing cycles, each day can be part of several seasons. In a third step, we compute the shares of days within the 3-month income period that fell into the different village-specific seasons. These shares may differ between households within one village, depending on the timing of the interviews and thus on the timing of the periods for which incomes were computed. Further, the shares related to one income quarter that fall into different seasons do not necessarily add up to one, as seasons may overlap and days may fall into neither planting, harvesting, nor growing season. For example, an income quarter from January to March could be classified to be 1 month planting, 2 months growing, and 2 months harvesting season as a result of overlapping cropping cycles for different crops, and the overlap of harvesting and growing seasons for several crops such as bananas or tea.

1.5. Additional Controls

We include mean annual temperatures, mean annual precipitation levels, agricultural suitability, and crop diversity as additional variables in robustness tests. Temperature and precipitation levels are gridded data with 0.5° resolution from the Climate Research Unit of the University of East Anglia (CRU TS3.21) (Harris et al. 2014). To measure agricultural suitability, we use the agricultural suitability index that was developed within the framework of the Global Agro-Ecological Zones (GAEZ) from the International Institute for Applied Systems Analysis and the Food and Agriculture Organization of the United Nations to evaluate the global agricultural potential in high spatial resolution (~0.1°). We use the soil and terrain suitability index for low input rain-fed agriculture, which is based on soil characteristics such as nutrients availability and retention capacity as well as on terrain variables such as slope and aspect (Fischer et al. 2012). To further measure crop diversity we sum the total number of unique crops that a household planted over the survey period. This measure controls for the portfolio effect of crop diversity (Di Falco and Chavas 2009), which is potentially correlated with natural biodiversity.

2. MODEL

In this section we develop the modeling framework that guides our empirical analysis and the interpretation of our results. Our theoretical framework describes the production decisions of a rural household facing environmental fluctuation in an economic environment without insurance markets. We will first provide the intuition before we present the model.

We consider a multisector model but start by describing the two sectors that largely rely on the environment, agriculture, and forestry. Droughts affect biological growth negatively and therefore reduce output from both sectors. Although both income sources rely on biological growth, they differ in important aspects. Crop production requires investment of labor and capital during the growing season, otherwise no biomass can be harvested during the harvesting season. With very few exceptions, only biomass that grew during the preceding growing season is harvested, making crop production susceptible to weather fluctuations. In contrast, income from unmanaged forests mainly relies on a stock of biomass that accumulated over many years; it requires no planting or growing effort by definition and can therefore yield a constant stream of income that is relatively unaffected by weather fluctuations. However, increases in resource extraction to mitigate income shocks can lead to resource overexploitation and consequently to resource degradation and a decline in resource incomes (Delacote 2009). We discuss the impact of common pool externalities on our results in appendix D.3.

The impact of droughts on sector incomes depends on the response of the households to the shock. Households may respond to shocks by increasing expenditures to compensate losses or they may allocate inputs to less affected income sectors. Measuring the costs of droughts only by changes in gross crop production therefore misses the effect of droughts on input reallocation and compensatory expenditures.

Biodiversity reduces the impact of droughts on biomass production (Isbell et al. 2015) either directly or by stabilizing ecosystem services such as pollination or nutrients cycling in agriculture (Millennium Ecosystem Assessment 2005). Biodiversity also stabilizes the biomass production in unmanaged ecosystems, as species that are less affected by environmental fluctuations benefit from the reduced competition (see Lehman and Tilman 2000; Loreau and Mazancourt 2013). We follow Baumgärtner and Quaas (2010) by assuming that biodiversity has no effect on production levels in general, that is, when no drought occurs, but that it stabilizes production by reducing the impact of droughts. This assumption plays no role in our empirical specification, as effects of biodiversity on income levels are absorbed by the household-level fixed effects, but it simplifies the theoretical analysis.

In addition to incomes from forests and crop production, households may derive incomes from wage work or other income sources. Incomes from these other sources may serve as an additional insurance mechanism if they are less affected by droughts than resource-based production. We lump income from all other income sources that do not depend on biological growth together and assume that they represent the opportunity costs of resource-based production.

To formalize our arguments, we analyze a three-sector, two-period household decision model with uncertain weather outcomes. We focus completely on short-term dynamics within one year neglecting the long-term dynamics of forest stocks and capital investments. Let Y_{is} denote income in sector i in season s, with $i = a$ for agriculture, $i = f$ for forest, and $i = o$ for income from other sources. The first period is the growing season, denoted by $s = 1$, and the second period is the harvesting season, denoted by $s = 2$. Income is output, denoted by y_{is}, scaled by the impact of a potential drought. We first describe output generation before we turn to the impact of droughts.

Let y' and y'' denote the first and second derivative of output and let us assume $y' > 0$ and $y'' < 0$ to ensure interior solutions. Let l_{is} denote the input into sector i in season s.

Output from the forest sector only depends on the harvesting inputs in the respective season. We therefore omit accumulated biomass as production input for simplicity, as it is exogenous in the moment of the decision. Agricultural output in the growing season is zero, that is, $y_{a1} = 0$, and income in the harvesting season depends on the input in the harvesting season as well as on biomass b produced during the growing season. Biomass, in turn, is a combination of effort in the growing season $b(l_{a1})$—with $b' > 0$ and $b'' < 0$—and weather conditions in the growing season.

The variable $\epsilon_s > 0$ measures the severity of droughts while $\bar{d}$ denotes the biodiversity level. To model the impact of a drought on income, we impose the following conditions. First, we impose that droughts have a negative direct effect on production. Second, we require that the impact of a drought is proportional to output (see Just and Pope [1978] for discussions of risk in production functions). This assumption also implies that droughts reduce the marginal productivity of inputs, which is in line with the findings of Leblois et al. (2014) or Emerick et al. (2016) but may not be true for inputs such as irrigation. Third, based on the findings in the ecological literature, we assume that biodiversity reduces the direct impact of droughts on output by reducing the drought's impact on biomass growth. Therefore, we write sector income Y_{is} and biomass B as

$$Y_{fs} = y_{fs}(l_{fs})e^{(-\alpha_f + \beta_f \bar{d})\epsilon_s}, \tag{1}$$

$$Y_{os} = y_{os}(l_{os})e^{(-\alpha_o + \beta_o \bar{d})\epsilon_s}, \tag{2}$$

$$\begin{aligned} Y_{a2} &= y_{a2}(l_{a2}, B)e^{(-\alpha_a + \beta_a \bar{d})\epsilon_2}, \\ B &= b(l_{a1})e^{(-\alpha_a + \beta_a \bar{d})\epsilon_1}, \end{aligned} \tag{3}$$

with $-1 < (-\alpha_i + \beta_i \bar{d})\epsilon_s < 0$ for $i = a, f$. The second inequality of the condition states that biodiversity never reverses the negative effect of droughts, while the first inequality ensures that biodiversity reduces the impact of droughts.[5] As there may be spillover effects from droughts, for example, on labor income in agriculture, we model

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[5] The impact of biodiversity on the production level is always smaller than its impact as a buffer. This assumption complements that of biodiversity having no impact if no drought occurs. For more details, see app. D.2.

other income similar to forest income. The case of no spillover effects is included, by setting either $\beta_o = 0$ or $\alpha_o = \beta_o = 0$.

Input markets are often imperfect in developing countries. We consider the two extreme cases in the following. In the first environment, input markets work perfectly and inputs can be bought at the constant market price p_s. In the second environment, we assume that input markets are absent and that households are constrained by their initial endowments, L. However, in both cases, output markets work perfectly. While we consider either one or the other situation, most situations in the developing world are somewhere in between. We further assume that in both market environments, households can transfer income—but not endowments—between seasons.

The household observes weather outcomes at the beginning of each season. Accordingly, the household decides on input allocation in the growing season under uncertainty about weather outcomes in the harvesting season. In contrast, the household makes the input decision in the harvesting season when all uncertainty is resolved.

The problem of the household is to allocate inputs in order to maximize discounted utility U with the interseasonal discount factor δ. We assume that preferences are represented by a concave utility function, $U' > 0$ and $U'' < 0$, which implies risk aversion. However, the results also hold for safety-first preferences (see app. D.3) as discussed in Delacote (2010). When input markets are present, the household therefore aims to maximize expected utility

$$E[U(Y_{f1} + Y_{o1} - p_1 \sum_{i \in a,f,o} l_{i1} + \delta(Y_{f2} + Y_{o2} + Y_{a2} - p_2 \sum_{i \in a,f,o} l_{i2}))]. \tag{4}$$

When input markets are absent, the household maximizes expected utility, taking into account that its total input endowment is L. Let λ_1 and λ_2 denote the shadow prices. Then, the household considers

$$E[U(Y_{f1} + Y_{o1} + \delta(Y_{f2} + Y_{o2} + Y_{a2})) + \lambda_1(L - \sum_{i \in a,f,o} l_{i1}) + \lambda_2(L - \sum_{i \in a,f,o} l_{i2})]. \tag{5}$$

We solve the decision problem by using backward induction. In the harvesting season, the rural household decides on the optimal input allocation, taking the accumulated biomass and weather conditions as given. Optimality conditions require that marginal returns to inputs are equalized across sectors, independent of the functioning of markets (see app. C for details). In the growing season, input allocation in the harvesting season is taken as a best-response function to input allocation in the growing season, among others. While the weather outcomes during the growing season are known, weather outcomes in the harvesting season are unknown at this stage. Again, optimality requires that expected marginal returns to inputs are equalized across sectors, independent of the functioning of the markets (see app. C for details).

We now use the model to predict how droughts affect sector incomes for different levels of natural biodiversity. As inputs may be reallocated when a drought occurs, the impact on sector incomes is not clear a priori. For example, a sector may increase production in response to droughts if it is comparatively less affected than the other sectors and input reallocations overcompensate the direct losses from droughts. We refer to the scaling of the output due to the drought shock as the "direct effect" and to input reallocation as the "indirect effect." The direct effect from a drought on income is negative by assumption. The sign of the indirect effect is not clear, however. In the following we discuss the impacts of droughts on total sector incomes and on total income. With "total sector incomes" we refer to $Y_i = Y_{i1} + Y_{i2} - p_1 l_{i1} - p_2 l_{i2}$, while "total income" is $Y_T = Y_f + Y_a + Y_o$.

Proposition 1 states the model's prediction on how droughts in the growing or the harvesting season affect total sector incomes and total income.

Proposition 1: A drought in the harvesting season or in the growing season

1. reduces total sector incomes when input markets are present,
2. either reduces or increases total sector incomes when input markets are absent and
3. reduces total income independent of whether input markets are present or absent.

Proof: See appendix D.1. QED

When input markets are present, the indirect effect cancels out as marginal productivities equal prices. This result hinges on the assumption of exogenous input prices and may hold in the real world only for small idiosyncratic shocks. For large correlated shocks but well-functioning input markets, the result may equal the results for absent input markets, in which shadow prices of inputs are determined endogenously by productivity changes across sectors.

When input markets are absent, the impact of a drought on total sector incomes is ambiguous and depends on the relative drought sensitivity of the sectors. Inputs in the relatively more affected sectors act as complements to the shock while in the comparatively less affected sectors, weather and inputs act as substitutes. If a drought occurs, inputs are reallocated from relatively more affected sectors to relatively less affected sectors, thus increasing the magnitude of the shock in relatively more affected sectors while at the same time dampening the shock in relatively less affected sectors.

The results for total income relate to the fact that the indirect effects cancel out. This result can be obtained directly by applying the envelope theorem to the maximized objective function.

Next, we consider how biodiversity affects the weather-induced income shocks. An increase in biodiversity reduces the direct effect of a weather shock. The following proposition concerns the stabilizing role of biodiversity for rural incomes.

Proposition 2: Higher biodiversity levels

1. decrease the impact of droughts on total sector incomes when input markets are present,
2. either increase or decrease the impact of droughts on total sector incomes when input markets are absent and
3. decrease the impact of droughts on total income independent of input market functioning.

Proof: See appendix D.2. QED

Higher biodiversity levels reduce the direct impact of weather on production by assumption. This explains the first and the third part of the proposition. However, the direct impact of biodiversity may be heterogeneous across sectors, that is, biodiversity may stabilize some production sectors more than others. Production that depends closely on ecosystem services may benefit more from biodiversity than production that is more independent of natural biodiversity. If biodiversity stabilizes production more in less weather-sensitive production sectors and when input markets are missing, input reallocation may intensify to an extent where it destabilizes sector income. Thus, when input markets are missing, results for total sector incomes are ambiguous. Although intuition suggests that the destabilizing case of biodiversity is less likely, the outcome is ultimately an empirical question.

In the following, we use the theoretical framework to develop the empirical specifications.

3. EMPIRICAL STRATEGY

Our empirical strategy to estimate the impact of droughts on income conditional on biodiversity levels depends on (i) the panel nature of our data set and (ii) the exogenous variation of droughts. Of particular interest is the interaction between droughts and biodiversity. The quarterly income data matched with the agricultural seasons further allow us to estimate the impact of droughts related to their timing. To derive the equations to be estimated, we assume Cobb-Douglas technologies and take logs of the functions (1) and (3). Then, total crop income is given by

$$\log(y_{a2}) = \log(y_a(l_{a2}, l_{a,1})) - \alpha_a \epsilon_2 + \beta_a \bar{d} \epsilon_2 - \alpha_a \epsilon_1 + \beta_a \bar{d} \epsilon_1. \tag{6}$$

Droughts affect total crop income in the harvesting season directly through the impact on biomass growth in the growing season ($s = 1$) and through their impact on the harvesting process and the quality of the harvest in $s = 2$. Droughts affect total crop income also indirectly through input reallocation during the growing season and during the harvesting season. Factor inputs in both seasons are therefore implicit functions of droughts as well. To test our model assumption that forest and other income are only affected by current-period shocks, we use the same set-up as for agricultural income.

Income quarters in our data do not align exactly with agricultural seasons, as cropping seasons vary with the local climate and households grow different crops with different growing cycles simultaneously. We introduce subscript t to denote an income quarter. To take seasonality into account, we construct seasonal variables s_k, with $k = 1, 2, 3$ to represent the planting, growing, and harvesting season. Each variable depicts the share of a given quarter that falls into each of these seasons. To estimate the seasonal impact of a weather shock on rural incomes, we interact the drought variable with these seasonal variables. Seasonal variables in noninteracted form capture the effect of seasonality on rural incomes and allow us to compare the impact of droughts and biodiversity to the baseline fluctuations of rural incomes.

Based on equation (6) we estimate

$$\log(Y_{hjt}) = \sum_{k=1}^{3} \gamma_k s_{khjt} + \sum_{k=1}^{3} \alpha_k s_{khjt} \epsilon_{hjt} + \sum_{k=1}^{3} \beta_k s_{khjt} \epsilon_{hjt} \bar{d}_j + \nu_{hj} + \eta_t + \mu_{hjt}, \quad (7)$$

in our baseline specification with the dependent variable Y_{hjt} representing income of household h in village j in quarter t. The season variables s_{khjt} with $k = 1, 2, 3$ indicate the share of days during the income quarter that fell into the planting, growing, and harvesting season. The season variables as well as the weather shock ϵ_{hjt} are household specific, as the timing of the interviews differed across households, resulting in differing individual income quarters. Biodiversity $\bar{d}_j$ denotes the village-specific biodiversity level, ν_{hj} are household fixed effects, η_t are year fixed effects, and μ_{hjt} denotes the error term. We add additional lagged weather shock variables to capture the effect of droughts during the growing season on the harvestable biomass based on equation (6).

The coefficient γ_k captures the effect of seasonality on income in season k. Large coefficients indicate strong seasonal fluctuations of incomes. Based on our model we predict that crop production exhibits more seasonal fluctuations than forest production or other incomes. The seasonal impact of droughts on rural incomes is captured by α_k. The parameter β_k measures the impact of biodiversity on income stability. If α_k and β_k have opposite signs, biodiversity reduces the impact of droughts on incomes. However, α_k could have both signs, as input reallocation in less affected sectors could overcompensate the direct impacts of droughts as discussed earlier.

Income is transformed using the inverse hyperbolic sine (IHS) transformation (Burbidge et al. 1988), as this transformation is defined for nonpositive values that occur in seasons dominated by expenditures. Additionally, the transformation accounts for the log-normal distribution of incomes. The interpretation of the coefficients is similar to the interpretation for log-transformed incomes.

The shock variable, ϵ_{hjt}, measures the drought anomalies. To ease interpretation, we reversed the scale of the drought index such that positive drought values indicate water deficits and negative coefficients β indicate negative impacts of droughts on rural incomes. In the baseline specification, we include droughts in linear form assuming that within a specific season droughts have either positive or negative impacts. This specification still allows for a nonlinear response of rural production to droughts as the effect may vary by season. In two robustness checks we include the drought variable in a binned version and in a nonnegative or censored version to verify whether our linearity assumption is justified.

Biodiversity is measured in the number of species per grid cell. We standardize biodiversity at the World Bank region level to control for unobserved differences across regions that may bias the estimation of the interaction terms (see Balli and Sørensen [2013] for a discussion on fixed effects and interaction terms in panel data). It also simplifies the interpretation of the coefficients. After demeaning, β_k measures the marginal effect of droughts on income for average region-specific biodiversity levels. As biodiversity is measured within larger geographical areas or protected areas with limited human influence there is little concern about the endogeneity of biodiversity. However, in our main regression specification we use a biodiversity measure that uses geographic variables to interpolate biodiversity levels between observations. In a robustness check we use an alternative biodiversity measure that is solely based on the spatial distribution of biodiversity records (see sec. 1).

However, the same geographic features that help to explain biodiversity distributions may potentially also affect the response of rural incomes to droughts. For example, the baseline climate or agricultural suitability could influence the response of rural incomes to droughts. In a further robustness check we therefore include agricultural suitability based on soil and topographic characteristics as well as climate variables, both interacted with the seasonal droughts, as additional controls in our regression. Including these controls would largely reduce the estimate for the impact of biodiversity on rural incomes if geographic factors would explain biodiversity levels as well as the response of rural incomes to droughts.

Finally, natural biodiversity may be correlated to crop diversity, which has been shown to stabilize rural incomes (Di Falco and Chavas 2009). In a last robustness check we include household-level crop diversity interacted with the seasonal drought variables to test whether crop diversity drives the relationship between biodiversity and the stability of rural incomes.

4. RESULTS

First, we present our results on the impact of droughts on rural incomes excluding the interaction of droughts with biodiversity. We use these results to compare the magnitude of the impact of droughts on rural incomes to the baseline seasonal income fluctuations. Based on the discussion of these results, we then proceed by reporting our results on the impact of natural biodiversity on the stability of rural incomes. We conclude the section by discussing the robustness of our results as well as mechanisms that drive the relationship between droughts, incomes, and biodiversity.

Figure 4 reports the marginal effects for the baseline regression specification with linear drought variables but without the biodiversity interaction term. The individual panels show the marginal effects of seasonality and droughts on crop, forest, other, and total incomes. The bars indicate the 90% confidence intervals. The coefficients represent semi-elasticities, that is, the percentage change of income in response to a one standard deviation drought. The complete regression results for this baseline specification without biodiversity are reported in appendix E.1.

The first three terms on the vertical axis of the panels in figure 4 depict the impact of seasonality on rural incomes. The seasonal variables range from zero to one and indicate the share of days within one income quarter that fell into one of the three seasons. Seasonal income fluctuations are substantial. Crop incomes are 139% lower in the planting season and 134% higher in the harvesting season compared to the off and to the growing season. This result is no surprise as the planting season is dominated by input expenditures (and net incomes are negative) while the revenues accrue in the harvesting season. Parts of the harvest may be stored and contribute to incomes in the off season.

In contrast, forest incomes and incomes from other sources are weakly countercyclical, although most seasonal coefficients are statistically insignificant. The absence of

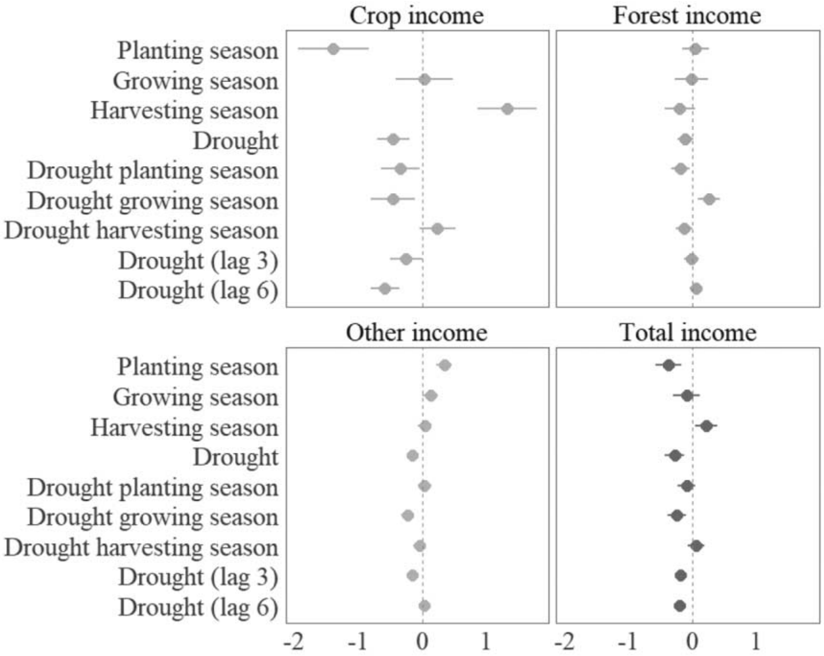

Figure 4. Marginal effects of seasonality and droughts on sector and total incomes. Color version available as an online enhancement.

strong seasonality in forest and other incomes stresses their importance for seasonal income smoothing. As a result, the seasonality of total income is reduced compared to crop income. This finding is in line with our assumption about the seasonality of incomes from forestry and other sources in the theoretical section of this article. The increase in other incomes during the planting and growing seasons can be attributed to the fact that most other income stems from wage work in agriculture.

Droughts have a large impact on rural incomes. On average, a drought of one standard deviation reduces crop incomes by 45%. The impact of droughts on crop production varies across seasons. The marginal effect (ME) of droughts on seasonal incomes is given by the sum of coefficients of the overall drought variable and the seasonal drought variable. Droughts during the growing season have the largest impact on crop incomes while droughts during the harvesting season have no statistically significant impact on crop income.

Droughts during the growing season affect agricultural expenditures, but also biomass production. To separate both effects, we further include lagged drought variables for the harvesting season. These lagged drought variables only capture the impact of droughts on the accumulation of harvestable biomass and exclude the direct impacts on expenditures during the growing season. A drought that occurred 3 months before the harvest reduces crop incomes during the harvesting season by 25%. A drought that occurred 6 months before the harvest reduces crop incomes in the harvesting season by 59%. The larger effect of droughts with 6 months time lag compared to 3 months time lag seems surprising. However, this result is in line with the findings of Vicente-Serrano et al. (2012), who show that the greatest impact of droughts occur with a lag of several months in most ecosystems. The reason for this time lag may be that water deficits at the end of one period carry over to next period through lower ground water levels and dry soil conditions.

The impact of droughts also varies across sectors. Forest incomes respond much less to droughts than crop incomes. The marginal impact of a one standard deviation droughts on forest incomes is −19% in the planting season, +26% in the growing season, and −13% in the harvesting season. The positive impact of droughts on forest incomes in the growing season suggests input reallocation from crop to forest production. This finding is in line with the theory of common pool resources as insurance mechanisms for rural households. Forest incomes are also unaffected by lagged droughts, which is in line with our assumption that individual droughts have little impact on accumulated harvestable biomass in forests.

Incomes from other sources also stabilize total incomes, although they are negatively affected by droughts, especially during the growing season. The high sensitivity of incomes from other sources to droughts can be explained by the large component of agricultural wage work in this income category. The negative impact of droughts on agricultural production in the growing season possibly leads to less demand of agricultural labor and therefore to less income from agricultural wage work.

The coefficient that measures the impact of droughts on sector incomes overestimates—or underestimates—the direct impact of droughts on rural incomes as it includes both the direct impact of droughts and the indirect impact through input reallocation. For total incomes, the indirect impacts cancel out, as shown in section 2, such that the response of total incomes to droughts only reflects the sum of direct impacts (envelope theorem, see proposition 1). In line with this finding, droughts that occur 3 or 6 months before the harvest reduce total incomes only by 19% and 21%, respectively. A drought of one standard deviation has little impact on total incomes during the planting and the harvesting season, but it reduces total income by 25% if it occurs during the growing season. These results suggest that the impact of droughts during the harvesting seasons is low. It could be that water is either less relevant during this part of the growth cycle, or that farmers have a certain flexibility concerning the timing of harvesting. Accordingly, they choose the timing in order to circumvent negative impacts of droughts.

The impact of droughts on crop income is small compared to the seasonal income fluctuations of crop income. A drought of one standard deviation during the growing season reduces crop income by 47%. In comparison, crop income drops by 139% during the planting season every year. However, seasonality is much more predictable than droughts, and households can compensate these predictable income fluctuations. The relative difference between impacts from seasonality and droughts is therefore much smaller for total income compared to crop income. Total income declines by 25% in response to a one standard deviation drought while it declines by 38% during the planting season compared to the off season. In addition, it is important to note that we are measuring income fluctuations and not fluctuations of consumption and that an unpredictable income shock may affect consumption and welfare more than predictable income fluctuations.

Next, we discuss the robustness of these baseline findings. The results for a regression specification with a drought variable that is restricted to positive values (water deficits) and is zero otherwise are presented in appendix E.2. The direction of the marginal effects is the same as for the complete range of water balances reported in appendix E.1 but the magnitude of the coefficients is larger. This result therefore suggests that the effect of water balances on rural production is not symmetric around zero. The results for a binned version of the drought variable reported in appendix E.3 support this interpretation. Water deficits (droughts) have large and negative effects on production while positive water balances have only small and sometimes positive effects on production. To be on the conservative side, we discuss the results for specifications using the full range of SPEI values in the main text and report the results for specifications using a restricted SPEI or binned SPEI variable in the appendix.

Next, we present results for the regression specification with biodiversity interacted with droughts. To ease the interpretation of our results, we show the marginal effects in figure 5, omitting overall seasonality from the figure. However, we report the com-

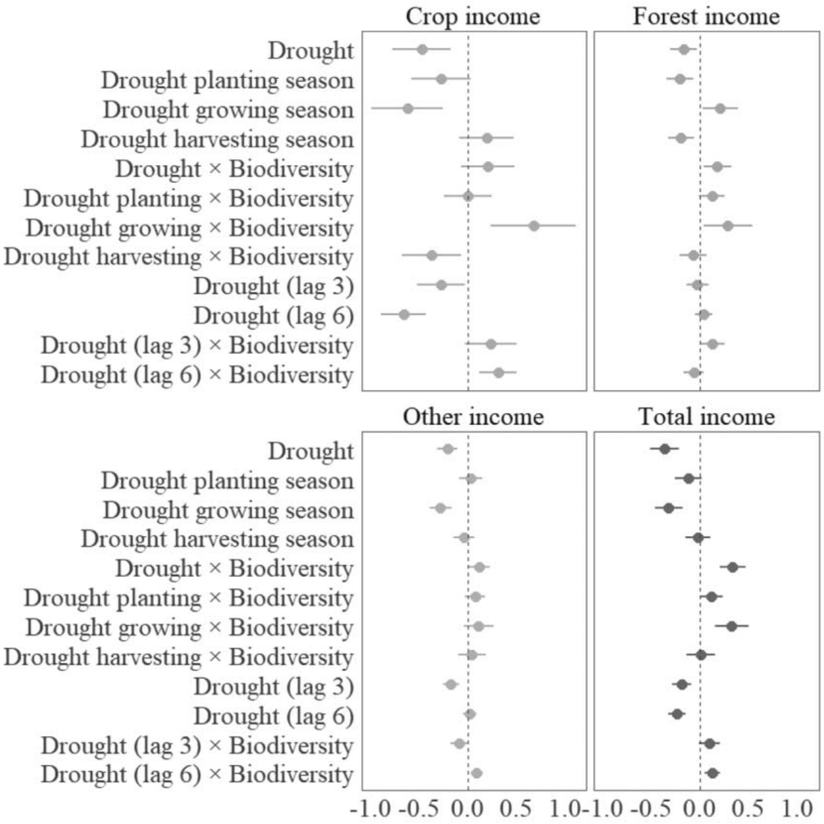

Figure 5. Marginal effects of droughts and biodiversity on sector and total incomes. The coefficients represent semi-elasticities, that is, the relative change of incomes in response to a one standard deviation increase in the drought or biodiversity level. The size of the marginal effects multiplied by 100 approximates the percentage change of income. Color version available as an online enhancement.

plete results in table 2. Biodiversity does not enter the regression equation in non-interacted form as its direct impact on rural incomes is absorbed by the household fixed effects. The biodiversity variable is demeaned at the regional level such that the estimates for the impact of droughts on rural incomes are comparable to the estimates reported in figure 4.

Figure 5 depicts the marginal effects and the 90% confidence intervals of droughts and biodiversity on rural incomes. The marginal effects of seasonal droughts are given by the sum of the overall impact of droughts and the season-specific deviations from the overall impact (drought + drought × season), while the marginal season-specific effects of biodiversity are given by the sum of the overall impact of biodiversity on

Table 2. Droughts, Natural Biodiversity, and Rural Incomes

	IHS Transformed Income			
	Crop	Forest	Other	Total
Planting	−1.44***	.01	.34***	.44***
	(.33)	(.13)	(.08)	(.13)
Growing	.15	.01	.13	−.14
	(.26)	(.16)	(.09)	(.13)
Harvesting	1.23***	−.22	.01	.12
	(.27)	(.14)	(.06)	(.11)
Drought	−.47**	−.17**	−.20***	−.36***
	(.18)	(.08)	(.06)	(.09)
Planting × drought	.20	−.04	.24***	.24***
	(.19)	(.09)	(.07)	(.08)
Growing × drought	−.15	.37***	−.07	.04
	(.20)	(.09)	(.07)	(.08)
Harvesting × drought	.67***	−.03	.17***	.34***
	(.16)	(.08)	(.06)	(.08)
Drought × biodiversity	.21	.18**	.12*	.34***
	(.17)	(.08)	(.07)	(.08)
Harvesting × drought (lag 3)	−.27*	−.03	.17***	.19***
	(.15)	(.07)	(.05)	(.06)
Harvesting × drought (lag 6)	−.65***	.04	.02	.24***
	(.14)	(.05)	(.04)	(.05)
Planting × drought × biodiversity	−.20	−.06	−.04	−.22**
	(.18)	(.10)	(.09)	(.10)
Growing × drought × biodiversity	.47**	.11	−.01	−.01
	(.19)	(.11)	(.07)	(.08)
Harvesting × drought × biodiversity	−.58***	−.25**	−.07	−.33***
	(.21)	(.10)	(.07)	(.09)
Harvesting × biodiversity × drought (lag 3)	.24	.13	−.09	.10
	(.16)	(.08)	(.06)	(.06)
Harvesting × biodiversity × drought (lag 6)	.31***	−.06	.09**	.12***
	(.12)	(.06)	(.04)	(.05)
Observations	28,629	28,629	28,629	28,629

Note. The table shows the estimates and standard errors (in parentheses) for regression (7) with biodiversity and the drought variable in linear form. Incomes are transformed using the hyperbolic sine (IHS) transformation. The seasonal variables indicate how much of the income quarter fell into planting, growing, and harvesting season. The baseline season is the off season. The drought index measures the difference from normal conditions in standard deviations. Positive values indicate dryer than normal conditions. Biodiversity is measured in standard deviations from the regional mean. Standard errors are clustered at the village level.

* $p < .1$.

** $p < .05$.

*** $p < .01$.

droughts plus the seasonal deviations from this overall impact (drought × biodiversity + drought × biodiversity × season). The marginal effects of seasonal droughts represent the impact of droughts on rural incomes for areas with region-specific mean biodiversity levels. All marginal effects are measured in the percentage change of income in response to a one standard deviation drought and a one standard deviation increase in biodiversity levels, respectively.

As before, droughts affect crop production mostly when they occur during the growing season, that is, either in the growing season or 3–6 months prior to the harvesting season. Biodiversity reduces the impact of droughts on crop income mainly during the growing seasons, either measured as a drought during the growing season or a drought 3–6 months prior to the harvesting season. Figure 5 shows that increasing biodiversity by one standard deviation above the regional mean reduces the impact of droughts on crop income to almost zero. Put differently, reducing the biodiversity level by one standard deviation below the regional mean almost doubles the negative impact of droughts on crop income. This effect is most visible in the growing season where the negative marginal effect of droughts on crop income (−0.62) equals the positive marginal effect of biodiversity interacted with droughts (0.68).

Biodiversity also affects forest incomes. Although biodiversity stabilizes forest incomes in most cases (i.e., the effect of droughts and the drought-biodiversity interaction have opposite signs) it also destabilizes forest income in other cases. In contrast to resource-based incomes such as forests and crops, biodiversity has no statistically significant impact on incomes from other sources. However, the stabilizing impact of biodiversity on rural incomes is also visible for total incomes, and all destabilizing effects through input reallocation cancel out, as predicted by the model. The stabilizing effect of biodiversity on total incomes is especially pronounced during the growing season or 3–6 months prior to the harvesting season. Increasing biodiversity levels by one standard deviation above the regional mean reduces the impact of a one standard deviation drought on total income during the growing season to zero.

Next, we discuss the robustness of our results as well as possible mechanisms for the impact of biodiversity on rural incomes. Appendixes E.4 and E.5 report the results, including the interaction with biodiversity for a drought variable that is restricted to positive values (water deficits) and a drought dummy that equals one for droughts larger than one standard deviation and is zero otherwise. Droughts larger than one standard deviation occur approximately every 6 years independent of the location (Vicente-Serrano et al. 2010). Although the estimated coefficients are generally larger due to the focus on negative or extreme events in these specifications, the general conclusions are confirmed: droughts during the growing seasons reduce incomes, the negative impact of droughts is larger for crop incomes than for forest and total incomes, and biodiversity reduces the impact of droughts on rural incomes, especially during the growing season.

Biodiversity could be driven by geographic variables such as the agricultural suitability of an area or baseline climates which may also affect the response of rural incomes to droughts. The household fixed effects do not solve the problem for the interaction terms, as discussed in Balli and Sørensen (2013). Kreft and Jetz (2007) also use geographic variables to interpolate biodiversity values in their main specification. In a first robustness check, we therefore use an alternative biodiversity measure from Kreft and Jetz (2007) that is based exclusively on the spatial distribution of biodiversity (kriging). The results for this specification are reported in appendix E.6. Using the alternative biodiversity measure has almost no impact on the direction and magnitude of the results. To test directly whether geographic features drive both biodiversity and the size of the drought impact on rural incomes, we add interaction terms of the drought variables with regionally normalized temperature means and precipitation means as well as the agricultural suitability from the GAEZ project in a second robustness test.[6] Including these controls interacted with the seasonal drought variables would reduce our estimates for the impact of biodiversity on rural incomes to zero if our results for biodiversity were driven by the underlying geography. In contrast to these predictions, including the additional interacted controls leaves our qualitative result unchanged and increases the impact of biodiversity on droughts in the growing season. The complete results are reported in appendix E.7. We therefore conclude that our results are not completely driven by geographic variables. Further, our results could be affected by macroeconomic shocks at the country level. However, including country-year fixed effects has very little impact on the overall results. The results for the baseline specification with additional country-year fixed effects are reported in appendix E.9.

Finally, crop diversity and natural biodiversity are potentially related. For example, a high natural biodiversity could provide a broad genetic basis for the cultivation of crop species. Crop diversity is know to stabilize rural incomes (Di Falco and Chavas 2009) and could therefore explain the stabilizing role of natural biodiversity. In a last robustness test we include crop diversity on the household level interacted with the seasonal drought variables as an additional control. Including crop diversity as an additional interacted control has very little impact on the results, however (see app. E.8).

5. CONCLUSION

We have examined the effect of biodiversity on drought-induced income shocks. Our empirical results confirm our theoretical predictions, that is, that droughts reduce total income especially during the growing season and that biodiversity reduces these negative income shocks. The empirical results suggest further that input reallocation between agriculture and common pool resources occurs and that biodiversity reduces this factor movement. Although biodiversity could theoretically increase the effect of droughts on sector incomes, the empirical analysis shows that this is not the case.

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[6] http://www.fao.org/nr/gaez/en/.

Our robustness tests suggest further that natural biodiversity itself and neither agricultural suitability nor crop diversity explains the positive relationship between biodiversity and the stability of rural incomes. We therefore interpret our results as evidence for the stabilizing role of biodiversity for ecosystem services supporting agricultural production such as pollination, nutrients cycling, and water retention. Droughts or high precipitation levels may not only affect these supporting services directly (Brittain et al. 2013; Garibaldi et al. 2016; Henselek et al. 2017) but also the synchrony between the provision and the demand for these services (Bartomeus et al. 2013). Although the research on biodiversity and the stability of supporting ecosystem services in agriculture has mainly focused on pollination services, there is increasing evidence that biodiversity also increases other supporting services such as natural pest control (Larsen and Noack 2017).

Our results therefore stress the importance of biodiversity and natural resource conservation for rural households. They show that halting deforestation and global biodiversity loss can also benefit rural households in developing countries. However, our results suggest further that there are large positive externalities of natural biodiversity for agricultural production. Our findings therefore contribute to the land-sharing and land-sparing debate. While the predominant finding in this literature is that conservation outcomes can be maximized by separating land conservation and agricultural production (Phalan et al. 2011), other studies argue that this approach neglects the positive externalities from biodiversity conservation for agriculture (Garibaldi et al. 2017). Although these externalities are generally recognized, they have rarely been quantified due to the lack of data (Garnett et al. 2013). This paper's results fill this gap and show that these positive externalities can be substantial. Our results therefore suggest that conservation can complement production by providing risk-reducing ecosystem services.

Improved access to financial markets reduces the importance of natural resources and biodiversity as alternative insurance mechanisms (Quaas and Baumgärtner 2008; Baumgärtner and Quaas 2010). Weather index insurances, for example, can mitigate the income risk of farmers in developing countries and therefore reduce their dependence on natural biodiversity. However, high data requirements, spatial variability of shocks, and uncertainty over payouts reduce their potential benefits and can explain the current low penetration rates of formal crop insurances in rural areas of developing countries (Leblois et al. 2014; Smith 2016; Platteau et al. 2017). Informal insurance in combination with loans for productive purposes often exist (Riekhof 2016), but their local coverage may not suffice to deal with correlated weather shocks.

Households may increase the presence of natural resources on their land if they recognize the positive benefits of biodiversity for income stability (Delacote 2007). However, much of the biodiversity and natural resources in developing countries are managed as common pool resources, and households provide too little habitat for biodiversity on their land if the benefits accrue also as externalities on neighboring farms. High dependence of rural households on natural resources may further lead to their degradation and overexploitation if use rights are imperfectly defined. Privatization of resources can improve both resource conservation and development outcomes (Noack et al. 2018), but privatization also reduces the insurance property of common pool resources (Baland and Francois 2005). Other resource management tools that incentivize resource conservation without compromising the insurance property of common pool resources are needed to manage common pool resources in developing countries.

We have shown in this study that biodiversity and forest conservation can reduce the vulnerability of the rural poor to climate change. This is especially important if climate change increases weather variability. Other mechanisms to mitigate the impact of droughts on poor rural households, such as access to credit and insurance markets, weather-robust crop varieties, or better access to labor markets, can supplement biodiversity conservation. However, biodiversity conservation may be more efficient, especially if the off-side benefits of biodiversity conservation are taken into consideration.

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