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RESEARCH ARTICLE

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Large-scale land acquisition as a potential driver of slope instability

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Abstract

Recently, vast tracts of land have been acquired by foreign and domestic–foreign partnerships to satisfy an increasing demand for agricultural products, often resulting in the conversion of forested landscapes into agricultural fields. Those conversions often occur in areas characterized by high slope angles with the potential to cause mass wasting and shallow landslides. An interesting case-study is the Licungo basin in Mozambique, where from 2000 nearly 160,000 ha of forest were converted, 17% of which occurred in areas acquired through large-scale land acquisitions (LSLAs). This study analyses the relationship between deforestation occurring within LSLA areas and the likelihood of landslide occurrence. To this end, we use a spatially distributed physically based model that couples the assessment of slope stability with hillslope-scale hydrological processes and evaluates the change in slope stability associated with remotely sensed forest loss. Relative to conditions where no human modification of land cover has occurred, we find that LSLAs have the potential to increase the extent of areas susceptible to slope failure by as much as 15,000 ha. We also quantified potential direct and indirect implications of such events for the food supply of local populations, estimating that 4,000 people could lose approximately 700 kcal cap^{-1} d^{-1} if all LSLAs are put under production. This study demonstrates the linkages between LSLAs, slope instability, and knock-on environmental and societal impacts. Governments should therefore take such impacts into account (in addition to those related to habitat destruction and carbon emissions) when issuing permits and concessions within forested lands.

KEYWORDS
deforestation, food supply, intensity duration frequency curves, landslides, large-scale land acquisitions

1 | INTRODUCTION

Global demand for agricultural products is continuing to increase as a result of population growth, dietary trends (D'Odorico et al., 2018; FAO, 2017), and emerging bio-energy policies (OECD/FAO, 2014). Combined with the uncertainty of future climate change, these factors have heightened concerns in many countries that the resources locally available to support domestic food production will be insufficient in the coming decades, particularly within land- and water-limited nations (Davis et al., 2017; Suweis, Rinaldo, Maritan, & D'Odorico, 2013). A recent phenomenon in response to this increased pressure on local agricultural resources has been for countries and investors to begin acquiring large tracts of arable land in the developing world (Borras et al., 2011; Franco, 2012). By doing so, they can increase the agricultural resources under their control, gain access to inexpensive lands with relatively high-yield gaps, and buffer against future climate uncertainty (Chiarelli, Davis, Rulli, & D'Odorico, 2016; Davis, Rulli, & D'Odorico, 2015; Davis, Yu, Rulli, Pichdara, & D'Odorico, 2015). While these land deals are often made with the promise of enhanced rural development, job creation, and increased local food availability, it remains to be seen whether these types of investments are beneficial for global food security as well as for rural livelihoods within targeted countries. There is however growing evidence that many of these land deals are leading to profound and unintended social and environmental consequences (Dell'Angelo, D'Odorico, Rulli, & Marchand, 2017; D'Odorico, Rulli, Dell'Angelo, & Davis, 2017; Rulli, Offeddu, & Santini, 2013).

Covering a total of 47.5 Mha (Land Matrix, 2019)—an area equivalent to Spain—large-scale land acquisitions (LSLAs) occur throughout Latin America, Southeast Asia, and subSaharan Africa. The increasing availability of georeferenced land concession maps—combined with satellite-based land cover products—has allowed for recent quantitative analyses of land cover change induced by LSLAs (Davis et al., 2020), particularly in Southeast Asia (Davis, Yu, et al., 2015). Yet for many places, the resultant land cover changes of these investments and the biophysical consequences thereof remain poorly understood. This is especially true for subSaharan Africa, where 15.8 Mha of land has been acquired and 10.0 Mha is intended by foreign companies to date (Land Matrix, 2019).

One of the most apparent land cover changes occurring as a result of LSLAs in Africa is forest loss, a process with numerous ecological and biophysical consequences. Among the most important and least understood of these is mass wasting (or land sliding) induced by forest removal. Land concessions are potentially especially prone to this phenomenon, given the rapidity with which land cover changes can occur in these areas, as investors seek to quickly transition the land to being agriculturally productive.

Among the African countries most targeted by LSLAs is Mozambique, a nation whose government recently announced that 7.8 Mha of land was being made available for large-scale economic activities (3.8 Mha for agriculture: INE, 2011; Nhantumbo & Salomão, 2010). While the private ownership of land is not permitted in Mozambique, the government can recognize the right to make use of land through a Direito do Uso e Aproveitamento da Terra (DUAT). These DUATs can fall under a host of agricultural, residential, and commercial categories and are granted to both individuals and companies. This detailed information from the Mozambican Government therefore affords a unique opportunity for the quantitative assessment of effects of large-scale land deals on land development and degradation (via mass wasting) in an African context. Such analyses are urgently needed in this area in order to objectively assess their potential environmental consequences and to determine whether this is an acceptable compromise for a country should the deals be achieving the intended development and food security goals.

One such area that has experienced substantial land investment, forest loss, and landslides in recent years is Mozambique's Zambezia Province and its Licungo basin. The Province's wet climate, hilly terrain, the continuos floods (Dutch Risk Reduction Team, 2015) and various human activities provide ideal conditions for the occurrence of frequent and substantial mass wasting events. Indeed, 10% of the more than 300 landslides observed in Mozambique in the last 15 years occurred in the Licungo River basin alone (Broeckx, Vanmaercke, Duchateau, & Poesen, 2018).

Because of the link between land cover change and increased mass wasting, and the rapid land conversion associated with LSLAs, here we assess whether the presence of land concessions significantly enhances mass wasting in Licungo basin as a result of forest removal. To do so, we use a spatially distributed and physically based model to predict possible landslide occurrences in the Licungo basin under nine different rainfall events for six different return periods. We combine this information with georeferenced maps of land concessions and high-resolution satellite-derived maps of annual forest cover. Through this study, we seek to better understand the natural hazards associated with the location and use of these allocated lands. Better connecting land concessions in Mozambique to potential environmental consequences can help to inform policy-makers not only where land deals could be located to minimize natural hazards from extreme rainfall events but also what sustainable practices and oversight can be put in place where land deals are already established.

2 | METHODS

2.1 | Study area

We combined information on topography, land use, and hydrological processes under four different land cover scenarios to examine the potential effects of deforestation (i.e., through the loss of cohesion provided by plant roots) and land concessions in triggering soil instability and impacting food production in the Licungo basin in Zambezia (Figure 1). The basin covers an area of about 22,600 km^2 lying between latitude 17.7S and 15.3S and longitude 35.8W and 37.5W, with high mountains located in the north in the Gurue and Milange Districts. There are different ethnic groups living in the Province (i.e., Chuabo, Sena and Lomwe) mainly involved in subsistence agriculture (Benfica & Tschirley, 2012)—the main source of income for 75% of the country's population (Hanouz, Geiger, & Doherty, 2014). Approximately, 82% of the population in Zambezia lives under the poverty headcount ratio of US$1.90 per day, and 46% of the population suffers from stunting (IFPRI, 2017). In these rural areas, poverty has persisted through time, while in the south of Mozambique, there has been a reduction in poverty during the last 20 years (World Bank, 2016).

2.2 | Input data

Elevation data (30 m × 30 m) came from the ASTER digital elevation model dataset (Tachikawa et al., 2011a). Data on soil characteristics

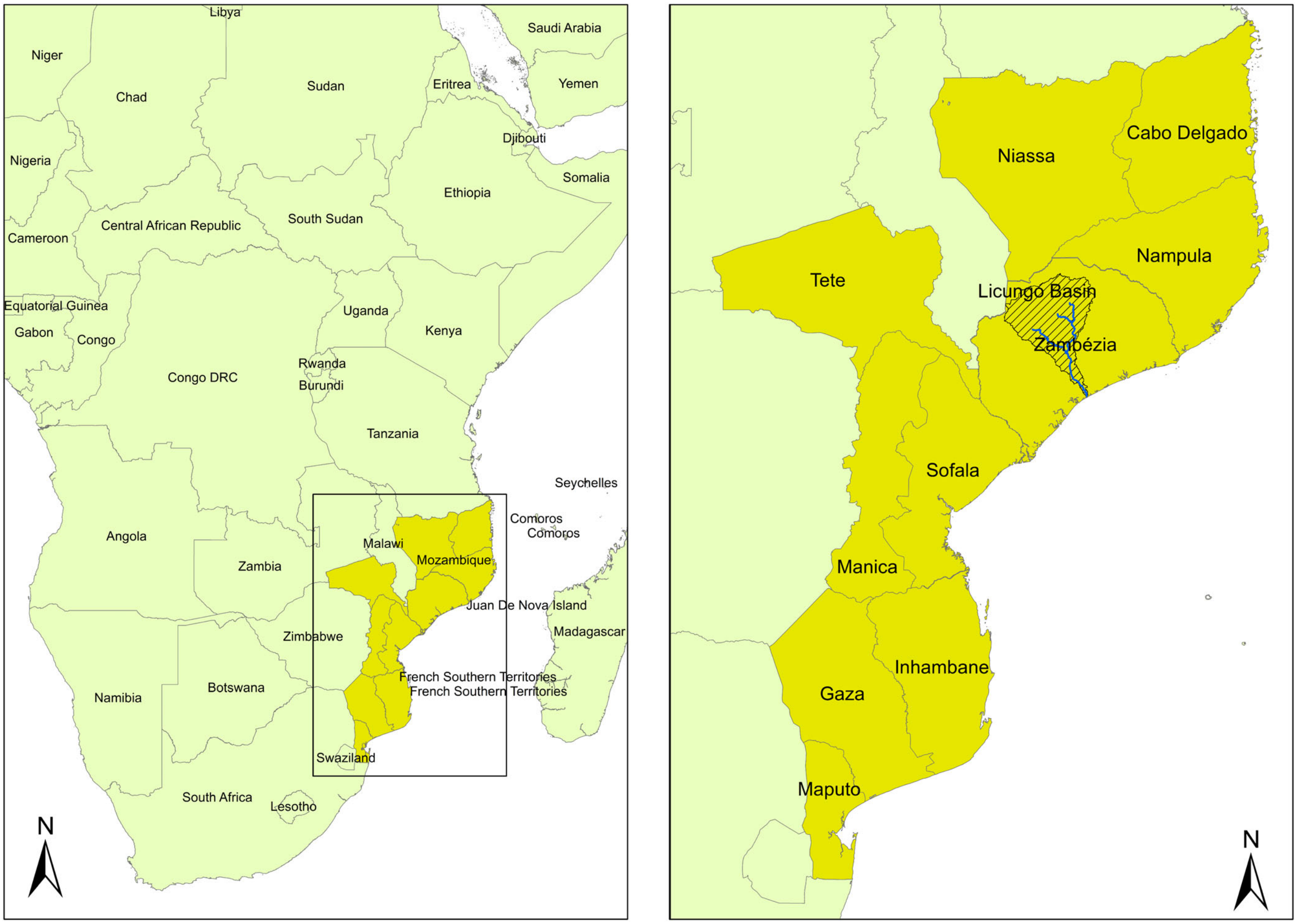

FIGURE 1 Licungo River basin in Zambezia Province in Mozambique [Colour figure can be viewed at wileyonlinelibrary.com]

(i.e., bedrock depth, soil texture class, void index, bulk density) were taken from the ISRIC SoilGrids dataset (Hengl et al., 2017). Due to a lack of in situ data in the study area, we considered two different friction angles, specifically set equal to 35° and 40°, that represent average values for rock and gravel soil. The density of gravel grains or rocks was set to an average value of 2,700 kg m^{-3} (ASTM D 854-92). LANDSAT-derived data on percent tree cover in the year 2000 and annual forest loss for the years 2000–2014 came from Hansen et al. (2013). Forest gain (reforestation) was not considered in this study as only 3% of total forests lost in Zambezia from 2000 to 2015. Information on LSLAs was taken from Land Matrix (2019—Accessed June 2019). Land concessions were taken both from Land Matrix datasets (Land Matrix, 2019) and from government concession maps (DUAT; Ministry of Agriculture and Food Security, Maputo, 2017). For the deals reported by Land Matrix, the effect on slope stability was evaluated by considering a circular buffer area equal to the size of reported contracted area and centered on the reported coordinates. Land deals are often concluded with a lack of transparency by investors and local governments, making it difficult to obtain detailed and precise information about each deal. As such it is important to note that the location reported by Land Matrix can sometimes only be accurate to the state or county level and does not necessarily correspond to the specific location of the actual land deal. For DUATs, this approximation through buffering was not needed, as these individual deals were reported in georeferenced maps.

2.3 | Stability model

To predict local instability, we used a grid-based (30 m × 30 m) spatially distributed and physically based model (Rosso, Rulli, & Vannucchi, 2006) that couples a slope stability equation with a hillslope hydrological model. We considered an infinite planar slope (Terzaghi, 1950; Terzaghi et al., 1996) and defined the shear strength of the soil along the slope, following the Mohr Coulomb failure law, as:

$$\tau_f = c' + (\sigma - u)\cdot \tan\varphi' \qquad (1)$$

Where: c' is soil cohesion, σ is the normal weight (per unit area), u is the pore water pressure, and φ' is the internal friction angle. If we denote with τ the actual shear stress, we can define the safety factor (FS) as the ratio between the shear strength and the actual shear stress τ:

$$FS = \frac{\tau_f}{\tau} \quad (2)$$

The actual shear stress depends on the amount of water stored in the soil *w* (defined as the ratio between the water level in the soil *h* and the depth of soil bedrock *z* and considered parallel to the slope) and can be expressed as:

$$\tau = [(1-w)\cdot\gamma + w\cdot\gamma\mathrm{sat}]\cdot z\cdot \mathrm{sen}\theta\cdot\cos\theta \quad (3)$$

Where: γ is the bulk unit weight of soil, γ_{sat} is the saturated unit weight of soil, and θ is the slope.

The water level during the storm (i.e., the water content $w = h/z$) was calculated treating the hillslope as a flow tube of contour length *b*, assuming that overland flow is due to an excess of saturation and that the average void ratio *e* and the average degree of saturation *Sr* are both constant (Rosso et al., 2006). The effective rainfall (*p*) on the contributing upslope area *a* draining across the contour length *b* for each studied cell was then calculated as:

$$ap - q = \frac{dS}{dt'} = a\cdot\frac{e}{1+e}\cdot(1-Sr)\cdot\frac{dh}{dt'} \quad \text{for } h \le z \quad (4a)$$

$$ap - q - r = 0 \quad \text{for } h > z \quad (4b)$$

Where: t' denotes the time after the beginning of the rainfall event, *r* is the overland flow, and *q* is the downhill subsurface flux out of the hillslope. This flux was expressed using Darcy's law as:

$$q = b\times h\times K\times\sin\theta \quad (5)$$

where *K* is the saturated conductivity of the soil (Rosso et al., 2006) derived from ISRIC dataset (Hengl et al., 2015; 2017).

By integrating the differential equation (Equation 4) for an initial stable piezometric condition for the duration of the event, we have that:

$$h = \min\left(\frac{a\cdot p}{Kb\cdot\sin\theta}\left[1-\exp\left(-\frac{(1+e)\cdot Kb\cdot\sin\theta t}{a\cdot(e-e\cdot Sr)}\right)\right] + h_i\cdot\exp\left(-\frac{(1+e)\cdot Kb\cdot\sin\theta t}{a(e-e\cdot Sr)}\right), z\right) \quad (6)$$

Two different initial values for h_i (i.e., 0.15 and 0.3) were used for forested pixels and other land use areas, respectively. This difference was included to reflect the fact that forested areas continuously evapotranspire during the whole year, while rates of evapotranspiration from cropland and other land uses tend to peak seasonally.

When the actual shear stress exceeded the resistance of the slope for a given level of precipitation and for a given pixel (FS < 1 in Equation 2; that is, the value of soil saturation exceeded the critical value of stability), the cell was considered unstable, and if the slope angle was higher than the internal friction angle, the cell was categorized as unconditionally unstable.

2.4 | Storm description—Intensity–duration–frequency curves

Intensity–duration–frequency (IDF) curves were not available for the studied province, though IDF curves exist at a country scale for Mozambique. There is also a lack of precipitation data at fine enough spatial and temporal resolutions. To overcome these limitations, we utilized daily data taken from the CHIRPS precipitation dataset (Funk et al., 2015) for the centroid of the Licungo river basin—located near Mocuba (16,84S; 36,99E)—and averaged for the period of 1961–1990. Daily averages were then temporally downscaled using a random cascade approach (Over & Gupta, 1994, 1996), as in Bocchiola and Rosso (2006) and Groppelli, Bocchiola, and Rosso (2010). The cascade model for the downscaling of precipitation was set using hourly data from the Chitengo rainfall station (Ryan, 2009) about 350 km south of the Licungo basin, verifying that disaggregated information preserved the total mass of precipitation, the mean, the variance, the maximum hourly rainfall value, and the number of wet and dry days. This information was then used to develop IDF curves, following a Gumbel distribution for hourly extremes for six different return periods (5, 10, 20, 50,100, and 200 years; see Figure 2). IDF curves for the studied basin were assessed as:

$$i = a_T d^{(n-1)} \quad (7)$$

Where: the rainfall intensity *i* is in mm h^{-1}, the duration *d* is expressed in h and the parameter *a*(*T*) and *n* are reported in Table 1. Our results agree well with the IDF curves reported in Decreto Ministeriales 30/2003 for public construction for Mozambique, having a difference of about 32%, 15%, and 0.9% for the 10, 30, and 100 min events respectively with a 10 years' return interval. We developed a model to map the potential instable areas under a spectrum of different storm characteristics (six return periods and nine durations) and under feasible scenarios of forest loss, and we compare our results with historical events that occurred in the regions.

2.5 | Scenarios of forest loss

To examine the effects of forest loss on slope stability, we altered the value of cohesion c' in Equation (1), which was defined as the sum of terrain cohesion—setting soil cohesion equal to 0 kPa for each soil type as safety factor (Lu & Godt, 2008; Rosso et al., 2006)—and the cohesion provided by plant roots (Chok, Jaksa, Kaggwa, & Griffiths, 2015; Schmidt et al., 2001). Because Chafuta forest is the dominant forest composition in the northern part of Mozambique (i.e., north of the Zambesi River), we assigned the root cohesion value for these types of forests (15 kPa) to all forested cells (Cislaghi, Chiaradia, & Bischetti, 2017; Schmidt et al., 2001).

In altering these values of root cohesion, we then examined selected scenarios aimed at evaluating the effects of forest cover and forest loss on slope stability assuming complete forest removal. For

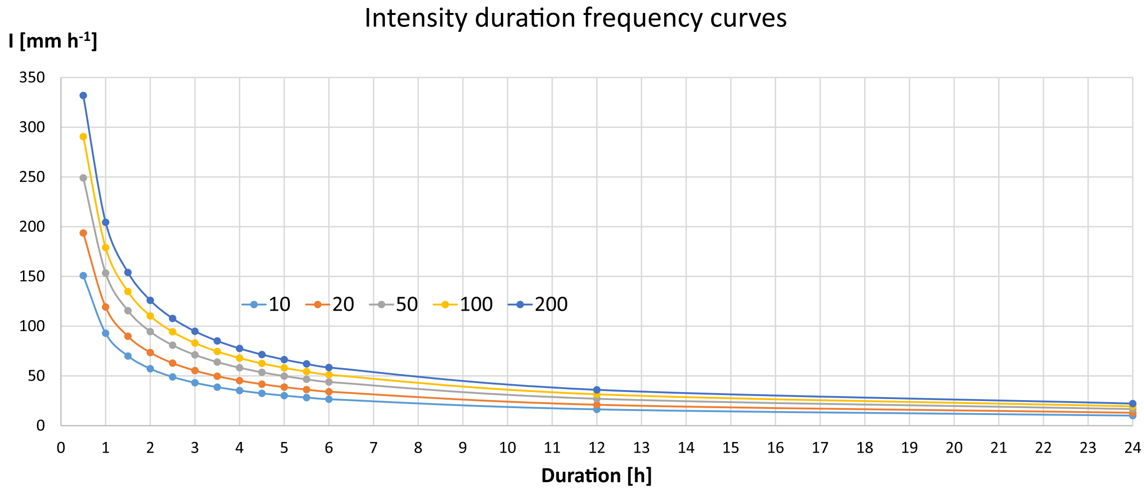

FIGURE 2 Intensity duration frequency curves for Licungo basin in Zambezia [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Parameters for intensity duration frequency curves for five different return period using a Gumbel distribution of hourly extreme

Return period (T)	5	10	20	50	100	200
n	0.30	0.30	0.30	0.30	0.30	0.30
a (T)	83.2	92.9	119.3	153.4	179.0	204.4

the *first* scenario (Case 1), we defined forested pixels as any grid cells with an initial (year 2000) percent tree cover greater than 50% (Hansen et al., 2013) and assigned a root cohesion value of 15 kPa to these pixels, following Schmidt et al. (2001). All other cells within the province were assigned a root cohesion value of 0 kPa. For the *second* scenario (Case 2), we then considered how cumulative forest loss from the years 2000–2014 impacted slope stability by assigning a root cohesion value of 0 kPa to deforested grid cells. For the *third* scenario (Case 3), we evaluated the potential impact on slope stability that could be caused by future deforestation occurring specifically within LSLAs assuming that all grid cells within LSLAs undergo forest loss and therefore have a root cohesion value of 0 kPa. Finally, for the *fourth* scenario (Case 4), we followed the same method for Case 3 considering deforestation within all areas under government concessions known as DUATs (Figure 3).

In this analysis of deforestation scenarios, we assume complete forest loss and no additional cohesion provided by remaining forest roots. This assumption is only weakly sensitive to the choice of root cohesion values, as we found that only limited variations (i.e., less than 10% in the extent of unstable areas) occurred if root cohesion is halved. Regarding land cover, our analysis only differentiates between forest and nonforest areas. Thus all nonforest land cover types are assigned the same cohesion values, while soil cover is indirectly accounted for in the soil depth parameter (i.e., differentiating between rock top soil or layer of vegetated soil). Urban areas cover only a negligible portion of soil and in the majority of cases are located far from unstable areas. We did not consider any local infrastructure (i.e., drainage system, terracing) made to prevent local instability (Rulli, Offeddu, & Santini, 2013) nor streets and road infrastructures to access plantations (Singh, Umrao, & Singh, 2014) or forests fire (Rosso, Bocchiola, & Rulli, 2007) that may further aggravate local instability, as our analysis was at the basin scale. Lastly, while some of the soil parameters were estimated in terms of average values without accounting for their spatial variability, we acknowledge that variability in soil parameters can strongly affect slope stability. Indeed, even a modest change in the internal friction angle (e.g., 5°) can have a large impact on slope stability (i.e., up to 50%).

2.6 | Impacts on food supply

When mass wasting occurs within croplands, the area suitable for cultivation is reduced, with potential indirect effects for the food supply of local populations. Such an occurrence can be especially impactful in a place like Mozambique where so much of the population relies directly on the land for their nutrition and livelihoods. To this end, we assess the reduction in calorie supply as a result of deforestation and subsequent soil instability within LSLAs. Agricultural information and regional crop yields for Zambezia were taken from a Food and Agriculture Organization of the United Nations (FAO) country report (FAO, 2000; 2010), while information on average per capita food supply and malnourishment data came from the FAO's FAOSTAT database (Faostat, 2017). To assess the potential loss in crop production, we examined whether landslides and mass movement occurred within current croplands. To do so, we overlapped a 30 m cropland map (Xiong et al., 2017) with our results on soil instability. We then used the metric of maize equivalent [i.e., all areas have been harvested with maize, considering local yield equal to 1.19 t ha^{-1} and a caloric

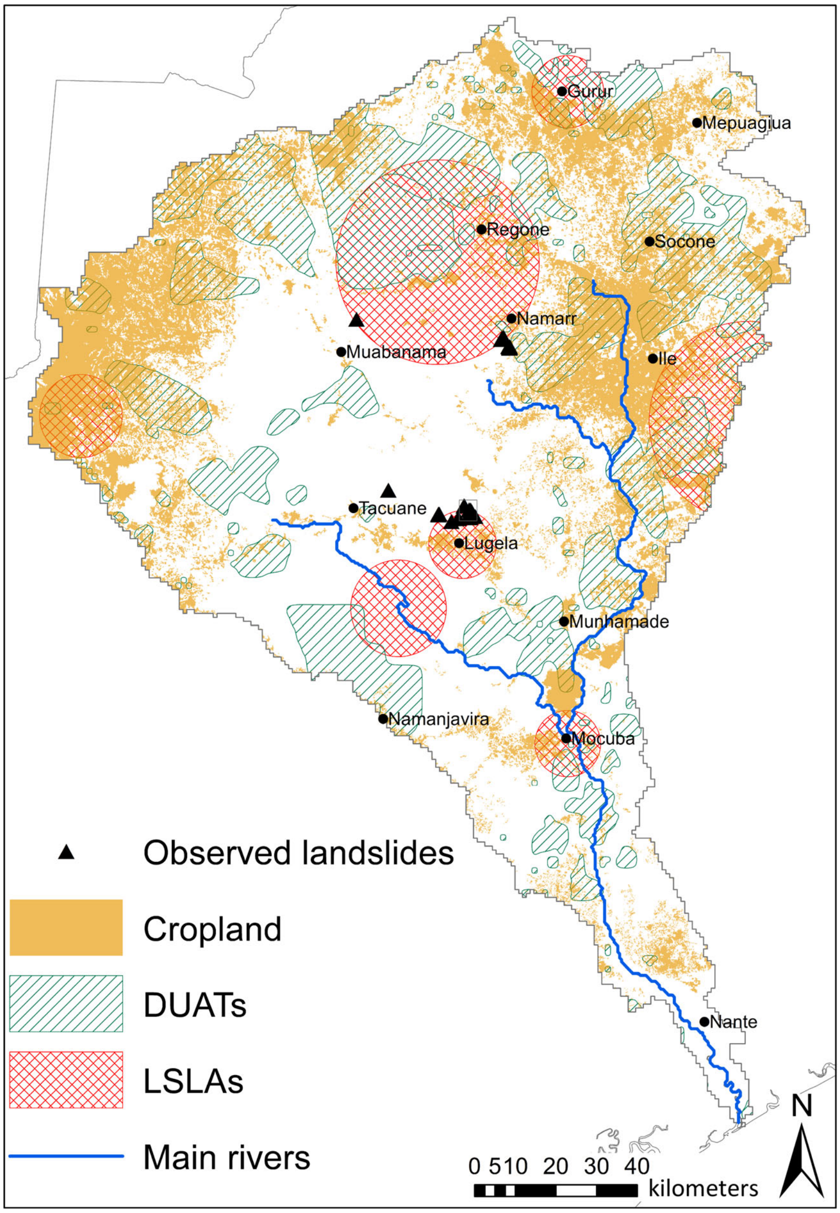

FIGURE 3 DUATs, LSLAs, and cropland in Licungo River basin. The black triangles represent observed landslides (Broeckx et al., 2018) [Colour figure can be viewed at wileyonlinelibrary.com]

content of maize of 356 kcal per 100 g of crop (D'Odorico et al, 2014a, 2014b)]. Specifically, to evaluate the indirect impacts of LSLA on local population food supply, we considered the loss of crop production in cells outside of LSLA boundaries but destabilized by changing conditions within the LSLA. The number of inhabitants for the studied areas was derived from Worldpop data (Linard, Gilbert, Snow, Noor, & Tatem, 2012).

3 | RESULTS

3.1 | Slope stability in the year 2000—Case 1

Zambezia is the most forested province in Mozambique with nearly half of its area (more than 6.5 Mha, Hansen et al., 2013) covered by forests. In the year 2000, forests covered 38% of the Licungo river basin. Under a 30-min rainfall event with a 100-year return period, we estimate that 12,475 ha (0.5% of Licungo basin) and 20,446 ha (0.7% of Licungo Basin) would become potentially unstable for internal friction angles of 40° and 35°, respectively (Table 2). This excludes unconditionally unstable areas that account for 13,787 and 20,226 ha, respectively. These unstable areas are mainly located in the mountainous northern section of the basin, and nearly all of these pixels are characterized by slope angles between 30° and 40°.

3.2 | Slope stability in the year 2014—Case 2

From 2001 to 2014, 2.5 Mha of forests were lost in Mozambique, with almost 30% of that loss occurring in Zambezia (Hansen et al., 2013). In

TABLE 2 Unstable areas under storm of nine different durations and six return periods for internal friction angle of 35° and 40°

Slope stability		Unstable area [ha]								
Friction angle = 40°		*Duration*								
Return period (years)		*30 min*	*60 min*	*90 min*	*120 min*	*150 min*	*180 min*	*360 min*	*720 min*	*1,440 min*
Case 1	5	7,368	8,165	8,758	9,249	10,081	10,791	12,026	14,909	19,395
	10	7,767	8,721	9,433	10,048	11,091	12,010	13,579	17,362	23,363
	20	8,966	10,426	11,589	12,630	14,390	15,945	18,756	25,654	32,974
	50	10,801	13,235	15,190	16,959	20,147	22,988	27,780	33,834	34,492
	100	12,475	15,798	18,618	21,171	25,623	29,187	33,060	34,475	34,494
	200	14,377	18,879	22,717	26,064	30,976	33,277	34,356	34,494	34,494
Case 2	5	7,507	8,328	8,938	9,444	10,305	11,038	12,316	15,317	20,031
	10	7,918	8,899	9,634	10,271	11,348	12,300	13,928	17,888	24,239
	20	9,151	10,661	11,864	12,942	14,773	16,400	19,356	26,685	34,705
	50	11,049	13,571	15,609	17,464	20,822	23,839	28,972	35,710	36,606
	100	12,783	16,246	19,209	21,905	26,652	30,496	34,802	36,574	36,608
	200	14,760	19,485	23,549	27,123	32,457	35,054	36,380	36,608	36,608
Case 3	5	8,419	9,394	10,126	10,729	11,756	12,640	14,182	17,824	23,554
	10	8,908	10,079	10,958	11,715	13,016	14,163	16,131	20,948	28,711
	20	10,377	12,182	13,638	14,938	17,157	19,141	22,727	31,706	42,152
	50	12,653	15,695	18,175	20,429	24,521	28,214	34,549	43,677	45,084
	100	14,744	18,953	22,547	25,849	31,663	36,484	42,291	45,032	45,090
	200	17,141	22,884	27,863	32,243	39,028	42,665	44,722	45,090	45,090
Case 4	5	8,312	9,286	10,018	10,623	11,666	12,559	14,115	17,803	23,651
	10	8,799	9,970	10,853	11,623	12,936	14,095	16,092	20,987	28,930
	20	10,272	12,097	13,566	14,877	17,132	19,148	22,802	32,047	42,933
	50	12,572	15,650	18,162	20,458	24,634	28,417	35,000	44,560	46,238
	100	14,683	18,956	22,619	25,985	32,000	37,009	43,078	46,175	46,240
	200	17,117	22,962	28,047	32,600	39,660	43,479	45,791	46,240	46,240
Friction angle = 35°		*30 min*	*60 min*	*90 min*	*120 min*	*150 min*	*180 min*	*360 min*	*720 min*	*1,440 min*
Case 1	5	12,825	14,049	14,954	15,706	16,965	18,021	19,810	23,907	30,140
	10	13,435	14,891	15,981	16,909	18,456	19,782	22,018	27,337	35,468
	20	15,263	17,478	19,202	20,657	23,169	25,383	29,254	38,481	47,867
	50	18,035	21,518	24,301	26,783	31,147	34,964	41,236	49,004	49,802
	100	20,447	25,165	29,067	32,531	38,437	43,018	47,977	49,786	49,803
	200	23,153	29,414	34,610	39,002	45,299	48,270	49,653	49,803	49,803
Case 2	5	13,161	14,438	15,388	16,177	17,501	18,616	20,511	24,877	31,560
	10	13,796	15,322	16,465	17,442	19,077	20,482	22,858	28,547	37,316
	20	15,715	18,041	19,866	21,410	24,088	26,454	30,606	40,592	51,078
	50	18,630	22,328	25,300	27,951	32,641	36,769	43,609	52,434	53,576
	100	21,187	26,221	30,403	34,134	40,543	45,575	51,206	53,540	53,578
	200	24,070	30,778	36,383	41,162	48,122	51,551	53,303	53,578	53,578
Case 3	5	15,309	16,877	18,044	19,023	20,649	22,018	24,357	29,723	37,866
	10	16,090	17,963	19,382	20,577	22,590	24,322	27,250	34,194	44,860
	20	18,448	21,311	23,560	25,468	28,754	31,643	36,708	48,842	62,176
	50	22,036	26,600	30,236	33,465	39,179	44,187	52,540	64,131	65,889
	100	25,196	31,357	36,459	40,990	48,782	54,988	62,349	65,828	65,894
	200	28,734	36,914	43,716	49,534	58,227	62,829	65,456	65,894	65,894

(Continues)

TABLE 2 (Continued)

Slope stability		Unstable area [ha]								
Case 4	5	15,277	16,874	18,062	19,055	20,722	22,119	24,506	30,054	38,512
	10	16,069	17,978	19,420	20,648	22,703	24,470	27,482	34,706	45,788
	20	18,472	21,397	23,695	25,644	29,043	32,042	37,306	49,933	63,933
	50	22,137	26,800	30,585	33,940	39,865	45,079	53,788	66,002	68,083
	100	25,359	31,745	37,049	41,741	49,869	56,369	64,112	68,008	68,086
	200	29,020	37,519	44,588	50,654	59,759	64,628	67,526	68,086	68,086

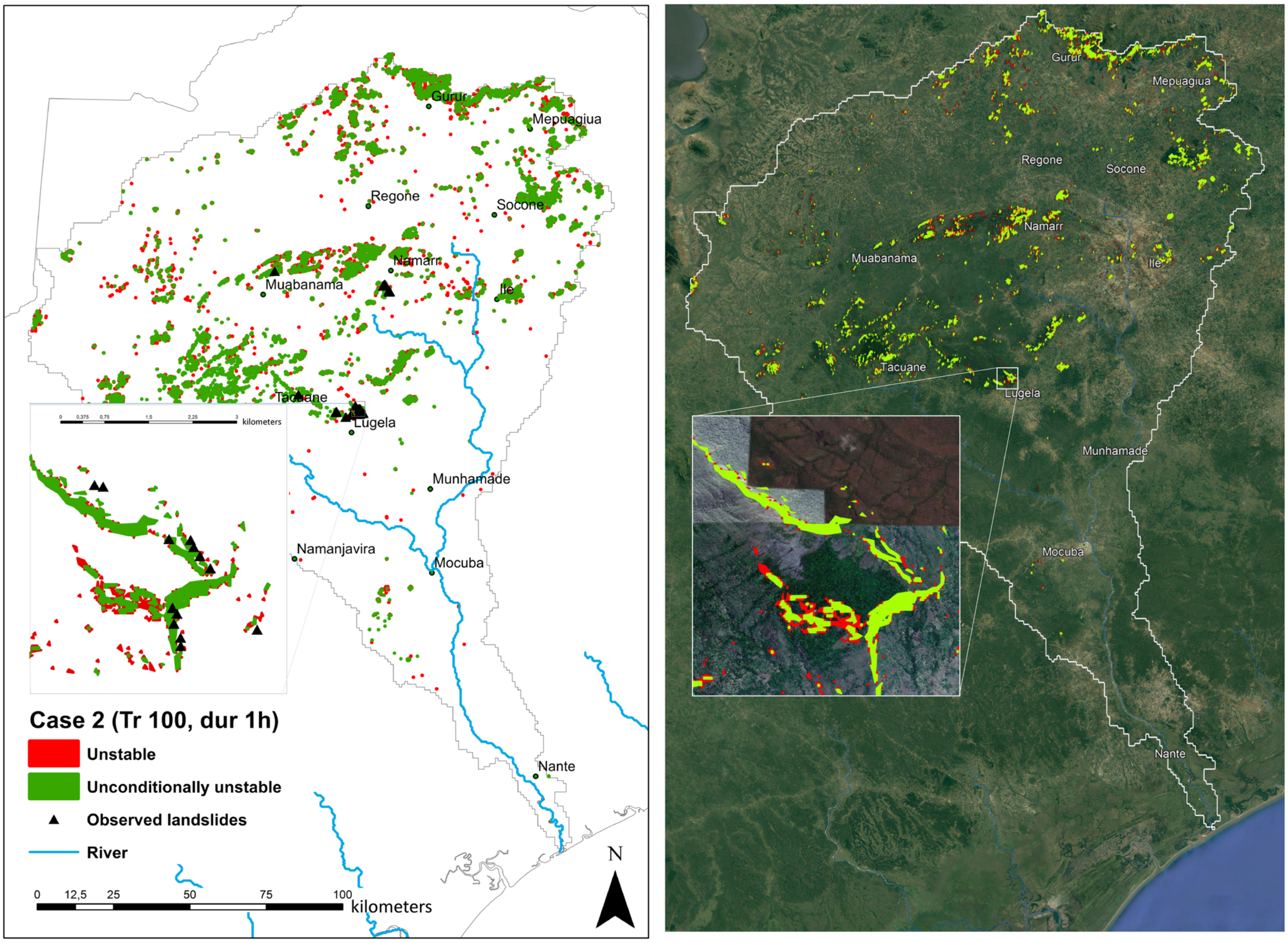

FIGURE 4 Observed landslides (Broeckx et al., 2018) versus predicted unstable areas for Case 2. The zoom is focused on a particularly unstable area north to Lugela Village [Colour figure can be viewed at wileyonlinelibrary.com]

Zambezia province, deforestation occurred mainly in high altitude areas but was broadly distributed across the province, suggesting increased fragmentation of natural forest habitats and enhanced potential for slope instability. The Licungo River valley was affected by deforestation as well, with the clearing of 159,520 ha (or 18.5%) of forests relative to the year 2000. This substantial forest loss decreased root cohesion across the basin, where we registered a 1.9–7.6% increase in the potential instability for different rainfall durations and friction angles. The vast majority of these vulnerable pixels were again characterized by slope angles between 30° and 40° (Table 2).

3.3 | Validation of current slope stability—Case 2

To validate our study, we also compared the results from Case 2 with observed landslides mapped using a Google Earth map analysis (Broeckx et al., 2018) and found good overall agreement. Landslides were observed in two main areas, one in the north near Lugela (Figure 4, inset) and the other in the western part of the study province near Gurue, where our model predicts the occurrence of landslides. Specifically, out of 31 landslides identified by Broeckx et al. (2018), 11 fall inside unstable areas predicted by our model, and another

18 are within 500 m of our predicted areas (Figure 4). Further, we checked our unstable areas in Google Earth Pro, considering satellite images during different periods. Comparison are reported in Figure S1.

3.4 | Slope stability under complete forest clearing within LSLAs—Case 3

Agricultural expansion for crop production and pastureland is a major driver of forest clearing in Mozambique. We estimate that since the start of the century about 25% of the country's forest loss occurred for pastureland expansion [as calculated by overlapping maps of forest loss (Hansen et al., 2013) with pastureland maps for the year 2015 (Xiong et al., 2017)]. The planned expansion of agricultural areas within the Province is split between DUATs (i.e., Government concessions for agriculture that account for 1.74 Mha of land in Zambezia Province and 0.63 Mha in the Licungo River basin) and LSLAs (i.e., foreign and foreign-domestic investments that cover approximately 0.51 Mha in the Province, Land Matrix, 2019). Of these LSLA areas, 74% are contained within the Licungo River basin (377,020 ha), one of the basins most targeted by foreign investments. While DUATs are mainly located in flat areas, in the studied area, 5% of contracted LSLA areas occur in areas with an elevation higher than 1,000 above s.l., and 15,080 ha have a slope greater than 30°. Currently, only 11,143 ha of LSLAs in Licungo River are actively under production, while an additional 517,000 ha are intended for further investments in the basin out of 540,000 ha total in the Zambezia Province (Land Matrix, 2019). Of the total contracted areas in the Licungo basin, 26.4% (or 134,000 ha) were forested in the year 2000, and approximately 15,000 ha have experienced forest loss to date. If all of these LSLA areas within the Licungo were put to productive use, this would likely mean substantial and rapid changes in land cover, with important consequences for soil stability. From 2000 to 2014, 16.9% of forests lost within the Licungo basin occurred inside LSLA buffer areas, with the potential to reach 43.7% if all forests within contracted LSLA areas were cleared. Under this scenario, the area of potentially unstable slopes (under a 3-hr storm with 20-year return period and 40° angle of internal friction) would increase by 20.0% (from 15,945 to 19,141 ha) relative to year 2000 slope instability (i.e., Case 1; Table 2 and Figure S1 and Figure S2).

3.5 | Slope stability under complete forest clearing within DUATs—Case 4

There is no private ownership of land in Mozambique. Land and its associated resources are the property of the State. The Land Law, however, grants private persons the right to use and benefit from the land known as Direito do Uso e Aproveitamento da Terra (DUAT). In the Licungo basin, DUATs occupy approximately 0.63 Mha, with about 25% of the basin's current croplands (Tachikawa et al., 2011b) falling within DUATs. By comparison, 33% of the basin's croplands fall within LSLA buffer areas (Figure 5). Thus, there is no evidence that acquired land is also registered as a land government concessions (DUATs), even if some of the reported coordinates by Land Matrix correspond to some of the government concessions. In our analysis, we simulated the scenario in which all government concessions (DUATs) are cleared of forests and put under production, estimating an average difference (for all durations and return times) in the size of unstable areas lower than 5% compared to the instability consequent to clearing of Land Matrix buffer areas (Figure 5 and Table 2).

3.6 | Effects of landslides on food supply

The current average diet in Mozambique consists of 2,282 kcal cap^{-1} d^{-1}, a value lower than the recommend intake of 2,400 kcal cap^{-1} d^{-1} (Faostat, 2017). Cassava contributes 30% of daily average intake, followed by maize (19%), rice (10%), and wheat (5%) (Faostat, 2017). With crop production from Zambezia's harvested areas, it is possible to locally meet around 90% of the calorie requirements of the average diet in Mozambique.

Because land investments can often exclude informal land users from cultivating the land and because the crops produced within land investments are often shipped elsewhere and made unavailable to local communities, we first evaluated how LSLAs may impact the average diets of people living within the Licungo River basin. Using the metric of maize equivalent, we estimate that, should all LSLAs be put under production and their crops be unavailable to local communities, the local food supply would decrease by 740 kcal cap^{-1} d^{-1}, which corresponds to 32.4% drop with respect to the current per capita calorie intake in Mozambique. In addition to this exclusion from the use of fertile land and consumption of its products, the removal of forests within LSLAs (and the resultant increased likelihood of landslide occurrence) could affect nearby (downhill) areas and negatively impact their productivity. Under these potential indirect impacts to adjacent cropland, we estimate that 4,000 people could lose approximately 700 kcal cap^{-1} d^{-1} of crop production. Thus, the direct and indirect effects of LSLAs can be quantified as the sum of direct losses due to the acquisition of roughly 88,000 ha of current harvested cropland and the potential loss in production in downhill croplands as a result of land use change (i.e., deforestation) within LSLAs and downhill propagation of landslides. Similar impacts on food supply due to landsliding can be expected to result from forest clearing within DUATs.

4 | DISCUSSION

Mozambique's economy relies heavily on agriculture, with over two-thirds of its population living in rural areas and practicing subsistence farming (INE, 2011; Benfica & Tschirley, 2012). Because of the country's vast arable land and high crop yield gaps, there is a large potential to enhance human development in Mozambique through investments that improve the agricultural sector and that support rural livelihoods (Deininger & Byerlee, 2011). Along these lines, the mandate of the short-lived Agriculture Promotion Centre (CEPAGRI) was to facilitate large-scale foreign investment in the country's agricultural sector.

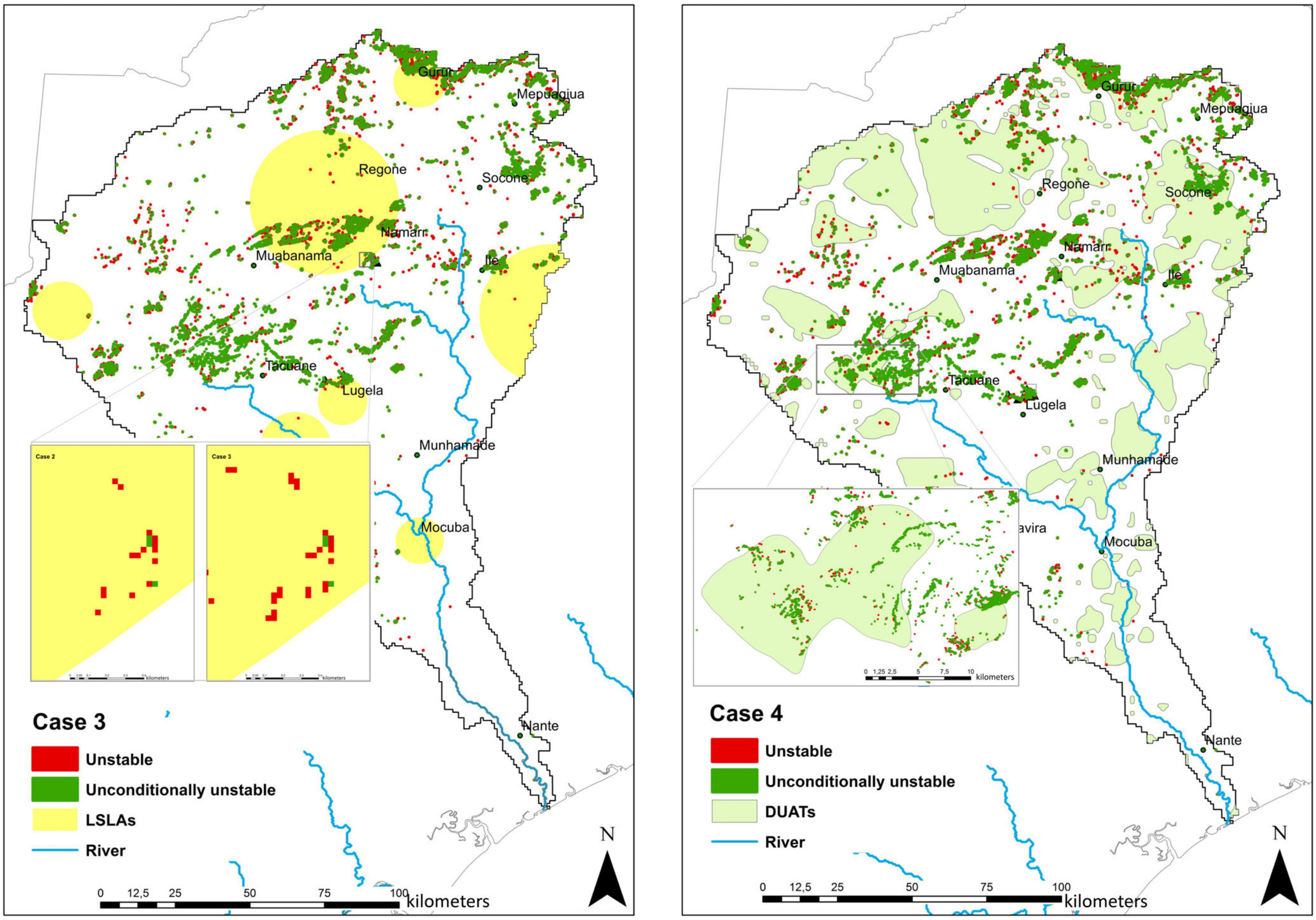

FIGURE 5 Slope instability considering clearing of forest within LSLA (Case 3—on the left) and DUATs (on the right) for an event duration of 1 hr with a return time of 100 years and a friction angle of 40° [Colour figure can be viewed at wileyonlinelibrary.com]

While the CEPAGRI closed in 2016, LSLAs still occur widely across Mozambique and in Zambezia Province in particular (Land Matrix, 2019), with the majority of the more than 100 land deals that occurred after the year 2007 still in effect. While previous work has focused on the direct impacts of LSLAs on natural resources, water security, and food supply (Rulli & D'Odorico, 2013; Rulli & D'Odorico, 2014; Rulli, Offeddu, & Santini, 2013; Rulli, Passera, Chiarelli, & D'Odorico, 2018; Rulli, Saviori, & D'Odorico, 2013), our work examines another important environmental consideration for LSLAs—mass wasting as a result of rapid land use change and forest loss. Currently, only 3% of contracted LSLA areas are under production in Mozambique (Land Matrix, 2019), and it is uncertain whether all contracted areas will ultimately be cleared. However, because these investments are intended for agricultural use, there is a high likelihood of land clearing. For instance, forest loss between the years 2000 and 2014 has increased the area of potentially unstable slopes up to 10% (i.e., the difference in the extent of slope instability between Case 1 and Case 2). By comparison, this difference grows to about 30% if all forests within LSLAs were to be cleared for agriculture (Table 2). Similar impacts are expected within DUATs.

Clearly, even if it is unlikely that landslides will happen concurrently across the entire potentially unstable area as reported in our work, mass movements create an irreversible loss of fertile soil, with the potential to ultimately impact food supply (Pimentel, 2006; Pimentel & Burgess, 2013). Thus, the direct effect on food supply via crop losses would likely be minor for any single landslide event. However, the cumulative effect of multiple mass wasting events occurring within croplands could mean that a substantial portion of cultivatable area is rendered unusable due to long-term losses of fertile soil so impacting the resilience of the food system (Seekell et al., 2017) . Indeed, the study area frequently experiences extreme events such as storms and cyclones and is regularly subjected to flooding (Stal, 2011). We also note that the use of calories as a metric of food supply is only one aspect of the nutritional adequacy of crop production and diets. However, governments will typically prioritize addressing deficiencies in calorie supply before contending with challenges related to micronutrient deficiencies. Certainly, there remains a great need for analyses that examine multiple vitamins and minerals in assessing the impacts of land investments on the nutritional status of local communities, but this is beyond the scope of our study.

Our analysis on large-scale land acquisition has been based on Land Matrix data (Land Matrix, 2019). Land deals are notorious for their lack of transparency, and negotiations are not always public. Therefore, datasets on large-scale land acquisitions could be affected by biases (e.g., cancellations, new acquisitions, etc.) that are difficult to track. In our analysis, we consider land acquisitions reported by Land Matrix in June 2019, including all *concluded deals* recorded within the Licungo basin, even if some of these investments may be purely speculative and never see actual land development, while others have yet to be put to productive use (Zoomers and Quak, 2013). Further, our analysis is based on the most updated and spatially distributed detailed information available to our knowledge. Specifically, soil properties have a resolution of 250 m, while all the other information regarding land cover are at approximatively 30 m resolution. All datasets have been accurately validated (Hansen et al., 2013; Hengl et al., 2017; Tachikawa et al., 2011a), thus we are confident in using such information while recognizing that field campaigns and in situ data monitoring could improve our analysis.

While landslides represent a complete degradation of fertile soils, the widespread conversion of forests to croplands will induce much larger areas to experience land and soil degradation. Indeed, soil erosion and land degradation are persistent issues affecting this province, with one study estimating fertile soil losses of approximately 25 t ha^{-1} yr^{-1} (Folmer, Geurts, & Francisco, 1998). Soil erosion is particularly notable on cassava and maize fields, which occur widely across the Licungo basin and where soil nutrient deficit represents another limit to crop yield increases (Maria & Yost, 2006). Overall our results are conservative in terms of potential fertile soil loss because of both the potential for downhill landslide propagation and the fact that we did not account for other mechanisms of erosion (e.g., from rain-splashing, rilling, or overland flow) that are not associated with mass wasting (Folmer et al., 1998). Indeed, after the conversion of forested areas into agricultural fields, an increase in soil erosion is expected to occur as a result of the direct exposure of the land surface to rain and runoff (Mohammad & Adam, 2010; Mohr, Coppus, Iroumé, Huber, & Bronstert, 2013; Montgomery, 2007).

It has been estimated that approximately four-fifths of the population of Zambezia produces enough food for domestic consumption with limited or no access to markets. In addition, 81% of rural residents are not connected to reliable all-weather road networks (Baez & Olinto, 2016), which prevent reliable access to trade and food imports from other regions. Therefore, the local impacts of landslides or soil degradation on food production are likely to adversely impact local food supply. Limited access to markets is also reflected in the fact that—although Zambezia is one of the most productive provinces in Mozambique—it has persistent and high rates of poverty (poverty rate of 70%; the highest in the country; Benfica & Tschirley, 2012; Baez & Olinto, 2016). This also means that in this province, there is great potential to enhance crop yields and to complement this with efforts to improve market access and connectivity both locally and internationally (Benfica & Tschirley, 2012).

5 | CONCLUSIONS

Our study highlights the connections between land investments for agriculture, their potential consequences for mass wasting and soil degradation, and ultimately their potential direct and indirect impacts on local food availability. We also showed how smallholder farmers living adjacent to LSLAs may see enhanced soil instability as a result of land conversion within adjoining land deals. Specifically, we have shown how deforestation for agricultural purposes has the potential to increase susceptibility to landslide and local instability by about 20% compared to the current (i.e., Case 2) land cover scenario, which corresponds to approximatively 2,000 ha for a 30 min rainfall event with a return period of 100 years and a friction angle of 40°. Further, we have assessed how the loss of fertile soil may directly and indirectly impact food security, estimating that 4,000 people could lose approximately 700 kcal cap^{-1} d^{-1} if all LSLAs are put under production.

A better knowledge of the potential effects of land use change is urgently needed to better prepare the area against extreme events (Rosso and Rulli, 2002). To this end, our work investigates the effects of massive deforestation in the Licungo River basin and identifies those areas where such land conversions enhance the likelihood of sudden and catastrophic mass wasting. By better understanding the consequences of such actions taken by land investors, our results provide important information for decision-makers, private companies, and farmers to be more selective and cautious in where and how land investments are granted and implemented. By knowing the potential instability of specific areas, it is possible to investigate a suite of mitigation solutions and to be proactive in addressing such vulnerabilities. More broadly, our results point to an important potential consequence of large-scale land acquisitions that could occur in other African countries and that requires better understanding in those specific contexts. By more fully understanding the suite of social, economic, and environmental benefits and impacts of promoting land investments, governments can make more informed decisions about whether such a development mechanism truly helps to improve the well-being of their people and whether the trade-offs will be acceptable.

In conclusion, forests are known to play a crucial role in contributing to hillslope stability and preventing landsliding and mass wasting. Recent work has highlighted how large-scale acquisitions of forested land is often followed by rapid deforestation and landscape denudation (Davis et al., 2020; Davis, Yu, et al., 2015). This study demonstrates the linkages between LSLAs, slope instability, and knock-on environmental and societal impacts. Governments should therefore take such impacts into account (in addition to those related to habitat destruction and carbon emissions) when issuing permits and concessions within forested lands.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

Baez, J. E., & Olinto, P. (2016). *Accelerating poverty reduction in Mozambique: Challenges and opportunities*. World Bank Group, Washington DC, United States. Retrieved from http://www.worldbank.org/en/country/mozambique/publication/accelerating-poverty-reduction-in-mozambique-challenges-and-opportunities

Benfica, R., & Tschirley, D. (2012). The dynamics of agricultural market participation and performance in Central and Northern Mozambique: Evidence from a panel survey. Ministry of Agriculture, Directorate of Economics Flash, (61E). Retrieved from https://ageconsearch.umn.edu/bitstream/176722/2/RP76E.pdf

Bocchiola, D., & Rosso, R. (2006). The use of scale recursive estimation for short term quantitative precipitation forecast. *Physics and Chemistry of the Earth, Parts A/B/C*, *31*(18), 1228–1239. https://doi.org/10.1016/j.pce.2006.03.019

Borras, S. M., Jr., Hall, R., Scoones, I., White, B., & Wolford, W. (2011). Towards a better understanding of global land grabbing: An editorial introduction. *The Journal of Peasant Studies*, *38*(2), 209–216. https://doi.org/10.1080/03066150.2011.559005

Broeckx, J., Vanmaercke, M., Duchateau, R., & Poesen, J. (2018). A data-based landslide susceptibility map of Africa. *Earth-Science Reviews.*, *185*, 102–121. https://doi.org/10.1016/j.earscirev.2018.05.002

Chiarelli, D. D., Davis, K. F., Rulli, M. C., & D'Odorico, P. (2016). Climate change and large-scale land acquisitions in Africa: Quantifying the future impact on acquired water resources. *Advances in Water Resources.*, *94*, 231–237. https://doi.org/10.1016/j.advwatres.2016.05.016

Chok, Y. H., Jaksa, M. B., Kaggwa, W. S., & Griffiths, D. V. (2015). Assessing the influence of root reinforcement on slope stability by finite elements. *International Journal of Geo-Engineering*, *6*(1), 12. https://doi.org/10.1186/s40703-015-0012-5

Cislaghi, A., Chiaradia, E. A., & Bischetti, G. B. (2017). Including root reinforcement variability in a probabilistic 3D stability model. *Earth Surface Processes and Landforms*, *42*(12), 1789–1806. https://doi.org/10.1002/esp.4127

Davis, K. F., Rulli, M. C., & D'Odorico, P. (2015). The global land rush and climate change. *Earth's Future*, *3*, 298–311. https://doi.org/10.1002/2014EF000281

Davis, K. F., Yu, K., Rulli, M. C., Pichdara, L., & D'Odorico, P. (2015). Accelerated deforestation driven by large-scale land acquisitions in Cambodia. *Nature Geoscience*, *8*(10), 772–775. https://doi.org/10.1038/ngeo2540

Davis, K. F., Rulli, M. C., Garrassino, F., Chiarelli, D., Seveso, A., & D'Odorico, P. (2017). Water limits to closing yield gaps. *Advances in Water Resources*, *99*, 67–75. https://doi.org/10.1016/j.advwatres.2016.11.015

Davis, K. F., Koo, H. I., Dell'Angelo, J., D'Odorico, P., Estes, L., Kehoe, L. J., … Ribeiro, N. (2020). Tropical forest loss enhanced by large-scale land acquisitions. *Nature Geoscience*, *13*(7), 482–488. https://doi.org/10.1038/s41561-020-0592-3

Deininger, K., & Byerlee, D. (2011). The rise of large farms in land abundant countries: Do they have a future?. Washington, DC: World Bank Group. https://doi.org/10.1596/1813-9450-5588

Dell'Angelo, J., D'Odorico, P., Rulli, M. C., & Marchand, P. (2017). The tragedy of the grabbed commons: Coercion and dispossession in the global land rush. *World Development*, *92*, 1–12. https://doi.org/10.1016/j.worlddev.2016.11.005

D'Odorico, P., Carr, J. A., Laio, F., Ridolfi, L., & Vandoni, S. (2014a). Feeding humanity through global food trade. *Earth's Future*, *2*(9), 458–469. https://doi.org/10.1002/2014EF000250

D'Odorico, P., Carr, J. A., Laio, F., Ridolfi, L., & Vandoni, S. (2014b). Feeding hu-manity through global food trade. *Earth's Future*, *2*(9), 458–469. https://doi.org/10.1002/2014EF000250

D'Odorico, P., Davis, K. F., Rosa, L., Carr, J. A., Chiarelli, D., Dell'Angelo, J., … Rulli, M. C. (2018). The global food-energy-water nexus. *Reviews of Geophysics*, *56*(3), 456–531. https://doi.org/10.1029/2017RG000591

D'Odorico, P., Rulli, M. C., Dell'Angelo, J., & Davis, K. F. (2017). New frontiers of land and water commodification: Socio-environmental controversies of large-scale land acquisitions. *Land Degradation & Development*, *28*(7), 2234–2244. https://doi.org/10.1002/ldr.2750

Dutch Risk Reduction Team. (2015). DRR-team Mission report. Licungo Basin, Mozambique: Author. Retrieved from http://www.drrteam-dsswater.nl/wp-content/uploads/2015/06/DRR-report-Mozambique-Licungo-Final-Report-15-June-2015.pdf

FAO. (2017). FAOSTAT website. FAO Statistic Division. Retrieved from http://www.fao.org/faostat/en/

FAO Statistic Yearbook. (2010). Resources. Retrieved May 9, 2011. https://doi.org/10.1128/AAMCol.24Apr.2009

FAO/WFP. (2000). Crop and food supply assessment mission to Mozambique—May 31, 2000. Retrieved from http://www.fao.org/docrep/004/X7372e/X7372e00.htm

Folmer, E. C. R., Geurts, P. M. H., & Francisco, J. R. (1998). Assessment of soil fertility depletion in Mozambique. *Agriculture, Ecosystems & Environment*, *71*(1–3), 159–167. https://doi.org/10.1016/S0167-8809(98)00138-8

Franco, J. C. (2012). Global land grabbing and trajectories of agrarian change: A preliminary analysis. *Journal of Agrarian Change*, *12*(1), 34–59. https://doi.org/10.1111/j.1471-0366.2011.00339.x

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., … Michaelsen, J. (2015). The climate hazards infrared precipitation with stations—A new environmental record for monitoring extremes. *Scientific Data*, *2*, 150066. https://doi.org/10.15780/G2RP4Q

Groppelli, B., Bocchiola, D., & Rosso, R. (2010). Precipitation downscaling using random cascades: A case study in Italy. *Advances in Geosciences*, *26*, 39–44. https://doi.org/10.5194/adgeo-26-39-2010

Hanouz, M. D., Geiger, T., & Doherty, S. (2014). Global enabling trade report. In World Economic Forum, Geneva. Retrieved from http://www3.weforum.org/docs/WEF_GlobalEnablingTrade_Report_2014.pdf

Hansen, M. C., Potapov, P. V., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., … Kommareddy, A. (2013). High-resolution global maps of 21st-century forest cover change. *Science*, *342*(6160), 850–853. https://doi.org/10.1126/science.1244693

Hengl, T., Mendes de Jesus, J., Heuvelink, G. B. M., Ruiperez Gonzalez, M., Kilibarda, M., Blagotić, A., … Kempen, B. (2017). Soil grids 250 m: Global gridded soil information based on machine learning. *PLoS ONE*, *12*(2), e0169748. https://doi.org/10.1371/journal.pone.0169748

Hengl, T., Heuvelink, G. B., Kempen, B., Leenaars, J. G., Walsh, M. G., Shepherd, K. D., … Tondoh, J. E. (2015). Mapping soil properties of Africa at 250 m resolution: Random forests significantly improve current predictions. *PLoS ONE*, *10*(6), e0125814. https://doi.org/10.1371/journal.pone.0125814

INE Istituto Nacional de Estatistica - Mozambique (2011) Censo Agro Pecuario 2009-2010 Resultados Definitivos Mozambique.

International Food Policy Research Institute (IFPRI), & Datawheel. (2017). Retrieved from https://DataAfrica.io

Linard, C., Gilbert, M., Snow, R. W., Noor, A. M., & Tatem, A. J. (2012). Population distribution, settlement patterns and accessibility across Africa in 2010. *PLoS ONE*, *7*(2), e31743. https://doi.org/10.1371/journal.pone.0031743

Lu, N., & Godt, J. (2008). Infinite slope stability under steady unsaturated seepage conditions. *Water Resources Research*, *44*(11), 1–13. https://doi.org/10.1029/2008WR006976

Maria, R. M., & Yost, R. (2006). A survey of soil fertility status of four agro-ecological zones of Mozambique. *Soil Science*, *171*(11), 902–914. https://doi.org/10.1097/01.ss.0000228058.38581.de

Mohammad, A. G., & Adam, M. A. (2010). The impact of vegetative cover type on runoff and soil erosion under different land uses. *Catena*, *81*(2), 97–103. https://doi.org/10.1016/j.catena.2010.01.008

Mohr, C. H., Coppus, R., Iroumé, A., Huber, A., & Bronstert, A. (2013). Runoff generation and soil erosion processes after clear cutting. *Journal of Geophysical Research: Earth Surface*, *118*(2), 814–831. https://doi.org/10.1002/jgrf.20047

Montgomery, D. R. (2007). Soil erosion and agricultural sustainability. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(33), 13268–13272. https://doi.org/10.1073/pnas.0611508104

Nhantumbo, I., & Salomão, A. (2010). *Biofuels, land access and rural livelihoods in Mozambique*. London: IIED.

OECD/FAO. (2014). *Agricultural outlook 2014–2023: Biofuels*. Rome: OECD-FAO.

Over, T. M., & Gupta, V. K. (1994). Statistical analysis of mesoscale rainfall: Dependence of a random cascade generator on large-scale forcing. *Journal of Applied Meteorology*, *33*(12), 1526–1542. https://doi.org/10.1175/1520-0450(1994)033<1526:SAOMRD>2.0.CO;2

Over, T. M., & Gupta, V. K. (1996). A space-time theory of mesoscale rainfall using random cascades. *Journal of Geophysical Research: Atmospheres*, *101*(D21), 26319–26331. https://doi.org/10.1029/96JD02033

Pimentel, D. (2006). Soil erosion: A food and environmental threat. *Environment, Development and Sustainability*, *8*(1), 119–137. https://doi.org/10.1007/s10668-005-1262-8

Pimentel, D., & Burgess, M. (2013). Soil erosion threatens food production. *Agriculture*, *3*(3), 443–463. https://doi.org/10.3390/agriculture3030443

Rosso, R., & Rulli, M. C. (2002). An integrated simulation method for flash-flood risk assessment: 2. Effects of changes in land-use under a historical perspective. *Hydrology and Earth System Sciences*, *6*(2), 285–294. http://dx.doi.org/10.5194/hess-6-285-2002.

Rosso, R., Rulli, M. C., & Vannucchi, G. (2006). A physically based model for the hydrologic control on shallow landsliding. *Water Resources Research*, *42*(6), 1–16. https://doi.org/10.1029/2005WR004369

Rosso, R., Bocchiola, D., & Rulli, M. C. (2007). Transient catchment hydrology after wildfires in a Mediterranean basin: Runoff, sediment and woody debris. *Hydrology and Earth System Sciences*, *11*(1), 125–140. https://doi.org/10.5194/hess-11-125-2007

Rulli, M. C., Offeddu, L., & Santini, M. (2013). Modeling post-fire water erosion mitigation strategies. *Hydrology and Earth System Science, Vol.*, *17*(6), 2323–2337. https://doi.org/10.5194/hess-17-2323-2013

Rulli, M. C., & D'Odorico, P. (2014). Food appropriation through large scale land acquisitions. *Environmental Research Letters*, *9*(6), 064030. https://doi.org/10.1088/1748-9326/9/6/064030

Rulli, M. C., & D'Odorico, P. (2013). The water footprint of land grabbing. *Geophysical Research Letters*, *40*(23), 6130–6135. https://doi.org/10.1002/2013GL058281

Rulli, M. C., Passera, C., Chiarelli, D. D., & D'Odorico, P. (2018). Socio-environmental effects of large-scale land acquisition in Mozambique. In *Sustainable urban development and globalization* (pp. 377–389). Cham: Springer.

Rulli, M. C., Saviori, A., & D'Odorico, P. (2013). Global land and water grabbing. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(3), 892–897. https://doi.org/10.1073/pnas.1213163110

Ryan, C. (2009). Carbon cycling, fire and phenology in a tropical Savanna woodland in Nhambita, Mozambique. PhD thesis, University of Edinburgh, Edinburgh, 257 pp.

Seekell, D., Carr, J., Dell'Angelo, J., D'Odorico, P., Fader, M., Gephart, J., …, Tavoni, A. (2017). Resilience in the global food system. *Environmental Research Letters*, *12*(2), 025010. http://dx.doi.org/10.1088/1748-9326/aa5730.

Singh, R., Umrao, R. K., & Singh, T. N. (2014). Stability evaluation of road-cut slopes in the lesser Himalaya of Uttarakhand, India: Conventional and numerical approaches. *Bulletin of Engineering Geology and the Environment*, *73*(3), 845–857. https://doi.org/10.1007/s10064-013-0532-1

Schmidt, K. M., Roering, J. J., Stock, J. D., Dietrich, W. E., Montgomery, D. R., & Schaub, T. (2001). The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. *Canadian Geotechnical Journal*, *38*(5), 995–1024. https://doi.org/10.1139/t01-031

Stal, M. (2011). Flooding and relocation: The Zambezi River valley in Mozambique. *International Migration*, *49*(1), e125–e145. https://doi.org/10.1111/j.1468-2435.2010.00667.x

Suweis, S., Rinaldo, A., Maritan, A., & D'Odorico, P. (2013). Water-controlled wealth of nations. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(11), 4230–4233. https://doi.org/10.1073/pnas.1222452110

Tachikawa, T., Kaku, M., Iwasaki, A., Gesch, D. B., Oimoen, M. J., Zhang, Z., … Abrams, M. (2011a). ASTER global digital elevation model version 2-summary of validation results. *NASA*. *1*, 1–26. https://doi.org/10.1073/pnas.1222452110

Tachikawa, T., Kaku, M., Iwasaki, A., Gesch, D., Oimoen, M., Zhang, Z., … & Abrams, M. (2011b). ASTER Global Digital Elevation Model Version 2–Summary of Validation Results August 31, 2011. Retrieved from http://pubs.er.usgs.gov/publication/70005960

Terzaghi, K. (1950). Mechanism of landslides. Application of geology to engineering practice, *Geological Society of America*, 83–123.

Terzaghi, K., Peck, R. B., & Mesri, G. (1996). *Soil mechanics in engineering practice*. New York: John Wiley & Sons.

The Land Matrix Global Observatory. (2019). International Land Coalition (ILC), Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), Centre for Development and Environment (CDE), German Institute of Global and Area Studies (GIGA) and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). Web. Retrieved from https://landmatrix.org/en/

Xiong, J., Thenkabail, P. S., Tilton, J.C., Gumma, M. K., Teluguntla, P., Congalton, R. G., …, Massey, R. (2017). NASA making earth system data Records for use in research environments (MEaSUREs) global food security-support analysis data (GFSAD) @ 30-m Africa: Cropland extent product (GFSAD30AFCE). NASA EOSDIS Land Processes DAAC. Retrieved from https://doi.org/10.5067/MEaSUREs/GFSAD/GFSAD30AFCE.001

World Bank. (2016). Retrieved from https://www.tralac.org/news/article/11022-mozambique-report-discusses-poverty-trends-and-recommends-way-forward.html

Zoomers, A., & Quack, E. (2013). Untangling the myth of the global land rush. Land grabbing threatens food security and increases inequality. *The Broker*, *1*.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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