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Review

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Explaining the emergence of land-use frontiers

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Land-use expansion is linked to major sustainability concerns including climate change, food security and biodiversity loss. This expansion is largely concentrated in so-called 'frontiers', defined here as places experiencing marked transformations owing to rapid resource exploitation. Understanding the mechanisms shaping these frontiers is crucial for sustainability. Previous work focused mainly on explaining how active frontiers advance, in particular, into tropical forests. Comparatively, our understanding of

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how frontiers emerge in territories considered marginal in terms of agricultural productivity and global market integration remains weak. We synthesize conceptual tools explaining resource and land-use frontiers, including theories of land rent and agglomeration economies, of frontiers as successive waves, spaces of territorialization, friction and opportunities, anticipation and expectation. We then propose a new theory of frontier emergence, which identifies exogenous pushes, legacies of past waves and actors' anticipations as key mechanisms by which frontiers emerge. Processes of differential rent creation and capture and the built-up of agglomeration economies then constitute key mechanisms sustaining active frontiers. Finally, we discuss five implications for the governance of frontiers for sustainability. Our theory focuses on agriculture and deforestation frontiers in the tropics but can be inspirational for other frontier processes including for extractive resources, such as minerals.

1. Introduction

Land-use change is key to many sustainability challenges. Conversion of natural ecosystems and conversion from extensive to more intensive land uses are among the main drivers of global environmental change, impacting carbon, biodiversity, water fluxes, livelihoods and many other ecosystem services and nature's contributions to people [1,2]. Much of this conversion is not distributed homogeneously but rather concentrated in certain areas. These areas can be described as *frontiers*—places or regions with specific land-use dynamics, leading to the rapid development of the exploitation of some land or resource, and that experience marked social–ecological transformation accompanying and resulting from resource exploitation.

Land-use frontiers include agricultural frontiers, where the resource is land not only suitable for agriculture but also fit a broader set of land uses (mining, forestry activities, energy production, conservation, as well as associated resources such as water). Frontiers can expand into natural ecosystems or already converted land. Frontiers can occur through so-called crop booms, which are sudden, rapid and intense transformations from one dominant type of land use to another, generally a commercial crop [3,4]. Frontiers appear in multiple contexts and exhibit a variety of spatio-temporal patterns. As political, technological, economic and environmental—e.g. climatic—conditions change, new frontiers emerge, such as new agricultural frontiers in northern (boreal and arctic) regions[5,6]. Beyond their environmental impacts, frontiers are also hotspots of profound socioeconomic change, impacting livelihoods, food security, development, social structures, cultures and Indigenous People and local communities' rights [7,8].

Deforestation frontiers characterize places with rampant conversion of forest ecosystems, generally related to agriculture [9] but agricultural frontiers can also expand into other, non-forest ecosystems such as grasslands and wetlands [10]. Current deforestation frontiers are largely located in the tropics. Over 50% of tropical deforestation in recent times has been concentrated in 24 deforestation fronts [11]. Across tropical dry forests and woodlands, about a third of deforestation occurs within landscapes characterized as frontiers [12]. Global-scale models and assessments using aggregate agricultural area or production data can easily misrepresent dynamics in deforestation frontiers, as these areas represent a small percentage of global area and production. Indeed, over a global agricultural land extent of ~4745 Mha (~1562 Mha of cropland and~3183 Mha of pastures) [13], the annual rate of agricultural-driven tropical deforestation is around~6.4–8.8 Mha yr^{-1} [9], thus corresponding to only ~0.1–0.2% of the global agricultural land base. Assessments and models of food production, yields and even land-use area can thus be highly accurate overall while grossly misrepresenting the specific dynamics of deforestation frontiers.

Furthermore, adequately understanding, explaining and possibly modelling the dynamics in land-use frontiers requires contextual, focused studies that acknowledge the complexities and multiple factors that shape them. Simple, universal logics such as based on economic theories alone might be insufficient. Indeed, at least a third of agriculture-driven tropical deforestation happens without land being subsequently used for recorded agricultural production, owing to messy dynamics involving speculation, tenure ambiguity and disputes, conflicts, mismanagement or institutional failures [9,14]. Global statistical models based on standard land rent theories (relying mainly on accessibility and agro-environmental qualities of the land) can explain the broad patterns of global cropland extent and distribution, but reveal vast heterogeneity in how these factors play out [15], and struggle to explain

recent global cropland expansion in frontiers [16]. Furthermore, past frontier dynamics partly explain recent dynamics, suggesting some forms of path dependence [16].

As we will show, much has been written to describe and explain the functioning of active frontiers, especially those related to deforestation and agricultural expansion. Yet much less research unravels how these frontiers initially emerged in territories considered marginal in terms of productivity and/or connections to global markets [17]. Our objectives are (i) to synthesize the conceptual and theoretical tools that can describe (§2) and explain (§3) frontier processes, and (ii) to build on these to propose an integrated theoretical understanding of frontier emergence (§4). We then discuss implications of our proposed theory for the governance of frontiers for enhancing sustainability (§5).

2. Describing different types of frontiers

Broadly speaking, frontiers correspond to spaces, places or regions characterized by rapid development of the exploitation of some resource and experiencing marked transformation accompanying and resulting from this exploitation. Although frontiers have been a focus of recent research and policy efforts, particularly in the context of tropical deforestation fronts, the phenomenon of frontiers in itself is not new, and has been happening across contexts and time periods throughout the development of human societies [18]. Academically, the notion of frontiers on which we build emerges in the works of the American historian Frederick Jackson Turner. In his work , *The significance of the frontier in American history* [19], the 'frontier' refers to the waves through which colonists and so-called civilization progressed across North America in the nineteenth century. In Turner's view, these material changes were intrinsically linked with and mutually influencing other societal processes including economic development as well as cultural, institutional and political changes. Turner's main thesis is now largely criticized, but also rediscussed and reinvented (§3.1). Yet, a core intuition remains, namely that the notion of 'frontier' can help understand the linkages between expansion dynamics and broader social and environmental changes.

Land-use frontiers can be characterized in many ways, based on the actors that drive the process, the type of land-use dynamics and the context in which they unfold, distinct stages (emerging, active, post-frontiers), the types of expanding land-use (agricultural frontiers, frontiers of forestry or conservation activities) and others. As this is often a point of confusion when discussing frontiers, we unpack here some of the terminologies and typologies that have been developed to characterize land-use frontiers, focusing on four dimensions: the dominant land cover at the time of frontier emergence; the actors involved in the frontier; the land uses driving the frontier; and the stages of frontier development.

2.1. Land cover: primary versus secondary frontiers

Several prominent conceptualizations of land-use transitions rely on successive 'stages' of land use [20–22]. Initial or primary frontiers, or primary conversion, are places where land use—mainly agriculture—expands into land that is covered predominantly by natural vegetation that has not been converted to another use in the recent past, although it may be under some form of management or use by humans. Primary frontiers are often referred to as deforestation fronts or pioneer fronts. These primary transitions give rise to secondary lands, referring to lands that have been already converted at least once in recent times [23]. In turn, secondary frontiers or secondary conversion refers to places where a new land use expands into secondary land, such as cropping agriculture expanding into cattle ranching or pastoralist rangelands, or a commercial crop expanding into areas used by semi-subsistence smallholders. This distinction is not straightforward or absolute, as most areas of natural forests or other natural ecosystems have been inhabited and used by indigenous people for a long time, and are thus characterized by gradients of intensity of use [24–26]. Yet, in practical terms, the human and environmental implications of frontiers expanding by conversion of natural or semi-natural ecosystems versus those expanding into already converted land are often vastly different [27].

2.2. Actors involved: colonists versus corporate frontiers

Many studies have distinguished frontiers based on the types of actors that drive land-use change. These distinct types of actors and dynamics relate to vastly different underlying processes and

resulting impacts. When frontiers are driven by the inflow of new actors into relatively low-population density areas, two broad categories emerge. First, *frontiers of settlement* [28]—also referred to as *colonist frontiers*, *populist frontiers* (29) or *smallholder frontiers* [30]—are driven by large numbers of settlers or colonists, who arrive from more populated areas in search of farmland. Settlers typically practice small-scale, semi-subsistence agriculture, including shifting cultivation or livestock husbandry, and their main asset is family labour [30]. These settlement frontiers have been amply documented, e.g. in the Brazilian Amazon [30–33], India, Bangladesh, the Philippines and Indonesia [28]. Colonists can be internal migrants, moving from core regions of the country that are typically more densely populated, where land uses are more consolidated, and which are more tightly integrated within the political institutions, as in the case of migrants from Southern Brazil to the Amazonia, or from Indonesian Java to Kalimantan or Papua Islands, or Kinh migrants in Vietnamese highlands. But colonists can also be from abroad, such as European settlers in American, African or Asian colonies. Historically, governments have played a central role in populist or colonist frontiers by planning or fostering their development, for instance through the construction of infrastructures like roads, setting up migration programs such as the Transmigration programs in Indonesia [34], or supporting colonists financially and politically. As discussed in §3.7, the state's motivations for initiating or supporting such settlement frontiers can encompass a range of aspects including geopolitical (territorial consolidation and securing borderlands), economic (fostering economic development and foreign earnings through commodity exports) or internal political stability motivations (mitigating potential social unrest from unequally distributed economic growth or population pressure in core regions of the country).

A second broad type of frontiers is driven by investors (corporations, companies, commercial farmers and other capitalized and market-oriented actors) operating medium- to large-scale commercial farms, cattle ranches or industrial plantations. This second type of frontier has been called the corporate frontier or corporatist frontier [29]. Similarly, Pacheco [30] distinguishes between the Bolivian agricultural frontiers dominated by smallholder farmers and landscapes dominated by large-holder cattle ranchers in the greater Amazon that produce a marketable commodity (beef), labelled as capitalist frontiers. The term commodity frontiers was introduced by Moore [35] to refer to frontier processes that operate for and through the development of a land-based commodity (e.g. timber, sugar, tobacco, cattle and other frontiers), integrating previously largely disconnected regions into the world economy, and often requiring large amounts of capital. These frontiers experience population inflows but typically much less than populist frontiers, with capital being the primary production factor flowing in. Recently, governments have shifted from a role of planning to one of facilitation [36] or nonintervention, giving rise to the notion of neoliberal frontiers [37,38], where export-oriented corporate farming is more strongly motivated by global demand and deregulated access to land than by government subsidies. From that, the term commodity frontiers was also used to describe areas where the expansion of the production of agricultural commodities (e.g. beef, soy or palm oil) by large-scale farms is shaped by the greater ability of these actors to influence and capture economic rents [39].

2.3. Land uses: logging, mining, conservation and restoration frontiers

Much of the literature and reasoning exposed in the previous and following sections have been initially formulated with a focus on deforestation and agricultural frontiers. Yet, similar frontier trajectories have been described for other land uses, such as timber [40,41], including waves of successive logging of trees of different qualities in natural forests [42], or for frontiers driven by extractivist or energy activities such as mining [43], oil and gas exploitation [44], hydropower construction [45] or the expansion of solar and wind power [46].

Research has also described eco-frontiers [47], green frontiers [48] and conservation frontiers, where conservation actors target land for conversion into a protected area for its perceived biodiversity, wilderness or ecological importance [49–52]. This can happen not only in remote, marginal lands but also in lands used or targeted by other actors. Consequently, conservation actors may actively compete with other actors and land uses, be they long-standing, such as local communities or new frontier agents (e.g. incoming migrants or agribusiness investors). Similarly, forest restoration frontiers, where restoration goals or carbon forestry have replaced commodity expansion as the main driver of the frontier, are playing an increasingly important role in land system dynamics [53]. All these frontiers can be apprehended through the frontier theories discussed in this article.

2.4. Stages of frontier development

Research on land-use transition has suggested 'stages' of frontiers (pre-frontier, post-frontier and so on). Frontiers typically develop in a non-linear way, with take-off or *frontier emergence* that can appear as 'abrupt' or 'surprising', then accelerate towards an *active frontier* with rampant land-use dynamics [39]. Although these can be useful to characterize distinct dynamics [54–56], one should not assume that frontiers necessarily move predictably through these stages (for a discussion, refer [57]. Rather, these stages mainly help to describe distinct combinations of actors, drivers, land-use dynamics and impacts. With this in mind, intensive research efforts have been focused on describing and explaining the functioning of active frontiers in relation to agricultural expansion [12,14,58]. Less focus has been put on explaining the processes that condition and shape *emerging* frontiers in territories considered marginal in terms of agricultural productivity and global market connections, but that are in the process of turning into rapidly expanding active frontiers [17].

3. Theories on land-use frontiers

Multiple theoretical perspectives shed light on distinct aspects of frontiers [59]. In a historical and etymological analyses of the word 'frontier' (in French), Febvre [60] already identified many of the tensions of the concept, i.e. between frontier as a hard boundary that roots a political space into a territory, versus something dynamic and expanding, e.g. under military force; frontier as a separation between different populations or, at the contrary, the place where these people meet; or frontiers as contested places versus marginal, neglected places.

In this section, we unpack the main theories developed to explain frontiers. From the original notion of frontier as a tidal wave of colonists and civilization [19], frontiers have been described as a process of pushing back 'wilderness' to create a space for development by taming the natural world [61], as well as spaces facing a rapidly expanding force that brings opportunities for a number of people [62]. Frontiers have also been framed as places of resource extraction or exploitation [18]. The 'resource' in these frontiers can be either newly discovered or 'reinvented', for example, if it acquires a new value owing to technological, institutional, socioeconomic, environmental or cultural changes [39]. This makes frontiers typical spaces of territorialization, i.e. spaces where institutional actors, including governments and corporations, turn places into 'territories' that they can understand, monitor, regulate and exploit [63]. Through these processes, frontiers are also places of interface and friction between different worlds, e.g. subsistence and capitalist economies, different cultures, sociopolitical systems and modes of relations to nature [64,65].

3.1. The tidal frontier

For Turner [19], in the context of settler colonialism [66], the expansion of the frontier and the rolling back of wilderness was an attempt to make liveable space out of an uncooperative nature. This process, which is seen as unfolding as a tidal wave, was more than simply a process of spatial expansion and the progressive taming of the physical world. For Turner, the development of the frontier was thus not only critical for the development of the country in economic and political terms but also the central experience which defined the uniqueness of the American national identity and values. Each new wave of expansion westward, in its conquest of nature, sent shock waves back east in the democratization of human nature [67]. Turner's thesis has now been largely criticized, including for its erroneous and harmful vision of land being 'empty' or 'unused' ([68]), justifying colonization and eviction of indigenous people and its teleological association between the frontier process and the supposed unique character and value of the United States and its people. Yet, Turner's frontier conceptualization remains a core basis for the 'classic' frontier model which sees frontier expansion as a progressive increase in population density, economic activity, land-use conversion and resource extraction, through successive waves of small-scale and then large-scale extraction, agricultural conversion with permanent settlements and then industrialization and urbanization, and its related actors (the pioneer, the settler, the urban) [20. Turner's conceptualization included seeds for many of the subsequent theoretical developments presented below, such as the notion of successive waves of frontiers (§3.2), how land uses in frontiers are influenced by local contexts (the ranching frontier in the Great Plains versus the mining frontier in the mountains), and how the frontier is not a thin boundary but rather a dynamic space, creating opportunities for some, in which different worlds encounter with frictions (§§3.8 and

3.9), and where states and other powerful actors deploy efforts to make the territory legible and assert control of it (territorialization, §3.7).

3.2. Frontiers as successive waves and interstitial frontiers

Many theorizations emphasize that frontiers do not manifest as a singular process happening once and for all in a certain space or region, but instead, as successive *waves*, which may build on each other, reverse each other and often overlap. The relationship between these waves can be seen as contingent or following a regular, predictable succession pattern. For example, the making of a 'second' new resource and commodity frontier in the twentieth century in Laos builds on a 'first frontier' in French colonial time, which profoundly transformed landscapes, property relations, institutions and the development trajectory, paving the way for this second recent frontier [69]. Hirsch [70] describes, in Thailand, the succession of an agricultural frontier, which came to an end after the 1990s, by a peri-urban frontier, both successively transforming landscapes and institutions.

The broad theory of land-use transitions corresponds to a typical conceptualization of frontiers occurring in predictable, regular waves. This theory sees land use following regular sequences from natural ecosystems to extensive, smallholder and subsistence land uses, then to intensive agriculture and forestry, then urbanization and the progressive rise of protected areas [21,22] (§2.1). Some deterministic versions of forest transition theories—i.e. large-scale shifts from deforestation to reforestation—articulate a similar sequence [57]. Other theories such as the capitalist penetration theory (§3.3) also posit regular sequences from smallholder frontiers to consolidated, large-scale hollow frontiers.

Furthermore, in von Thünen's land rent theory (refer §3.4), concentric circles of distinct land uses progressively expand or contract depending on changes in equilibriums of the costs and benefits of these different land uses. Land rent theory has been widely used to explain successive frontiers waves expanding in a region such as in timber exploitation [42] or across sequences of land uses, such as the sequence from logging to cattle ranching to intensive soy cultivation frequent in South America [71,72].

The apparent 'closure' of a frontier, i.e. the cessation of the expansion of the land use that was driving the frontier, does not imply that there is no more resource to exploit in this area, or that extraction activities will not resume in the future. Contextual changes can create the potential for renewed rent extraction by new actors arriving with previously absent capacities to create and extract rents (e.g. with new techniques or more capital than previous actors), or as new land uses trigger a new frontier [73] (refer §3.8). Similarly, the investigation of successive waves of investments in a frontier region in Northern Mozambique showed that, even when failing, early waves left *legacies* that might progressively build the conditions for another frontier wave to emerge, for example, in terms of business approaches and ways for investors to deal with land conflicts, institutions and policies, land with legible tenure (refer §3.7), brownfields (land already cleared and with infrastructures for agriculture), financial capital and social networks [17].

Several authors also contend that frontiers, rather than unfolding over the whole landscape like a blanket tidal wave as described by Turner, typically progress through hybridization, i.e. creating spaces where the former and incoming land uses, as well as actors and institutions, overlap [74]. These hybrid landscapes create the opportunities for interstitial frontiers, where early frontier waves leave behind interstitial spaces—such as forest remnants, uncultivated land or pockets of extensive or subsistence land uses that are neither unmodified nor completely transformed. In further waves, these interstitial spaces are progressively contested, as seen in the multiple forms of extractive activities in Indonesia [74], or in Palestine's West Bank, where interstitial spaces of land that was previously either uncultivated or used non-intensively suddenly become the object of intensive agriculture and struggles for water control [75]. These authors argue that much of the interactions and frictions (§3.8) that happen in frontiers as places of encounter between different worlds happen in these interstitial spaces rather than at the supposed edge of a frontier wave [76].

3.3. Theories of colonist and dualistic frontiers

Several theories have been formulated specifically to describe the processes of settlement, colonist or smallholder frontiers. A classic theory linking populist and corporate frontiers is the *capitalist penetration thesis* [32], which sees frontiers as occurring through waves where, after the initial populist, smallholder settlement of the frontier, the land is then progressively consolidated by capitalized,

corporate actors who switch land uses from mixed, semi-subsistence farming to simplified, large-scale commodity production, such as cattle ranching or soybean. This gives rise to depopulated *hollow frontiers*, while the initial colonists are pushed further away to the periphery, perpetuating the frontier process in more remote regions [37,77,78]. A complementary, *inter-sectoral articulation thesis* argues that smallholders at the frontier serve a functional role in urban economic development by providing low cost food (subsidized by unpaid family labour) and serving as a reserve of cheap labour that can be activated by inflows of capital whenever there is a surplus of capital in the core, urban economy [32]. The term *dualistic frontier* acknowledges that in a number of real-world contexts, in particular recent or contemporary frontiers, both populist/smallholder and corporate/commodity actors operate jointly to produce frontiers [20]. In the dualistic frontier model, a sector with low-productivity agriculture, such as smallholder semi-subsistence agriculture, utilizing poor quality land, coexists with a high productivity, commercially oriented sector such as of agriculture, plantations or mining, using high-quality land and natural resources. These two sectors are interlinked through land, labour and capital exchanges (refer also §§3.4 and 3.6).

A distinct set of theories, building on *Chayanov's peasant theory*, focus on how the *lifecycle of smallholder households* produces the frontier process [32,79,80]. These theories argue that smallholders initially settling in the frontier, typically young parents with non-working, dependent children, will focus on securing harvests on a relatively small land base, with minimal risks. This triggers an initial expansion spur, which has to be periodically renewed as soil fertility of cultivated plots declines. As children enter the workforce, household vulnerability decreases and they become more risk taking, typically expanding the land base and engaging in more risky but potentially more rewarding cash or commodity crops. The children subsequently establish their own household, furthering the frontier process. Older households with lower labour force would then turn to less labour-intensive activities such as cattle ranching. These successive cycles drive much of the spatio-temporal patterns of frontier expansion. Yet, various demographic and socioeconomic household and contextual factors lead to more complex relations between household life cycles and frontier dynamics [79–82].

3.4. Resource frontiers and land rents

A central conceptualization is that of resource extraction frontiers, frontiers as places of imbalance between abundant natural resources and a comparative lack of production factors (i.e. capital, labour) to exploit these resources [20,39,59]. Frontiers then form owing to the rapid inflow of production factors (labour, capital) and the associated increase in resource use rates as actors seek to capture economic rents. Rent theory has emerged as a dominant explanatory framework in economics for understanding frontier expansion and development [31,33,83,84]. It posits that rapid agricultural expansion is driven by the economic rents that actors capture in situations of land abundance. Rents influence land-use decisions such as whether and when to move into the frontier [85], where to invest, what to produce [33] and how much land to clear [31].

The classic land rent theories are those of von Thünen and Ricardo [59,86–89]. In these, the land rent is determined by accessibility and biophysical land quality, respectively. Von Thünen's theory proposes that land uses typically organize in concentric circles around a central place. Land rent theories build on the distinction between the actual economic rent that can be extracted from land, and the bid rent, i.e. the value that economic actors are willing to offer to acquire or use the land, and which corresponds to the overall return to agricultural production that is not paid out to the other inputs used, such as capital and labour, as well as transport costs. Explanations focussed on bid rent have relied on both an 'equilibrium' and a 'disequilibrium' view of land rent [90] In the equilibrium view, the bid rent adjusts to changes in accessibility, land productivity or market demand and thereby the area on which certain land uses can generate a positive rent expands or contracts. Thus, the frontier progressively expands along with improvements in roads, techniques for improving soils or adjusting crops to certain agro-environmental conditions, or increases in market demand or access to new markets. Sudden rises and decreases in rent can also trigger booms and bust dynamics. The bid rent typically represents the average rent that actors can extract: Depending on heterogeneity in assets, skills, location within the frontier and land quality, driving differences in productivity and efficiency, the specific rent that a given actor can expect varies somewhat around that average bid rent.

The equilibrium perspective can explain the longer-term development of frontier areas, but understanding the sometimes very abrupt, possibly surprising, dynamics in many frontiers requires to adopt a 'disequilibrium' perspective, based on the notion that some actors have an exceptional capacity to induce or capture changes in economic rent. While heterogeneity in expectations of rents between

agents are not central to the frontier process in the equilibrium view (the 'engine' of the frontier is the overall rise in rent), the disequilibrium perspective argues that outliers in that distribution actually play a particular role in early frontiers. Along this line of thought, 'early frontiers' emerge or their emergence is reinforced, when specific sets of actors with particular endowments identify and capture 'abnormally' high rents [39]. These rents arise from changes that affect them differently than other actors and generate a significant gap between their and other actors' expectations of rents—hence the disequilibrium. That way, previously uninteresting areas become especially valuable for a limited group of actors that have access to these differential rents. Four dimensions may explain the existence of a differential rent, i.e. a significant gap between the rents available to this subset of actors and those available to others: (i) differences in access, for example, preferential access to certain types of infrastructure and to new technologies; (ii) asymmetrical information, for example, about input and output markets transaction costs, or about (changing) agro-environmental conditions; (iii) variations in the agent preferences, for example, different risk profiles; and (iv) differences in political and economic agency, such as a particular ability to shape or benefit from policies or political decisions.

Different frontier contexts are expected to be more or less prone to the presence of such actors holding a differential rent. In capitalist, corporate frontiers, as well as in dualistic frontiers, rents are consolidated through markets, while the state plays a more indirect, though not unimportant, role through a different set of neoliberal policies [33]. The cattle frontier in the Brazilian Amazon for example, was driven by the rising global demand for beef in the early 2000s, but corporate ranchers could not have captured these market-generated rents were it not for the state to have continued building roads (reducing transportation costs), launching a campaign to eradicate foot-and-mouth disease (improving animal health and product quality) and introducing monetary and trade reforms that favoured export production and market liberalization during the previous decade [83,91]. Yet, beyond the role of the state, large-scale actors that drive corporate, commodity frontiers can have strong agency to shape and capture potential differential rents compared with smallholders, who have less agency in terms of access to new technologies, influence on policies or infrastructure development. These large-scale, capitalized actors are well-positioned to shape and capture these rents, and often outcompete small- and medium-scale farmers in contemporary corporate frontiers [20,39]. Yet, depending on a number of factors such as resources' ecological characteristics, inputs, labour and knowledge requirement, or the technical characteristics of downstream processing, smallholders may also have a comparative advantage, as smallholder-driven Southeast Asian frontier booms exemplify [92].

In populist frontiers, rents are primarily created by (authoritarian) states [33]. In Brazil, in the 1970s and 1980s, the migration and settlement of poor and landless farmers in the Amazon was planned and organized by the state through colonization schemes [32,93]. Even when migration followed a seemingly more spontaneous trajectory [31], state interventions such as road construction into hitherto inaccessible areas and agricultural or settlement subsidies [33] made it possible for struggling farmers to move [39]. In such contexts, the rent can be positive and may even change abruptly, but it is less likely that a specific group of actors would have access to a strong differential rent, and the equilibrium rent explanation would typically prevail.

3.5. Agglomeration economies in frontiers

Agglomeration economies correspond to economies of scale external to an individual company, but internal to the sector [94,95]. Agglomerations create localized clusters of specialized knowledge, inputs and industry-specific infrastructure and institutions. The process of clustering lowers transaction and production costs, promotes learning and innovation, increases local competition and enables leveraging collective political agency [94–97]. A central feature of agglomeration economies is that they are dynamic, and they build-up with the density of actors of a certain sector in a certain area [94]. Therefore, in early stages of frontiers where the expanding land use only occupies relatively small areas in the region, actors are confronted with low levels of agglomeration [98]. With the expansion of the frontier, agglomeration economies are expected to build and to support increased profitability and productivity of farming and other activities [99,100].

Theoretically, one therefore expects an inherent, but not perfect, degree of trade-off between the possibility of extracting rent from resource frontiers and the presence of agglomeration economies [98]. Resource frontiers and agglomeration economies encapsulate the compromise an investor makes in choosing cheap land with the potential to expand and achieve scale economies internal to the firm, as opposed to locating closer to an investment cluster to benefit from the existing scale economies

external to the firm. Actors may also seek a compromise, i.e. places that still have sufficient resources for extracting rent while having already a certain amount of agglomeration economies to sustain operations.

3.6. Frontiers as places of accumulation by dispossession

The process of rent creation and capture described above (§3.4) has been theorized with the Marxist notion of primitive accumulation, i.e. the processes through which 'initial' appropriation of capital, in the form of natural resources or labour force (slavery), occurs [101]. This notion has evolved into the concept of accumulation by dispossession, i.e. the concentration of capital and resources in the hands of a few by dispossessing the public sector and the bulk of private actors, including through the establishment of property rights and the support of neoliberal policies [101,102]. Multiple forms of claims-making, through exclusion, expropriation and enclosure, violent or not, underlie such accumulation of land by dispossession [7,103,104] and contribute to the dynamics of capitalist penetration (§3.3), neoliberal and corporate frontiers and creation and capture of a differential land rent by corporate actors [20,39]. Smaller-scale actors can also sometimes play as agents of dispossession and land-grabbing, involving micro-level processes that mirror those that characterize large-scale land grabs [92]. Dynamics of accumulation by dispossession are, in principle, led by private actors, but they are nevertheless strongly interlinked with the role of states and subnational governments in frontiers. On the one hand, states can be actively engaged in or support this accumulation by dispossession, which can be intrinsically linked to dynamics of territorialization (§3.7). On the other hand, as frontiers are typically at 'the edge of the state' [105], i.e. at the margins of states' reach, the mere neglect or lack of control of remote frontier regions by state authorities and the neglect by public opinion in distant consumer markets and environmental organizations, can suffice to leave the ground open for powerful actors to concentrate land and resources [106].

3.7. Frontiers as spaces of territorialization

Another perspective put forward to explain frontiers is the idea of frontiers as spaces of territorialization [63,107]. Territorialization is the process through which states or other actors, e.g. large-scale corporate actors, turn a 'space' into a 'territory'—something that is legible, can be surveyed, monitored, recorded, administered, taxed and governed. In this perspective, frontier spaces are 'transitional reconfigurations of institutional arrangements' [63]. Frontiers are thus sites of contentious encounters over authority and redefinition of institutions and social contracts.

Territorialization, growing commodification and corporatization and accumulation by dispossession (refer §§3.2 and 3.6) can proceed together, as in the case of the Ethiopian pastoral frontier [108]. Korf *et al*. [108] rejoin Peluso & Lund's [103] observation that there is not one grand land grab, but a series of changing contexts, so that the Ethiopian pastoral frontier is not primarily driven by outside forces but by 'indigenous' capital and entrepreneurship that include investors from the diaspora and political 'big men' (Somalis inside and outside of Ethiopia). As part of the territorialization, the emergence of land markets, either based on formal or customary land laws, renders the land tenure legible for private actors—a crucial aspect that contributes to the expansion of commodity frontiers and rent appropriation [109].

Nation-states are often interested in enabling such territorialization processes for larger political purposes such as integrating marginal or peripheric territories, consolidating borders and establishing geopolitical claims over spaces and resources, as well as reducing population pressure and social unrest in 'core' regions of the country. This has been abundantly shown in contexts such as in the Brazilian Amazon [31], the Chaco region in South America or in Southeast Asia—Vietnam, Thailand and transmigrant programs in Indonesia [107,110,111].

3.8. Frontiers as places of frictions

Frontiers are also seen as places of *friction*, liminal places that are at the interface between different worlds, cultures, modes of relating to nature, patterns of environmental exploitation or sociopolitical systems, e.g. subsistence and capitalist economies [64,65,112]. This coming together of different worlds can cause frictions to arise. These frictions can manifest as ethnic and sociopolitical conflicts at the margins [105,113], such as forms of environmental exploitation [112] or spatial conflicts between an

underprivileged minority and the settler group which represents and is represented by the hegemonic national power [114]. Thus, whereas land conflicts in commodity frontiers are often conceptualized as the local consequences of global political–economic changes [35,115,116], a frictions perspective offers a more nuanced view—namely that land conflicts rarely correspond to mere projections of global dynamics, but are instead best understood as resulting from complex interactions involving local and global dynamics [117].

Conflict and friction are also often linked to processes of differential rent capture and dispossession by accumulation, as actors struggle for claims and control of resources (§§3.4 and 3.6). Frictions can also arise when the state and other actors engage in territorialization to change the readability, governability, or exploitability of frontier spaces (§3.7). Yet, as mentioned above, frictions extend beyond the political and economical realm and arise also from the encounter between different languages, communication modes, production systems or worldviews. They often reflect tensions to redefine the vision of what the frontier place is meant to be. For example, the act of imagining the territory of Mozambique as a blank slate to be exploited and transformed is an act of historical erasure of alternative visions of its history [118,119]. For Turner, the westward spatial expansion of the US frontier was associated with the forging of the US's national identity [67]. These frictions produce conflicts but also lead to reconfigurations and the emergence of new institutions and cultures.

3.9. Frontiers as spaces of opportunity, anticipation and imitation

Frontiers also connote a *space of opportunity* [62]. In that view, the 'resource' from resource frontiers theory can be seen more broadly as any untapped potential to fulfil certain objectives, for which the actors transform the place. In that view, *a 'frontier' refers to a place that is facing an expansive force* [62] in a rapid and overwhelming manner. This can be the penetration of a new technology or product into untapped markets but also the expansion of a religion, a political ideology, a technology such as electrification, etc. For example, African cities have become particularly attractive to the global property development sector, and are often referred to as the world's 'last frontier' for real estate developers. This view also necessarily implies that the frontier is transitory in space and time: at some point, the untapped opportunity is exhausted and the frontier, or window of opportunity, closes. Yet, it does not prevent another opportunity from arising and restarting a new frontier (§3.2).

Frontiers as spaces of opportunities can also be analysed through the notions of *expectations* and *anticipation*. Anticipation is about expecting something to happen and, importantly, doing something about that expectation [120]. In Northern Mozambique's land-use frontiers, many of the land-use decisions and practices have been anticipatory and shaped by expectations of future profits, speculations about resource potentialities and dreams of better futures [121]. Similarly, in northern Laos' agricultural frontiers, the expectation that a stable rubber market would develop drove farmers to adopt the crop long before such a local market materialized [4]. Anticipation thus shapes land-use change, particularly in emerging frontiers where the future is uncertain yet hopeful. Anticipation and expectation can fuel and be fueled by what Anna Tsing terms the *economy of appearances* [122]—the conscious making up of economic success to attract investors to a business idea even when, factually, sustainable economic gain is missing. Frontiers as spaces of opportunity lend themselves to such performance, as exemplified by the spectacular rise and fall of the mining company Bre-X claiming to have tapped into very large gold deposits in Indonesia, which never materialized [122]. As a counterpoint to expectation fuelled by appearances is the spread of information based on tangible, economic success, for example, of early innovation adopters. Such early successes can trigger processes of *imitation* that become self-reinforcing and can lead to boom-like expansion of agricultural crops [123].

4. Proposing an integrated theory of land-use and resource frontiers emergence

Several theories exist about how already active frontiers unfold, yet fewer works have proposed explanations of how frontiers do emerge or not. Here, we aim to put together these distinct pieces to propose a theoretical account of what happens before frontiers emerge, when they emerge and when they are active. We build on the notion of middle-range theory, understood as a *contextual generalization that describes chains of causal mechanisms explaining a well-bounded range of phenomena, as well as the conditions that trigger, enable, or prevent these causal chains* [59].

We structure this account by describing frontier dynamics as a set of stages (figure 1), where distinct mechanisms and factors dominate (figures 1 and 2). Not all areas are expected to experience frontier processes as a regular succession of these stages. Yet, there is a continuity in the chain of causal mechanisms across these stages, which are likely to occur over a certain range of conditions. We discuss some of the conditions below, but for some mechanisms, e.g. legacies, the characterization of these conditions remain incomplete and to be further researched. A focus on conditions helps explain why some regions with the potential for frontier emergence do not undergo such a process, if certain conditions are not fulfilled.

The first stage of frontier emergence corresponds to when a region has the potential for frontier development, but is not yet a frontier, i.e. it has an abundance of certain untapped resources and potential opportunities but it is not experiencing rapid inflow of production factors and resource extraction. A coarse analysis, for example, focusing on land-use conversion as seen from satellites or through production statistics, might show these regions as largely stable or static. However, a closer inspection might reveal multiple failed attempts by pioneers and other actors to put the resource into use, facing unfavourable conditions and obstacles to investment and production.

In some cases, these early investments form waves that can take the form of commodity boom and bust cycles, where the bid rent increases quickly as actors rush to acquire land with the prospects of high gains from extracting a certain resource or growing a certain crop. If the rent is not sustained according to expectations, because the resource is not as abundant or valuable as previously thought (e.g. land is abundant but much of it is poorly suitable for a certain crop), because production costs are higher than expected, or because demand for the products does not materialize, the rush ends up being only speculative and comes to a bust when resource extraction and bid rent all go down again. This mismatch of anticipated rents with actual ones is frequent in commodity frontiers where information on resource quantity and quality as well as costs and output markets is uncertain and intransparent. These regions are prone to 'economies of appearances', where various actors attempt to trigger and raise others' expectations of rents.

While these successive waves of investment and land rush may appear as some form of noise in the big picture, they are nevertheless key as they may progressively build a set of legacies in the form of business approaches, institutions and policies, land tenure legibility, brownfields, financial capital, social networks and lessons learned from land conflicts with local farmers [17]. The rent that actors may expect to extract from and would offer for land and other resources remains rather low, fluctuating with the successive waves depending on various factors (availability of capital, demand for products, actors expectations, etc). Yet, progressively, 'under the radar', the legacies of previous waves may accumulate and lead to a gradual, hard to notice, increase in the potential rent that some actors might gain.

At some point, the region might see the emergence of a frontier. How does it happen? This original emergence can occur through at least two different but non-exclusive mechanisms. On one hand, it can be driven by exogenous factors: there can be a strong external subsidy to start with (e.g. direct financial subsidy or through infrastructures building, opening roads through the forest and so on), typically by states, which support the cost of frontier establishment when, in the absence of agglomeration economies, land use has very low profitability and competitiveness. This happened in many settlement frontiers as discussed above. The notion of frontiers as places of territorialization is central here to explain how and why large external actors such as states or even, in some cases, corporations, would deploy such large efforts to overcome the constraints on frontiers kickoff. When led by private actors, these exogenous inflows of resources would typically reflect important changes in market demand for certain commodities, or would occur in periods of high capital availability and lower returns in other sectors (such as the global financial crisis in 2007–2008), or require what can be called 'deep pockets' actors, i.e. corporations or non-profit organizations that can tap into a large pool of resource during a sustained period of time, with long-term objectives guiding their decisions [98].

Another series of mechanisms driving frontier emergence are more endogenous, having to do with anticipation (i.e. expectations and actions thereupon) by actors, either local or external but focussed on that region. Building among others on legacies of earlier waves, pioneers may develop sufficiently strong beliefs that farming or other resource use can become profitable in the future to continue to invest even in the face of adversity and low profitability, and even attract more people that believe in their anticipation narratives, creating 'cohorts' of investors [84]. These activities might eventually drive the structural changes that create the conditions for rising the rent, for example, if the number of people and the amount of activity involved surpasses a certain economic throughput threshold to shift from 'economies of anticipation' to 'economies of agglomeration'—essentially enacting a self-fulfilling prophecy.

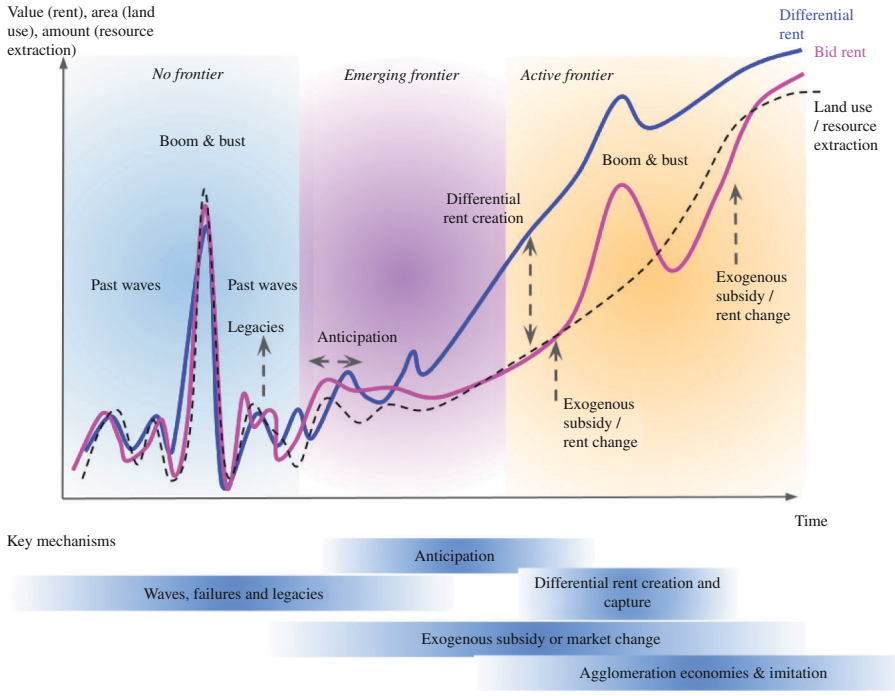

Figure 1. Our proposed frontier emergence theory. The starting point is an area that has the potential to become a resource frontier, but is not yet one (or was but in the past). The extent of land use and resource extraction fluctuates over time, as well as the bid rent (the value that most actors can extract and are willing to pay for the land), and the differential rent that only specific actors can achieve. In the 'no frontier' stage, the rent is low for all actors, there is no specific differential rent that certain actors can achieve. Under several key mechanisms, the area might become an emerging frontier and then an active one. Even though most mechanisms operate at the different stages (i.e. no frontier stage, emerging frontier stage and active frontier stage—for instance, booms and busts can occur throughout the process), the theory proposes that certain mechanisms are key at certain stages. The theory is not deterministic, i.e. it does not say that the area will necessarily go through these stages. The 'no frontier' stage, which can be characterized by multiple waves that do not trigger a large-scale frontier, can last for a long period and other trajectories are possible. As we focus on emerging frontiers, we leave the active frontier stage, where the rent continue to increase, as open-ended. s continues to increase, as open-ended.

When the rent starts to rise, the frontier process is activated. The differential rent that some specific actors with particular endowments can anticipate, create and capture [39] plays a specific role in kicking off or accelerating frontiers: as the overall rise in rent, the rise in differential rent incentivizes actors (here a subset of the actors) to expand the frontier land uses. But, even further, in many cases, the actors may expect their differential rent to dissipate over time, e.g. as their privileged information becomes available to all actors, or their political agency fades because of changes in political regimes. These actors are thus incentivized to expand as fast a possible to extract as much as possible of their differential rent. Such differential rents can be supported or exacerbated by various endogenous or exogenous processes, such as legacies of previous waves or processes of accumulation by dispossession. Exogenous subsidies, which include continuously increasing demand for the commodities produced, also continue to increase the overall rent. Eventually a certain critical mass is reached at which agglomeration economies take over and frontier expansion becomes self-reinforcing. Moreover, such self-reinforcing processes as well as the initial dynamics of anticipation can be further reinforced by other positive feedback loops, which are typically social, such as imitation, which feed into one another [123]. Boom and bust cycles also contribute to the frontier expansion [123,124].

At some point, the differential rent achieved by certain actors may dissipate, as noted above, eliminating the disequilibrium and, from that, driving frontier expansion in line with changes in land rents as explained by standard equilibrium land rent theories. Ultimately, the frontier may start to stagnate or saturate, particularly if the depletion of the resource makes it scarce or its extraction more costly. At this stage, the region can be described as 'consolidated', but it might at some point experience the emergence of a new frontier caused by renewed anticipation or a sudden new source of land rent disequilibrium. Land-use expansion into marginal lands and extractivist production modes frequently lead to land degradation in frontiers, causing the land rent to drop, possibly down to

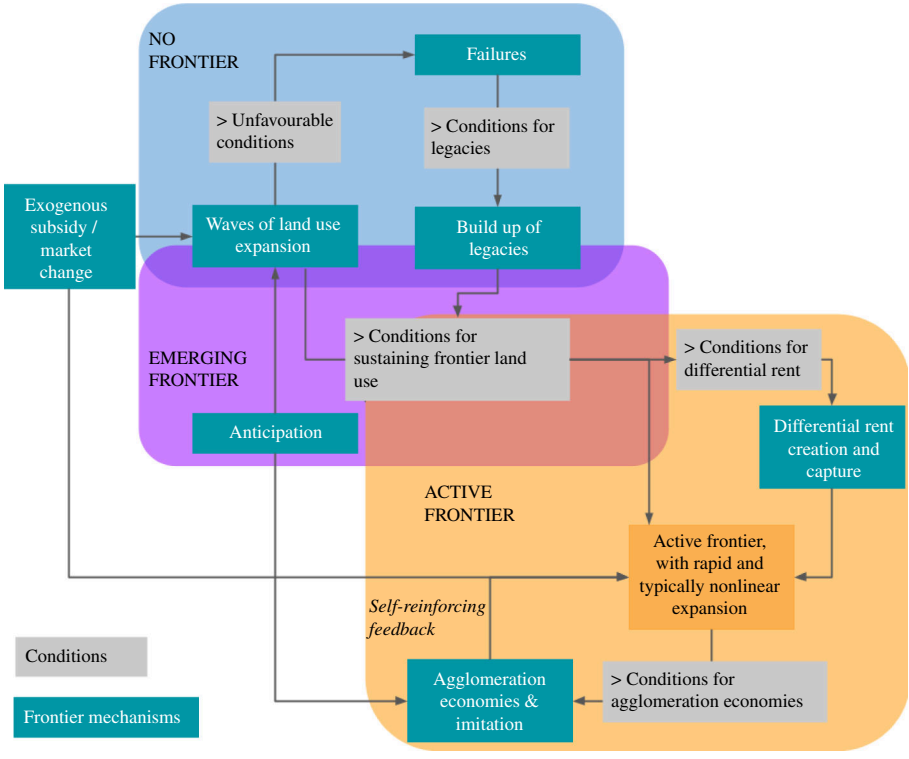

Figure 2. Mechanisms and conditions in our proposed theory of frontier emergence and activity. The starting point is an area that has the potential to become a resource frontier, but is not one. Through several mechanisms that operate under certain conditions, the area might become an emerging frontier and then an active one. Economically, 'unfavourable conditions' correspond to negative bid rent, 'conditions for sustaining frontier land-use' to positive bid rents and 'conditions for differential rent' to bid rents for specific actors being largely above the rent for the remaining actors. But the conditions encompass more than economic factors. Only key mechanisms are represented here. The theory is not deterministic, i.e. it does not say that the area will necessarily go through these stages, and other trajectories are possible.

zero, resulting in land abandonment. As we focus on frontier emergence, we did not represent these dynamics in figure 1.

The process of frontier emergence can fail owing to external factors like wars or economic crises, as well as endogenous dynamics, for example, if legacies of past waves are insufficient to raise the economic rent, or failures depress actors' anticipations and prevent a subsequent wave. Commodity boom and bust cycles can contribute to the depletion of assets and resources, for instance by degrading the land and making it harder for a further frontier wave to emerge. Conversely, boom and bust cycles might pave the ground for further frontiers by destabilizing land uses and social, economic and institutional structures: leaving behind an unprofitable or unmarketable crop that necessitates replacement by a different commodity crop, or changing local people's attitudes into a 'boom mentality' focused on 'quick money' [3].

States and other actors' exogenous subsidies and efforts may be too small to overcome the endogenous constraints on resource use. Territorialization efforts might face too strong a resistance from local populations. If no differential rent is created, the frontier can proceed only through incremental adjustments of the equilibrium land rent, which is presumably more gradual than the capacity for certain actors to create sudden, higher than mainstream rents. Throughout the process, the role of uncertainties and asymmetric information is crucial, including in creating gaps between economic and bid rent (overestimating or underestimating the value of a resource). Actors' anticipations are necessarily based on uncertain knowledge about the future. Differential rents are strongly linked to different actors having distinct levels of information (e.g. on quality of land for agriculture, timber or mining resources in an area, etc.), as well as power. The same decision taken in different circumstances can lead an actor to benefit from large differential rents, or to be doomed to failure if the rent is too low and that actor does not have the deep pockets to sustain investments over a long time.

This is a stylized account; real-world situations might deviate from this account or borrow only some of its elements. We highlight here the key mechanisms that operate at each state, but they can also operate at other times: anticipation and expectations of actors influence their decisions all along

the way; agglomeration economies can occur, even if only lightly, in early frontier situations, etc. This theory largely fits with distinct types of actors and land uses or resources, though with nuances. Frontiers dominated by smallholder colonists would typically be more supported by exogenous subsidies from governments, while in corporatist frontiers with powerful actors, the mechanisms of differential rent creation and capture might be more important.

5. Frontiers, sustainable development and governance

This article focuses on *how* frontiers emerge, more than *whether they should emerge* or not. Whether frontiers are desirable for local communities, external actors or stakeholders or sustainability in general is another question, which likely has no singular answer. While we do not respond to this question here, our frontier theory can provide insights for sustainable development in regions where frontiers do happen. How frontiers emerge and unfold, possibly fail or finally transform to other land-use dynamics has profound implications for the trajectories of rural development and sustainability outcomes in these frontier regions and beyond. Much of the early literature on frontiers in tropical, low- and middle-income countries had a rather pessimistic outlook about the fate of smallholders in colonist frontiers. Narratives have often revolved around how poor smallholders were opening frontiers, either spontaneously or with state support, to escape land scarcity and rising land prices in consolidated regions, yet arguing that their fate in frontiers was often not better, as their land use would lead to land degradation, soil exhaustion, poverty and failure [125]. Further waves of capitalist penetration through powerful actors would then consolidate the land and concentrate resources, leaving smallholders with the only option of furthering the frontier process ([126], refer §3.3). Yet, the evidence shows that different frontier trajectories can lead to vastly different outcomes. Some frontiers give rise to consolidated land systems that may allow conserving natural habitat, that maintain denser populations, or even have a positive distributional impact on land or economic flows. Some frontier regions may become economic 'power-horses' in the country, such as Mato Grosso in Brazil. A theorization of how frontiers emerge and unfold, as proposed above, leads to five insights on how to steer frontiers in order to contribute to sustainability and equity.

First, several theoretical lenses on frontiers presented above converge to typically conceive frontiers as places that are empty or unused. Indeed, the emergence of many frontiers builds on narratives about the abundance of unused land and untapped opportunities, and the resource frontiers theory itself is based on this notion. Multiple efforts have been made to assess the extent of lands that are considered as 'unused', 'underutilized', 'marginal', 'empty' or 'uncontested' [68]. Yet, ample evidence, backed by theoretical developments, make it clear that such lands are very rare. Most land is used somehow, even if for the purposes of being set aside, and thus, land-use frontiers almost always unfold on land that is already claimed, occupied, used, managed or transformed by people, or already provide benefits [24,26,68]. Traditional smallholder colonist frontiers often expand into land occupied by Indigenous people, as do many corporate or commodity frontiers, which also expand into areas occupied by smallholders, semi-subsistence or traditional land uses, including pastoralists systems. Recently emerging renewable energy frontiers also typically expand on land already used, although it can also 'stack' onto these lands, for example, through agrivoltaics [127].

In contrast, other frontier theories such as the capitalist penetration thesis or frontiers as spaces of territorialization and frictions are precisely based on the principle that these spaces are *not* empty when the frontier unfolds. Our theory of emerging frontiers, which builds on the notion of consecutive waves and their legacies, also highlights that frontiers do not emerge in a vacuum. This is not in contradiction with the resource frontier premise that the frontier emergence builds on the availability of a resource (land) targeted for some purposes. In frontiers, the resource is there, but it is often used for other purposes, at other rates of extraction, and/or by populations that do not have formal tenure rights, or have rights but have a power differential with other actors that aim to claim these resources. Recognizing that frontier processes almost always impinge on resource use rights and access might help to acknowledge and mitigate potential conflicts and losers, in contrast with a 'terra nullius' narrative.

Second, resource frontiers incentivize unchecked resource extraction and thereby typically create unfavourable conditions for efficient use of resources [18,20,128]. This implies that even though the frontier land use might be more intensive than the ones it replaces, land users are incentivized to expand to claim as much as possible of the resource, rather than dedicate their production factors to intensify. This is especially the case in primary frontiers where new land users enter into the area and

land use expands into not-yet-converted ecosystems.[1] Conversely, theories of induced intensification [59,129–131] show that, under the appropriate capital, technologies, knowledge and market conditions, strong constraints on land-use expansion in frontier regions can lead to intensification of agriculture, e.g. in the Brazilian Amazon [55,132–134]. This implies two things. First, governing frontiers for halting conversion of natural ecosystems and improving sustainability outcomes does not necessarily imply a trade-off with economic development. Second, assuming that intensification will occur spontaneously in frontier contexts, and that intensification—whether spontaneous or supported by policies—will lead to a closure of the frontier, goes against what we know about how frontiers work. Instead of assuming that intensification will spontaneously occur and reduce pressure on land [135], controlling land-use expansion should go ahead or at least hand in hand with interventions to support intensification.

Third, although *exogenous* subsidies, incentives, and triggers can play a key role in driving frontier processes, our proposition shows that *endogenous* dynamics including legacies of past waves, actors' anticipations,[2] mechanisms for differential rent creation and capture and the progressive built-up of agglomeration economies, also matter and may even be the main drivers of frontier dynamics. The focus on exogenous drivers likely influenced the somewhat pessimistic outlook often put forth in classic frontier theories—namely that of frontiers essentially emerging from external pressures on land and where the absence of 'virtuous' endogenous dynamics inexorably leads to degradation and impoverishment. Such narratives were dominant for a long time with regards to cattle frontiers, assumed to have low potential for intensification and sustainable rural development owing to a lack of both motivation and means, trapping cattle ranchers into extensive agriculture, poverty, land degradation and perpetual expansion of the frontier. More recent works have shown the importance of endogenous dynamics, including the role of medium-scale institutions (institutions between individuals and the state), such as agricultural cooperatives, in mediating the demands from individual farmers towards the state, establishing better negotiating conditions with input and output suppliers, and thus leading to more socioeconomically positive frontiers development and more productive agriculture [136]. This line of thought is pursued in works on agglomeration economies in soy [99,100,137,138]. Overall, these works explain how under certain circumstances an initial frontier can become more intensified, profitable and provide livelihood means to relatively dense populations.

Fourth, frontiers progress through different stages or steps, which correspond to different processes, and thus in which different forms of interventions can be more or less effective [12]. The proposed theory identifies emerging frontiers as a pivotal time, when the fate of land use and human-environment systems can still be steered through several levers [139,140]. At this stage, mechanisms of differential rent capture and agglomeration economies are not strong and thus vested interests that benefit from a rolling out of the frontier are not yet powerful. As exogenous pushes can be key to frontier emergence, any effort to preemptively drive institutions (states, financial investors, agribusiness companies and so on) to focus their investments on sustainable land uses and land-use planning efforts can be critical. Learning lessons from the pioneers who have been building and nurturing legacies of previous land-use waves can be crucial to avoid repeating mistakes, be they related to local population livelihoods or costly operations failures, which can risk creating large waves of land-use expansion with their deforestation and dispossession, for very little subsequent outputs [9,141,142]. Steering actors' anticipations towards more sustainable land uses is also possible at this stage. Preemptive or proactive measures can help to increase resilience and adaptability of social-ecological systems to frontier processes as a form of 'extreme event' [143]. Clarifying and strengthening land tenure rights of local communities, for example, can increase their resilience to sudden frontiers emergence.

Fifth, with this theory, does it mean that we can predict frontier emergence? The short answer is: probably not, as many aspects in this theory remain insufficiently quantified, and contingency and exogenous forces do play a major role in frontier emergence, but we can hopefully identify places that have a certain number of the characteristics that make them *prone* to see frontiers emerge within.

[1]In secondary frontiers that experience crop booms where one crop replaces another in already established agricultural landscapes, like banana boom replacing paddy in northern Laos (123), the resource (land) is likely seen as less freely available, as paddy lands are already clearly delineated, with secure tenure. In that case, incentives might favour relatively intensive land uses, though likely less than in regions where the frontier land use is already well established and consolidated. In these contexts, many aspects of the frontier theory remain valuable though, including those related to differential rents, spaces of opportunities, frictions and anticipations.

[2]Noting that not all actors with anticipations are endogenous, external actors can also form anticipations about the frontier region, and these two groups of actors can reinforce each other's expectations and anticipations.

Resource availability, exogenous push and subsidy, the build-up of legacies from previous waves and the rise of actors' anticipations of changes in land rent are the key elements that we identified as decisive to turn a region into a frontier. They can all be explored and monitored to some extent, although exogenous pushes are hard to forecast, and capturing legacies and anticipations require grounded knowledge of the contexts and actors. Inventories, mappings, forecasts and modelling exercises aiming to identify regions that are prone or vulnerable to sudden large-scale land-use expansion might aim for improved incorporation of such bottom-up knowledge on past land-use waves, legacies and actors' anticipations and expectations, while also investigating whether certain data can constitute adequate proxies for these factors.

6. Conclusion

We here synthesized a broad but theoretically grounded definition of resource and land-use frontiers, as well as different conceptualizations and theories explaining such frontiers. This work is rooted in the context of agricultural, forestry and deforestation frontiers in the tropics, but can be inspirational for other kinds of frontier processes involving extractive resources, like minerals, energy or conservation frontiers, or even broader forms of 'resources' such as opportunities for market, political or religious expansion. From that, we proposed a synthetic theory of emerging frontiers. This theory identifies exogenous pushes, legacies of past waves and actors' anticipations as the key mechanisms by which frontiers emerged from territories considered marginal in terms of agricultural productivity and connections to global markets, and processes of differential rent creation and capture and the progressive built-up of agglomeration economies as the key mechanisms that sustain active frontiers roll out.

We finally discuss five insights derived from our synthesis, on the crucial role of land-use policies to steer intensification in resource frontiers contexts; the importance of endogenous dynamics on the sustainability outcomes in frontiers; the pivotal role of emerging frontiers; and prospects for identifying potential frontier spaces. These insights remain general but might inspire more context-specific works on frontier governance. Together, these insights might help to better understand how to balance development, sustainability and equity concerns in regions that hold abundant resources but might be prone to rapid, uncontrolled, environmentally damaging and inequitable frontier processes.

Ethics. This work did not require ethical approval from a human subject or animal welfare committee.

Data accessibility. This article has no additional data.

Declaration of AI use. We have not used AI-assisted technologies in creating this article.

Authors' contributions. P.M.: conceptualization, funding acquisition, investigation, project administration, supervision, visualization, writing—original draft, writing—review and editing; D.A.: investigation, writing—review and editing; M.B.: investigation, writing—review and editing; A.B.: investigation, writing—review and editing; A.B.: investigation, writing—review and editing; C.C.: investigation, writing—review and editing; V.J.: investigation, writing—review and editing; A.K.G.: investigation, writing—review and editing; T.K.: funding acquisition, investigation, writing—review and editing; YlPdW.: investigation, writing—review and editing; E.O.: investigation, writing—review and editing; M.P.: investigation, writing—review and editing; S.Q.: investigation, writing—review and editing; V.R.G.: investigation, writing—review and editing; P.R.: investigation, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

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