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AREA

Area, 2014, 46.1, 74–82, doi: 10.1111/area.12072

Land grabbing as a driver of environmental change

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Revised manuscript received 13 November 2013

A worldwide increase in large-scale land acquisitions over the past decade has been described as a global land rush for access to natural resources. 'Land grabbing' is a dynamic of land-use change that can enable especially rapid environmental transformations across vast spatial scales. New scholarship is beginning to address these land deals in terms of their implications for social and political systems, but exploitative land uses also leave legacies of change in physical landscapes. Historical precedents from around the world, including various examples of frontier expansion, reflect the kinds of environmental responses that modern land grabbing could induce. Insights into land grabbing as a mechanism of abrupt, large-scale transitions in human–environmental systems is a research opportunity and a pressing grand challenge for Earth-surface science.

Key words: *environmental history, agriculture, soil erosion, geomorphology, Anthropocene*

Introduction

In the past decade, investment in large-scale land assets has surged as a geopolitically complicated cast of transnational corporations, investment funds, government agencies and other buyers have negotiated or purchased long-term leases or outright title to farmland, savannas and forests across Asia, Africa and Latin America. Academic attention to 'land grabbing', the vernacular term for these acquisitions, has lagged that of activist groups, non-governmental organisations and investigative reporters (Borras and Franco 2012; Pearce 2012; Scoones *et al*. 2013). While a growing body of scholarship in the social sciences has begun to address in detail the human dimensions of land grabbing (Borras *et al*. 2011 2012; Margulis *et al*. 2013; Scoones *et al*. 2013; Wolford *et al*. 2013), related environmental implications have received little examination to date from researchers in the physical sciences.

This paper draws on Earth-surface science perspectives of anthropic environmental transitions to motivate new research that will engage the coupled human and physical dynamics of land grabbing. Even in the wider context of human activities that are changing the surface of the Earth in unprecedented ways (Vitousek *et al*. 1997; Hooke 1994 2000; Crutzen 2002; Haff 2003; Ellis *et al*. 2013), land grabs produce singularly rapid transitions in physical environments at vast spatial scales. Land grabbing is a kind of dynamics within human–environmental systems for which there is no analogue among natural processes of landscape change. The rate at which land grabbing consumes large quantities of physical space destabilises functioning in environmental and social systems alike (Cotula 2012; Borras and Franco 2012). Historical patterns of frontier expansion, which modern land grabs in many ways resemble (Borras and Franco 2012; Margulis *et al*. 2013), suggest that land grabbing has the capacity to leave a geologic legacy on a planetary scale.

How much land is being grabbed?

Accounting for land grabs remains contested and controversial (Scoones *et al*. 2013) because these deals defy transparency: area, boundaries, ownership, jurisdiction, access and terms of use are difficult to verify (Borras *et al*. 2011; Cotula 2012; Edelman 2013; Scoones *et al*. 2013). Various organisations and researchers have attempted to catalogue recent land grabs, arriving at estimates of total area that range from 45 million hectares to five times that figure (Borras and Franco 2012). The salient criticism of these estimates is methodological (Scoones *et al*. 2013). What kind of transaction constitutes a land grab? How are the data collected? Are some regions of the globe over-represented while others go unrecognised (e.g. Visser and

Spoor 2011)? What about deals that are negotiated but never go into production? Although the specifics of 'how many land deals have been entered into, where and with what consequences' remain unclear (Scoones *et al*. 2013, 473), researchers tend to agree that 'while media reports appear to overestimate scale compared to figures based on in-country research, national inventories confirm that the phenomenon is massive and growing' (Cotula 2012, 655).

According to the Land Matrix, a land-grab database controversial for its reliance on crowd-sourced reports (Anseeuw *et al*. 2013; Oya 2013; Edelman 2013), acquisitions identified since 2001 as being related to agriculture or land clearing (labelled by sector in terms of agriculture, livestock, or forestry) total approximately 43 million ha (0.43 million km^2). This total area is the size of Iraq or California, equivalent to ~1% of all agricultural land worldwide. Figure 1A shows the areas of these land grabs mapped proportionally by country. Dubious reports or abandoned deals may inflate that quantity; oppositely, the total does not include grabbed land that is under cultivation but unreported to the database (e.g. Pearce 2013). Land grab data may be fraught, but they still have utility. Estimates of area at least enable a first-order approximation of the scale of physical landscape change that land grabs could produce if converted to extraction-intensive use. They help frame the past decade of land grabbing both in terms of global physical processes and analogous historical precedents.

Agricultural sediment flux and Anthropocene geology

If the cumulative area of land grabs is globally relevant, then so are the direct and indirect impacts of land grabbing on landscapes and ecosystems. Inevitably, uncertainty in the land grab data extends to any inferences drawn from them regarding environmental change. For example, a recent study that uses agricultural land-grab estimates to make definitive claims about the volume of irrigation water appropriated in those acquisitions (Rulli *et al*. 2013) has met sharp criticism regarding its quantitative validity (Pearce 2013; Scoones *et al*. 2013). However, given that human activities (e.g. agriculture, mining, highway construction, housing development) displace more soil and rock than natural geomorphic processes (e.g. rivers, tectonics, glaciers, hillslopes, waves, wind), and that the rate of these anthropic impacts has increased nonlinearly with time (Hooke 1994 2000; Haff 2003), it is reasonable to infer that land grabbing related to agriculture is capable of producing sediment flux on a global scale.

Farmland generates a global average sediment flux of approximately 75 Gt/y (Wilkinson and McElroy 2007). By comparison, the world's rivers, through natural processes of meandering and long-distance transport, produce an average sediment flux of approximately 54 Gt/y (Hooke 1994). Proportionally, by area, land grabs related to agriculture could account for a sediment flux of ~0.6 Gt/y (1% of the global average). However, sediment flux is sensitive to regional climate, among other geographic factors, and varies by latitude, with higher sediment fluxes tending to occur at lower latitudes (Wilkinson and McElroy 2007). The geography of land grabs is therefore important. The prevalence of agricultural land grabs at low latitudes (Figure 1A) suggests that these acquisitions could contribute a disproportionately high percentage of global sediment flux (Figure 1B). Normalising denudation rates from different latitudes by the global mean long-term denudation rate (62 m/my) yields latitude-related scaling factors for sediment flux (after Figure 2b in Wilkinson and McElroy 2007). With this adjustment, recent agricultural land grabbing involves enough land to collectively generate a total sediment flux of approximately 1 Gt/y, or ~1.5% of the global mean annual sediment flux from farmland. Stated another way: as a result of their geography, agricultural land grabs could account for ~50% more sediment production than their total area would otherwise suggest. The rate of 1 Gt/y is ~5% of the global mean natural sediment flux in rivers (Wilkinson and McElroy 2007), or roughly equivalent to the quantity of suspended sediment discharged annually from the Lower Amazon (Meade *et al*. 1985). This hypothetical flux estimate for agricultural land grabs is also on a par with fundamental processes of natural sediment transport: hillslopes, wave action and wind each move sediment at global rates of approximately 1 Gt/y (Hooke 1994; Haff 2003).

Scaling down from global mean sediment-flux data does not capture the detailed effects of anomalous sediment delivery within individual watersheds. For example, agriculturally derived sediment may be eroded but then stored on a floodplain a short distance downstream rather than fully exported from the catchment (e.g. Trimble and Crosson 2000). Gross estimation also invokes the simplifying assumptions that all land grabbed for cultivation goes into production, and that deforestation triggers sediment transport at rates comparable to those of tilled agriculture, at least to within the same order of magnitude (e.g. Milliman and Syvitski 1992). Furthermore, despite the obvious significance of mining operations in the context of sediment displacement, mining-sector land acquisitions are excluded here because mining is not factored into estimates of agricultural sediment flux.

Nevertheless, environmental history suggests that this new era of land grabbing could leave a signature in sedimentary stratigraphy. Lacustrine records of soil erosion from ancient Mayan land use in Guatemala (Anselmetti *et al*. 2007) and the Tascaran Empire in Central Mexico

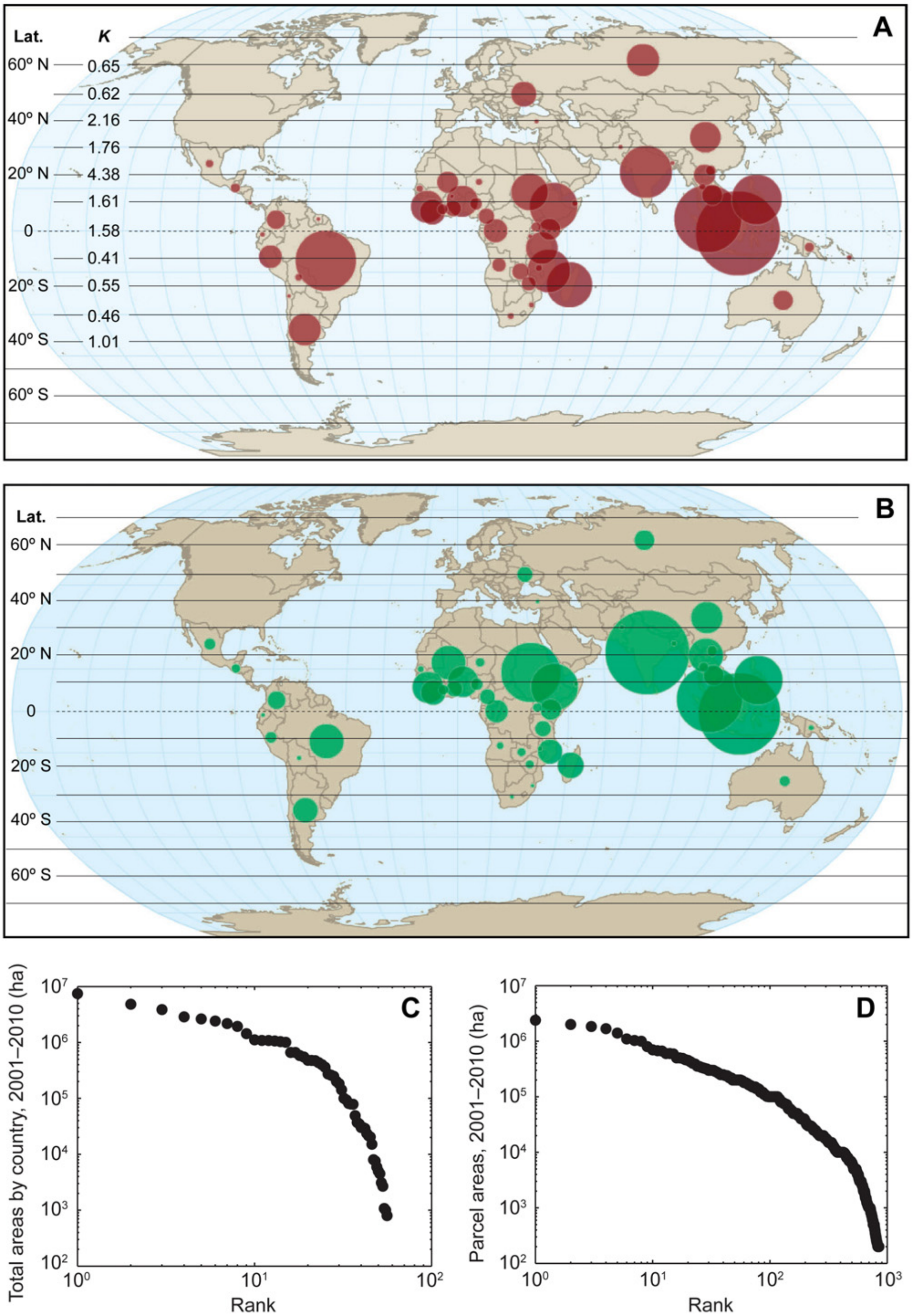

Figure 1 (A) Map of reported land grabs related to agriculture (agriculture, livestock and forestry sectors) since 2001, as listed in the Land Matrix database (Land Portal 2013). Symbols are proportional by country and do not correspond explicitly to spatial areas of land acquisitions. (B) Map of estimated sediment flux (Gt/y) from total land-grab areas by country, weighted by a latitude-related factor *K* shown in (A). (C) Rank-order plot of total area (in ha) by country for reported agriculturally related land grabs mapped in (A). (D) Rank-order plot of individual parcel sizes (in ha) for all reported agriculturally related acquisitions. Country-level data are provided in Table 1

(Fisher *et al*. 2003) show that erosion rates peaked during phases of initial land clearance or settlement, not when populations were at their highest or while indigenous agricultural practices such as terracing were established and maintained. Analyses of human–environment co-evolution on the Yellow River in China, spanning four millennia of historical and physical evidence, report periods of increased erosion and soil degradation associated with episodic population booms, agricultural intensification and dynastic frontier expansion (Chen *et al*. 2012). In the northeastern USA, widespread deforestation and farmland conversion concurrent with 18th- and 19th-century European settlement sent depositional slugs of river sediments into estuaries and accelerated coastal salt marsh growth throughout the region (Kirwan *et al*. 2011). Other geomorphologic research of the same US historical period has suggested that the cumulative effects of sediment trapping behind individual mill ponds ultimately changed the fundamental patterns of the region's river channels (Walter and Merritts 2008). The sedimentary legacy of the US Dust Bowl, which stripped hundreds of millions of tons of topsoil from the American Midwest in the early 1930s, resides in western North American lakes, where records show wind-blown sedimentation rates jumped by 500% after the introduction of mechanised industrial agriculture to the Great Plains (Neff *et al*. 2008).

Geoscientists who analyse deep-time sediment records attribute geographically disparate, temporally synchronous erosion events to changes in continental- or global-scale climatic conditions (Molnar 2004). Archaeologists and environmental historians examining more recent time scales have identified three global-scale waves of soil erosion related to agriculture, dating to approximately the second millennium BCE, the 16th to 19th centuries, and post-1945, respectively (McNeill and Winiwarter 2004). It is plausible to suggest that this present period of land grabbing could manifest in sedimentary records around the world as an approximately contemporaneous pulse of high sedimentation rates. Will future researchers relate this enigmatic sedimentation event to a particular anthropogenic disturbance phenomenon, part of a broader Anthropocene geology, or will this signal be one spike buried among others reflecting the variability of our changing climate? Will historians interpret it as a continuation of the post-1945, 'third wave' of soil erosion, or will these land-use transitions generate sediment fluxes of sufficient magnitude to constitute a new, 'fourth' wave?

Land grabbing and frontier dynamics

Parcel-size data for reported agricultural land grabs exhibit a 'heavy-tailed' distribution (Figure 1C and D; Table 1): most land deals involve several hundred or a few thousand hectares at a time, with the exception of a subset of deals that encompass areas that are several orders of magnitude larger (Cotula 2012). Although the reported land grabs compiled in Figure 1C and D are not necessarily geographically related to each other, collectively they show that land grabbing involves parcel sizes that span a wide range of spatial scales, and that the statistical distribution of those parcel sizes suggests a quantitative structure in the relationship between scales. Land-cover and land-use change research has demonstrated ways in which natural ecotones (transitional zones between two different ecological biomes) and human land-use frontiers (characterised by an influx of land-management practices that differ from those extant within a geographic area) share certain spatio-temporal properties (Malanson *et al*. 2006; Rindfuss *et al*. 2007; Parker *et al*. 2008). One such property is that a power law describes the heavy-tailed statistical distributions typical of occurrence frequency per disturbance size both in ecotonal and in frontier systems (Malanson *et al*. 2006). Statistical signatures like power laws sometimes mask the underpinning processes of social (Aldrich *et al*. 2006) and physical systems (Lazarus *et al*. 2011). However, efforts to recognise and explain organised quantitative structures have granted breakthroughs in fundamental insight into a variety of social and physical phenomena (Bak 1996; Strogatz 2001). Here, too, they are a key step toward integrated analysis of historical and contemporary land-use case studies (Rindfuss *et al*. 2007).

So why might land grabs – and spatial patterns of frontier land-use change more generally – exhibit a power law? Scaling patterns inherent in natural transportation networks such as river catchments (Horton 1945), and in technological transportation networks such as roads (Kalapala *et al*. 2006) and rail lines (Seaton and Hackett 2004), perhaps offer some explanation. Land acquisition patterns may reflect the underlying morphometric template of the drainage basins they claim, or of an infrastructural network as it propagates across the landscape as part of the acquisition process itself. Transportation routes, natural and engineered, facilitate new land claims by making territory accessible; new land claims in turn facilitate expansion of the transportation network necessary for importing and exporting resources. Consider that in the USA during the 19th century the extent and pace of land-use change shifted dramatically with the development of a transcontinental railroad network. Railroads both granted unprecedented access to natural resources in the nation's interior and stoked widespread land speculation during their planning and construction (Sakolski 1932; Barbier 2011). Comparable landscape transformations are associated with the current proliferation of transportation networks in undeveloped, ecologically sensitive regions of the world (e.g. Mertens and Lambin 2000; Rodrigues *et al*. 2009).

Table 1 Reported agriculture-related land acquisitions by country

Country	Land grabs (ha)	Land grabs (km^2)	*L* (%)	*F* (Gt/y)	*K*	*F* scaled by *K* (Gt/y)
Angola	183 000	1 830	0.000036600	0.002745000	0.405228758	0.001112353
Argentina	1 087 020	10 870.2	0.000217404	0.016305300	1.006535948	0.016411871
Australia	400 926	4 009.26	0.000080200	0.006013890	0.464052288	0.002790759
Bangladesh	5 000	50	0.000001000	0.000075000	4.379084967	0.000328431
Benin	1 036 100	10 361	0.000207220	0.015541500	1.607843137	0.024988294
Bolivia	37 156	371.56	0.000007430	0.000557340	0.549019608	0.000305991
Brazil	3 871 824	38 718.24	0.000774365	0.058077360	0.549019608	0.031885609
Burkina Faso	1 000	10	0.000000200	0.000015000	1.607843137	0.000024100
Cambodia	437 052	1 002	0.000087400	0.006555780	1.607843137	0.010540666
Cameroon	247 980	4 370.52	0.000049596	0.003719700	1.607843137	0.005980694
Chile	800	2 479.8	0.000000160	0.000012000	0.464052288	0.000005570
China	1 007 929	8	0.000201586	0.015118935	1.764705882	0.026680474
Colombia	360 820	10 079.29	0.000072164	0.005412300	1.581699346	0.008560631
Congo	581 870	3 608.2	0.000116374	0.008728050	1.581699346	0.013805151
Costa Rica	2 681	5 818.7	0.000000536	0.000040215	1.607843137	0.000064700
Ecuador	8 000	26.81	0.000001600	0.000120000	1.581699346	0.000189804
Ethiopia	2 412 562	80	0.000482512	0.036188430	1.607843137	0.058185319
Ghana	259 900	24 125.62	0.000051980	0.003898500	1.607843137	0.006268176
Guatemala	78 506	2 599	0.000015700	0.001177590	1.607843137	0.001893380
India	2 870 314	785.06	0.000574063	0.043054710	4.379084967	0.188540233
Indonesia	7 491 260	28 703.14	0.001498252	0.112368900	1.581699346	0.177733816
Ivory Coast	100 200	74 912.6	0.000020040	0.001503000	1.607843137	0.002416588
Kenya	480 000	4 800	0.000096000	0.007200000	1.581699346	0.011388235
Laos	478 153	4 781.53	0.000095600	0.007172295	4.379084967	0.031408089
Liberia	662 000	6 620	0.000132400	0.009930000	1.607843137	0.015965882
Madagascar	2 176 241	21 762.41	0.000435248	0.032643615	0.549019608	0.017921985
Malawi	30 147	301.47	0.000006030	0.000452205	0.405228758	0.000183246
Malaysia	4 819 483	48 194.83	0.000963897	0.072292245	1.581699346	0.114344597
Mali	471 891	4 718.91	0.000094400	0.007078365	4.379084967	0.030996762
Mexico	49 081	490.81	0.000009820	0.000736215	4.379084967	0.003223948
Mozambique	1 938 253	19 382.53	0.000387651	0.029073795	0.549019608	0.015962084
Niger	29 969	299.69	0.000005990	0.000449535	4.379084967	0.001968552
Nigeria	142 532	1 425.32	0.000028500	0.002137980	1.607843137	0.003437536
Pakistan	5 926	59.26	0.000001190	0.000088890	1.764705882	0.000156865
Papua New Guinea	79 178	791.78	0.000015800	0.001187670	0.405228758	0.000481278
Peru	548 171	5 481.71	0.000109634	0.008222565	0.405228758	0.003332020
Philippines	2 633 248	26 332.48	0.000526650	0.039498720	1.607843137	0.063507746
Russia	1 113 434	11 134.34	0.000222687	0.016701510	0.647058824	0.010806859
Rwanda	3 100	31	0.000000620	0.000046500	1.581699346	0.000073500
Senegal	34 800	348	0.000006960	0.000522000	1.607843137	0.000839294
Sierra Leone	1 085 742	10 857.42	0.000217148	0.016286130	1.607843137	0.026185542
Solomon Islands	7 577	75.77	0.000001520	0.000113655	0.405228758	0.000046100
Somalia	21 500	215	0.000004300	0.000322500	0.405228758	0.000130686
South Africa	23 681	236.81	0.000004740	0.000355215	0.464052288	0.000164838
South Sudan	20 450	204.5	0.000004090	0.000306750	1.607843137	0.000493206
Sudan	1 437 130	14 371.3	0.000287426	0.021556950	4.379084967	0.094399716
Suriname	1 073	10.73	0.000000215	0.000016095	1.581699346	0.000025500
Swaziland	15 124	151.24	0.000003020	0.000226860	0.464052288	0.000105275
Tanzania	1 064 179	289.12	0.000212836	0.015962685	0.405228758	0.006468539
Thailand	28 912	45	0.000005780	0.000433680	4.379084967	0.001899122
Turkey	4 500	810.12	0.000000900	0.000067500	2.156862745	0.000145588
Uganda	81 012	6 621.67	0.000016200	0.001215180	1.581699346	0.001922049
Ukraine	662 167	10 641.79	0.000132433	0.009932505	0.620915033	0.006167242
Vietnam	93 540	935.4	0.000018708	0.001403100	1.607843137	0.002255965
Zambia	273 413	2 734.13	0.000054700	0.004101195	0.405228758	0.001661922
Zimbabwe	201 171	2 011.71	0.000040200	0.003017565	0.549019608	0.001656702
Totals	43 198 678	431 986.78	0.008639675	0.647980170		1.048439080
Total global land area (km^2)			129 710 339			
Total agricultural area (km^2)			48 843 781			
Mean global sediment flux from agriculture (Gt/y)			75			

Note: Reports for agriculture, livestock and forestry sectors from the Land Matrix database (Land Portal 2013). Gt/y, gigatons per year. *L*, reported acquisitions as a percentage of global farmland; *F*, corresponding proportion, based on *L*, of estimated global mean agricultural sediment flux ($F = L \times 75$ Gt/y); *K*, dimensionless scaling coefficient that reflects differences in global sediment flux as a function of latitude (see Figure 1A). Latitude-related scaling for sediment flux derives from normalising denudation rate vs degrees latitude by the global mean long-term denudation rate of 62 m/my (after Figure 2b in Wilkinson and McElroy 2007). The final column shows the proportions of estimated total *F* rescaled by *K* (or $F \times K$, shown in Figure 1B). Global estimates for total land area and total agricultural land area are from the World Bank (http://data.worldbank.org/)

The rate at which landscape changes occur on a frontier is thus an embedded trait of these transportation networks. In physics-based contexts, transport phenomena are typically described using expressions that distinguish between advection and diffusion. Broadly posed, where advection is fast, diffusion is slow. Advection connotes active, direct transference of something from one place to another; diffusion is a passive, comparatively undirected process in which boundaries blur gradually by mixing. In this heuristic, if new land use is the system property being distributed via advection and diffusion, then land grabbing functions as an advective process within the dynamics of frontier expansion. Moreover, land grabbing is purposeful, not accidental (e.g. McNeill 1992; Barbier 2011). Purpose, as a means of both motivating and directing transport (Haff 2012), is arguably the fuel that makes land grabbing such a fast vehicle for subsequent landscape change.

Human–environmental feedbacks

Feedbacks from land-use transitions are now known to produce long-lived, large-scale changes to natural processes that alter physical environments in quantifiable ways. In Amazonia, for example, only recently have regional-scale changes in weather and climate been mechanistically linked to deforestation patterns stemming from decades of boom-and-bust development (Laurance and Williamson 2001; Negri *et al*. 2004; Rodrigues *et al*. 2009). Attenuation of cause and effect is a nonlinear result of the hierarchy of scales at which human–environmental systems function (e.g. Werner and McNamara 2007): long-term, large-scale, emergent environmental patterns will lag relative to the expression of short-term, local processes. Therefore, even when a land use is known to be problematic, the full extent of its indirect consequences may be difficult to identify, quantify and attribute to a systemic driver or set of drivers.

Other human–environmental cause-and-effect relationships operate on faster, more easily observable time scales. For example, modern agricultural land grabs are employing Green Revolution methods of industrial farming (Tilman *et al*. 2001; Borras and Franco 2012) that rely on a petrochemical-based supply chain. An environmental consequence associated with industrial agriculture is that hypoxic dead zones are increasing in distribution, frequency and size in coastal water bodies as a result of nutrient-loaded agricultural runoff enriched in nitrogen and phosphorous from petrochemical fertilisers (Rabalais *et al*. 2010). The same fertilisers that feed algal blooms in coastal waters also mask the soil depletion typical of monoculture cropping: in order to counter the steady removal (by harvesting) or loss (by erosion) of natural soil nutrients, fertiliser inputs become a kind of subsidy on which production grows increasingly dependent (Montgomery 2007). The more depleted the soils get, the bigger the nutrient subsidy must be to maintain – let alone boost – crop yields. As land grabs introduce industrial practices to presently nonindustrial settings, soil depletion, petrochemical fertilisers, eutrophication and coastal dead zones will likely become commonplace in locales where such events were previously unprecedented.

Historical agricultural land rushes have demonstrated the suddenness with which landscape stability can change. Technological expansion of US industrial agriculture in the late 19th century unwittingly triggered an environmental catastrophe in the early 20th century: the Dust Bowl came barely 40 years after a government-sponsored derby for homestead land (Montgomery 2007). Land-use actions that operate on time scales that outstrip natural responses to disturbance regimes raise the question of environmental hysteresis: if a given land use stopped tomorrow, would the landscape recover to its pre-land-use condition? Or would that environment be changed forever, anthropogenically knocked into an 'alternative stable state' (Beisner *et al*. 2003)? Cut down an old-growth forest in the Philippines, ditch and drain a wetland in Kenya, turn prairie into switchgrass in Brazil (Pearce 2012) – but what happens if the plan for production folds? For a given environmental setting, what is the largest anthropogenic disturbance a landscape can absorb before it scars, or switches to a regime that is different altogether? Invasive land uses motivated by short-term extraction and quick return on capital investment tend to leave deep environmental footprints, the legacy of which can persist long after the land users are gone (e.g. McDaniel and Gowdy 2000).

Future work on future landscapes

Insight into the dynamics of resource exploitation is not explicitly listed as a grand challenge for Earth-surface science, but the problem fits into the category of 'Future of Landscapes in the "Anthropocene" ', one of the horizons prioritised in a US National Academy of Sciences state-of-the-discipline report framing the challenges and opportunities in research on the Earth's surface (NRC 2010). Of the primary science objectives for anthropic landscapes outlined in the report, the concept of land grabbing as a driver of environmental change speaks directly to the first objective listed: the need for

> improved understanding of the long-term legacies of human impacts on landscapes and quantification of current rates of impacts (e.g. from mining, grazing, deforestation, creation of impervious surfaces, agricultural erosion and pollution, flow and sediment impoundment) – especially in environments that are sensitive to global climate change. (NRC 2010, 115)

The objective echoes a grand challenge described in a similar report published a decade earlier on next-generation environmental science, which likewise emphasises a need to 'develop a systematic understanding of changes in land uses and covers that are critical to ecosystem functioning and services and human welfare' (NRC 2001, 4).

Addressing the coupled dimensions of change in human–environmental systems demands a departure from standard analytical paths. Agent-based modelling approaches to linking human decision-making, economic markets, land use dynamics and natural landscape processes represent an especially fruitful interdisciplinary research direction (Werner and McNamara 2007; Parker *et al*. 2008; Wainwright 2008). More field campaigns are needed to document sedimentary records of human disturbance and other quantifiable indicators of human activities as forces of physical landscape change (Hooke 1994 2000; Haff 2003 2010 2012). Spatio-temporal analysis of remote-sensing imagery will allow researchers to track the physical footprints of land grabs as they either develop or fail to materialise. Publication of dramatic landscape transitions in popular media, such as the 'Earth Engine' collaboration between Google and NASA that draws on decades of Landsat satellite imagery to illustrate a variety of changes to the Earth's surface (Google 2013; Kluger and Walsh 2013), will also raise awareness among publics and policy makers in ways that academic literature on its own does not.

More than a topical news cycle or a problem specific to international economic development, land grabbing and the changes wrought in these pervasive landscape transitions may force the largest human-driven environmental transformations that current Earth-surface scientists will witness in their lifetimes. Social-science researchers have started to unpack the human-system dynamics behind these patterns of resource exploitation, hoping to reveal the scales at which government, institutional or self-organised social intervention may be most effective (Ostrom 2010; Margulis *et al*. 2013; Wolford *et al*. 2013). Unpacking the related environment-system dynamics, including the geomorphic processes concomitant with human settlement and land-use frontiers, is both a research opportunity for the physical sciences and a necessary step toward understanding and anticipating anthropic landscape evolution.

Acknowledgements

I am grateful to Alida Payson for the many discussions and editorial comments that improved this paper; to the 2010 Global Sustainability Summer School, funded by the US National Science Foundation, at the Santa Fe Institute (New Mexico, USA); to Tom Coulthard and two anonymous reviewers for their suggestions; and to Fred Pearce, whose investigative reporting on land grabs helped shape this work's premise.

References

Aldrich S P, Walker R T, Arima E Y, Caldas M M, Browder J O and Perz S 2006 Land cover and land-use change in the Brazilian Amazon: smallholders, ranchers, and frontier stratification *Economic Geography* 82 265–88

Anseeuw W, Lay J, Messerli P, Giger M and Taylor M 2013 Creating a public tool to access and promote transparency in global land deals: the experience of the Land Matrix *Journal of Peasant Studies* 40 521–30

Anselmetti F S, Hodell D A, Ariztegui D, Brenner M and Rosenmeier M F 2007 Quantification of soil erosion rates related to ancient Maya deforestation *Geology* 35 915–18

Bak P 1996 *How nature works* Springer, New York

Barbier E B 2011 *Scarcity and frontiers: how economies have developed through natural resource exploitation* Cambridge University Press, New York

Beisner B E, Haydon D T and Cuddington K 2003 Alternative stable states in ecology *Frontiers in Ecology and the Environment* 1 376–82

Borras S M Jr and Franco J C 2012 Global land grabbing and trajectories of agrarian change: a preliminary analysis *Journal of Agrarian Change* 12 34–59

Borras S M Jr, Hall R, Scoones I, White B and Wolford W 2011 Towards a better understanding of global land grabbing: an editorial introduction *Journal of Peasant Studies* 38 209–16

Borras S M Jr, Kay C, Gómez S and Wilkinson J 2012 Land grabbing and global capitalist accumulation: key features in Latin America *Canadian Journal of Development Studies* 33 402–16

Chen Y, Syvitski J P, Gao S, Overeem I and Kettner A J 2012 Socio-economic impacts on flooding: a 4000-year history of the Yellow River, China *AMBIO* 1–17

Cotula L 2012 The international political economy of the global land rush: a critical appraisal of trends, scale, geography and drivers *Journal of Peasant Studies* 39 649–80

Crutzen P J 2002 Geology of mankind *Nature* 415 23

Edelman M 2013 Messy hectares: questions about the epistemology of land grabbing data *Journal of Peasant Studies* 40 485–501

Ellis E C, Kaplan J O, Fuller D Q, Vavrus S, Klein Goldewijk K and Verburg P H 2013 Used planet: a global history *Proceedings of the National Academy of Sciences USA* 110 7978–85

Fisher C T, Pollard H P, Israde-Alcántara I, Garduño-Monroy V H and Banerjee S K 2003 A reexamination of human-induced environmental change within the Lake Pátzcuaro Basin, Michoacán, Mexico *Proceedings of the National Academy of Sciences USA* 100 4957–62

Google 2013 Earth engine (https://earthengine.google.org/#intro) Accessed 7 November 2013

Haff P K 2003 Neogeomorphology, prediction, and the Anthropic landscape in **Wilcock P R and Iverson R M** eds *Prediction in geomorphology* AGU Monograph Series #135 Washington DC 15–26

Haff P K 2010 Hillslopes, rivers, plows, and trucks: mass transport on Earth's surface by natural and technological processes *Earth Surface Processes and Landforms* 35 1157–66

Haff P K 2012 Technology and human purpose: the problem of solids transport on the earth's surface *Earth System Dynamics* 3 417–31

Hooke R LeB 1994 On the efficacy of humans as geomorphic agents *GSA Today* 4 217

Hooke R LeB 2000 On the history of humans as geomorphic agents *Geology* 28 843–6

Horton R E 1945 Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology *Geological Society of America Bulletin* 56 275–370

Kalapala V, Sanwalani V, Clauset A and Moore C 2006 Scale invariance in road networks *Physical Review E* 73 026130

Kirwan M L, Murray A B, Donnelly J P and Corbett D R 2011 Rapid wetland expansion during European settlement and its implication for marsh survival under modern sediment delivery rates *Geology* 39 507–10

Kluger J and Walsh B 2013 Timelapse: Landsat satellite images of climate change, via Google Earth Engine *Time Magazine* online (http://world.time.com/timelapse/) Accessed 7 November 2013

Land Portal 2013 Land matrix (http://landportal.info/landmatrix) Accessed 7 March 2013

Laurance W F and Williamson G B 2001 Positive feedbacks among forest fragmentation, drought, and climate change in the Amazon *Conservation Biology* 15 1529–35

Lazarus E D, Ashton A D, Murray A B, Tebbens S and Burroughs S 2011 Cumulative versus transient shoreline change: dependencies on temporal and spatial scale *Journal of Geophysical Research: Earth Surface* 116 F02014 doi:10.1029/2010JF001835

Malanson G P, Zeng Y and Walsh S J 2006 Complexity at advancing ecotones and frontiers *Environment and Planning A* 38 619–32

Margulis M E, McKeon N and Borras S M Jr 2013 Land grabbing and global governance: critical perspectives *Globalizations* 10 1–23

McDaniel C N and Gowdy J M 2000 *Paradise for sale: a parable of nature* University of California Press, Berkeley CA

McNeill J R and Winiwarter V 2004 Breaking the sod: humankind, history, and soil *Science* 304 1627–9

McNeill W H 1992 *The global condition: conquerors, catastrophes, and community* Princeton University Press, Princeton NJ

Meade R H, Dunne T, Richey J E, Santos U D M and Salati E 1985 Storage and remobilization of suspended sediment in the lower Amazon River of Brazil *Science* 228 488–90

Mertens B and Lambin E F 2000 Land-cover-change trajectories in southern Cameroon *Annals of the Association of American Geographers* 90 467–94

Milliman J D and Syvitski J P M 1992 Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers *Journal of Geology* 100 525–44

Molnar P 2004 Late Cenozoic increase in accumulation rates of terrestrial sediment: how might climate change have affected erosion rates? *Annual Review of Earth and Planetary Sciences* 32 67–89

Montgomery D R 2007 *Dirt: the erosion of civilizations* University of California Press, Berkeley CA

National Research Council 2001 *Grand challenges in environmental sciences* National Academies Press, Washington DC

National Research Council 2010 *Landscapes on the edge: new horizons for research on Earth's surface* National Academies Press, Washington DC

Neff J C, Ballantyne A P, Farmer G L, Mahowald N M, Conroy J L, Landry C C, Overpeck J T, Painter T H, Lawrence C R and Reynolds R L 2008 Increasing eolian dust deposition in the western United States linked to human activity *Nature Geoscience* 1 189–95

Negri A J, Adler R F, Xu L and Surratt J 2004 The impact of Amazonian deforestation on dry season rainfall *Journal of Climate* 17 1306–1319

Ostrom E 2010 Beyond markets and states: polycentric governance of complex economic systems *American Economic Review* 100 1–33

Oya C 2013 Methodological reflections on 'land grab' databases and the 'land grab' literature 'rush' *Journal of Peasant Studies* 40 503–20

Parker D C, Entwisle B, Rindfuss R R, Vanwey L K, Manson S M, Moran E, An L, Deadman P, Evans T P, Linderman M, Mussavi Rizi S M and Malanson G 2008 Case studies, cross-site comparisons, and the challenge of generalization: comparing agent-based models of land-use change in frontier regions *Journal of Land Use Science* 3 41–72

Pearce F 2012 *The landgrabbers: the new fight over who owns the Earth* Eden Project Books, Transworld Publishers, London

Pearce F 2013 Splash and grab: the global scramble for water *New Scientist* 217 28–9

Rabalais N N, Diaz R J, Levin L A, Turner R E, Gilbert D and Zhang J 2010 Dynamics and distribution of natural and human-caused hypoxia *Biogeosciences* 7 585–619

Rindfuss R R, Entwisle B, Walsh S J, Mena C F, Erlien C M and Gray C L 2007 Frontier land use change: synthesis, challenges, and next steps *Annals of the Association of American Geographers* 97 739–54

Rodrigues A S, Ewers R M, Parry L, Souza C, Veríssimo A and Balmford A 2009 Boom-and-bust development patterns across the Amazon deforestation frontier *Science* 324 1435–7

Rulli M C, Saviori A and D'Odorico P 2013 Global land and water grabbing *Proceedings of the National Academy of Sciences USA* 110 892–7

Sakolski A 1932 *The great American land bubble* Harper & Brothers, New York

Scoones I, Hall R, Borras Jr S M, White B and Wolford W 2013 The politics of evidence: methodologies for understanding the global land rush *Journal of Peasant Studies* 40 469–83

Seaton K A and Hackett L M 2004 Stations, trains and small-world networks *Physica A* 339 635–44

Strogatz S H 2001 Exploring complex networks *Nature* 410 268–76

Tilman D, Farigone J, Wolff B, D'Antonio C, Dobson A, Howarth R, Schindler D, Schlesinger W H, Simberloff D and Swackhamer D 2001 Forecasting agriculturally driven global environmental change *Science* 292 281–84

Trimble S W and Crosson P 2000 US soil erosion rates – myth and reality *Science* 289 248–50

Visser O and Spoor M 2011 Land grabbing in post-Soviet Eurasia: the world's largest agricultural land reserves at stake *Journal of Peasant Studies* 38 299–323

Vitousek P M, Mooney H A, Lubchenco J and Melillo J M 1997 Human domination of the earth's ecosystems *Science* 277 494–9

Wainwright J 2008 Can modelling enable us to understand the role of humans in landscape evolution? *Geoforum* 39 659–74

Walter R C and Merritts D J 2008 Natural streams and the legacy of water-powered mills *Science* 319 299–304

Werner B T and McNamara D E 2007 Dynamics of coupled human-landscape systems *Geomorphology* 91 393–407

Wilkinson B H and McElroy B J 2007 The impact of humans on continental erosion and sedimentation *Geological Society of American Bulletin* 119 140–56

Wolford W, Borras S M Jr, Hall R, Scoones I and White B 2013 Governing global land deals: the role of the state in the rush for land *Development and Change* 44 189–210