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Digitalizing forest landscape restoration: a social and political analysis of emerging technological practices

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ABSTRACT
Digital technologies are increasingly influencing forest landscape restoration practices worldwide. We investigate how digital platforms specifically reconfigure restoration practices, resources, and policy across scales. By analyzing digital restoration platforms, we identify four drivers of technological developments, including: scientific expertise to optimize decisions; capacity building through digital networks; digital tree-planting markets to operate supply chains; and community participation to foster co-creation. Our analysis shows how digital developments transform restoration practices by producing techniques, remaking networks, creating markets, and reorganizing participation. These transformations often involve power imbalances regarding expertise, finance, and politics across the Global North and Global South. However, the distributed qualities of digital systems can also create alternative ways of undertaking restoration actions. We propose that digital developments for restoration should not be understood as neutral tools but rather as power-laden processes that can create, perpetuate, or counteract social and environmental inequalities.

KEYWORDS Forest landscape restoration; forests; digital technologies; participation; social inequality

Introduction

Digital technologies are now proliferating through attempts to address environmental change and political demands (Gabrys 2016, Nitoslawski *et al.* 2021). Remote sensing, Lidar, machine learning, unmanned aerial vehicles (UAVs), smartphone apps and other digital operations have quickly transformed landscape restoration practices into digital procedures that link the ground to the cloud (Adams 2018, Elliott *et al.* 2020). These technologies are expected to ensure greater accuracy, productivity, and cost-effective interventions across spatial and temporal scales (de Almeida *et al.* 2020). From landscape assessment to ecosystem monitoring approaches, digital techniques directly influence restoration decision-making processes and potentially generate a new paradigm for restoration projects (Elliott 2016). While there is growing attention to and significant investment in digital

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developments for recovering degraded landscapes globally (Castro *et al.* 2021), these methods also shape multiscalar governance systems that can create or reinforce unequal power dynamics in knowledge production, financing, and market arrangements. This article examines how digital technologies can influence restoration policies and practices, specifically in the form of digital platforms to facilitate forest landscape restoration, and the social and political consequences of these technological practices.

Ecological restoration has quickly shifted over the last few decades from a field of applied ecology to a broader international political strategy to trigger sustainable development actions (Chazdon *et al.* 2017). Forest landscape restoration (FLR) has emerged in this context to address complex environmental challenges associated with biodiversity conservation, land-use change and regional development (Wolff *et al.* 2018). FLR is entangled with multiple stakeholders, knowledge systems, and management practices that configure speculative, rhetorical, and concrete aspects of how restoration is negotiated, implemented, and monitored to achieve different goals (Mansourian *et al.* 2020). For this reason, the political aspects of FLR exceed individual actors or policies to encompass a broad range of influences and effects. Digital technologies can have multiple political effects depending upon how they streamline or transform restoration activities.

In the wider arena of restoration policy, a number of international agreements and negotiations have set the ambitious task of restoring 350 million hectares of degraded lands by 2030, including the Bonn Challenge (IUCN 2011). Recently, the United Nations General Assembly designated 2021–2030 as the Decade on Ecosystem Restoration (UN 2021), followed by the announcement of the Glasgow Leaders' Declaration on Forests that 141 nations endorsed to end illegal deforestation and reverse land degradation during this decade (UNFCCC 2021). International restoration pledges are also directly aligned with the Aichi Biodiversity Targets, Sustainable Development Goals (SDG), and the REDD+ program to mitigate and adapt climate change and protect biodiversity while improving community livelihoods and regional development.

Although the aspiring worldwide targets and programs have promoted FLR as a central intervention for accomplishing an international conservation agenda, the design and implementation of these projects raises issues about the possible impacts of these interventions on places and people (Osborne *et al.* 2021). Large-scale restoration projects typically involve tree planting with commercial species that have limited ecological outcomes or socioeconomic opportunities, which can exacerbate social inequalities and expand land clearing (Fleischman *et al.* 2020, Holl and Brancalion 2020). While the need for improved approaches to restoration is well documented, these practices are frequently restricted by the high cost of implementation and lack of funding (Crouzeilles *et al.* 2020). As a result, a number of restoration practices focus on efforts to optimize resources and maximize productivity (Sacco *et al.* 2021). By adopting digital technologies, scientists and technologists anticipate that restoration interventions will recover the ecosystem functionality of degraded landscapes while reducing costs (Masarei *et al.* 2021).

Within landscape restoration, digital technologies can refer to a wide range of computing devices, tools, and resources that enable data collection, processing, storage, and transmission across systems (Hukal and Henfridsson 2017). In forest environments and other ecosystems, these technologies influence practices to manage and mitigate environmental change (Gabrys 2020). For example, digital technologies in the form of precision forestry can indicate how to plant the most suitable species according to time of year and location, while improving the effectiveness of restoration techniques (Castro *et al.* 2021). Emerging technologies further include the use of spatial prioritization techniques for landscape restoration, robotics for tree planting, digital devices for species identification, and automation of ecosystem monitoring (Elliott *et al.* 2020).

Digital platforms are the focus of extensive social science investigations that analyze how the 'politics of platforms' facilitate public discourse (Gillespie 2010). Platform ecosystems can facilitate democratic and public values, such as transparency and privacy, but they can also restrict participation (Van Dijck *et al.* 2018). However, there is comparatively little research on how platform dynamics shape environmental practices and policies. Here, we examine how digital platforms reconfigure the power dynamics in FLR and remake how practitioners, experts, community networks, policymakers, and funders influence restoration practices and negotiate political processes.

This article next presents our research methods, where we describe how we selected and assessed digital platforms for restoration activities. Following these descriptions, we present and discuss in more detail the four types of drivers of technological developments that we identified from this review of digital restoration platforms. Driver one relates to how scientific expertise influences restoration optimization discourses and shapes policies from local to global scales. Driver two pertains to how digital networks for capacity building create shared ideas, projects, and stakeholders that generate technological practices and resource allocation. With driver three, we analyze digital tree-planting markets to build global commercial arrangements for large-scale restoration projects. Finally, with driver four we describe the formulation of digital platforms that are developed from the bottom up and underpinned by local perspectives and demands.

Materials and methods

Reviewing digital platforms

As part of a broader research program on smart forest technologies, we first conducted a comprehensive scan of emerging technologies in increasingly digital forest spaces. Our initial search included scholarly literature documenting and analyzing forest sensors, machine learning and algorithms, satellites, Lidar, blockchain structures, mobile applications, and UAVs. Through a state-of-the-art review (Grant and Booth 2009), we undertook an extensive and global search of studies, practices, initiatives, and projects to identify literature and technological developments. Rather than following a retrospective approach, this review focused on identifying current trends and operative digital technologies. From March to September 2021, we undertook keyword searches (Appendix A) in literature databases (Scopus, Web of Science, and Google Scholar), search engines (Google), mobile application stores (App store, Google Play), and restoration-related websites (e.g. FAO, UNEP, CIFOR, and World Agroforestry Centre) to identify a range of digital technologies used in diverse ecosystem settings. These results were filtered to remove duplicates and select sources based on their relevance to current trends and developments. Given the wide scope of this search and the extensive availability of literature and technologies, this resulted in a large but non-exhaustive database (> 1,500 items including articles, web pages, projects, and digital platforms).

After completing this search, we identified digital platforms specifically oriented to restoration, reforestation, or tree planting actions as material for this study. We selected 55 digital restoration platforms for further review (Appendix B). With regards to FLR, these platforms include interactive applications, such as Google Earth Engine and Global Forest Watch, as well as platforms for tree planting, planning, or monitoring with local stakeholders. 'Digital platforms' or 'digital restoration platforms' in the context of this review include online and interactive connected spaces accessible via websites or mobile applications that enable users to participate in and influence restoration discourses, planning, or practices. This approach draws on related literature in platform studies that has adopted broader definitions of platforms as interactive computational architectures where users interact and exchange data, including through content-sharing websites and social media (Gillespie 2010, Helmond 2015). While we intended to review a diverse range of platforms, large-scale technological developments tend to be undertaken in the Global North for restoration projects in the Global South. Our selection – mostly projects and programs working at the global scale – reflects a similar trend.

Table 1. Guiding questions for analyzing selected digital platforms for forest landscape restoration.

Focus areas	Guiding questions
Development processes	Who influenced the development of the digital platforms? Which forms of knowledge and practices are recognized and used to build the digital platforms?
User interactions	How do narratives and aesthetics encourage different forms of engagement? How are the platforms designed to promote engagement, access information, and share knowledge?
Restoration transformations	Which restoration actions does the digital platform produce or support? How does it influence restoration techniques? How do the digital infrastructures change restoration practices, policies, or outcomes?

Social-political analysis of restoration platforms

We examined the selected digital platforms to understand their operations from a user's point of view by testing websites, following user guidelines, and reading technical reports. We undertook our assessments through six guiding questions that attend to development processes, user interactions, and the tangible impacts on restoration policies, actions, and outcomes (Table 1). We also identified the developers, the functionality of the platforms, and the specific contributions to the stages of restoration planning, designing, implementing, and outcome monitoring. Based on this process, we then summarized platform characteristics and their role in informing and transforming policies and practices. This analysis revealed social-political dimensions of restoration platforms that we analyze through four drivers of technological developments for FLR.

Digital engagements with forest landscape restoration

While international commitments, domestic regulations, and multisector investments contribute to the restoration of degraded lands (Chazdon *et al.* 2017, Mansourian *et al.* 2021), emerging technological developments configure and shape actual FLR activities (Figure 1). Digital platforms are becoming a core component of proposed multi-sector collaborations, campaigns, supply chains, and grassroots interventions to implement not only technical procedures but also remake how restoration is perceived, experienced, and applied on the ground. Here we summarize the results of our review of 55 digital restoration platforms and discuss how they configure distinctive engagements with FLR, as a practice and decision-making process (Table 2). These operations include multi-user databases, geospatial mapping and planning, smartphone applications, games, citizen- science databases, blockchain systems, crowd-funding networks, and social media. The

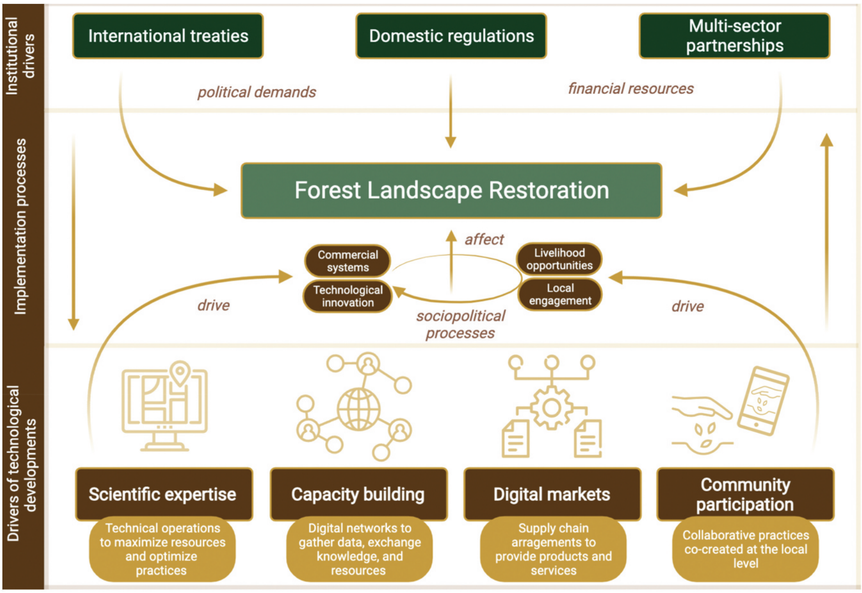

Figure 1. Drivers of technological developments that shape socio-political processes of forest landscape restoration across scales to implement political targets and programs driven by international treaties, domestic regulations, and multisectoral partnerships.

following sections each explore how these four digital development drivers remake restoration practices and transform socio-political processes at different levels.

Driver 1: scientific expertise to optimize restoration

Scientific expertise for FLR produces and organizes a wide array of technologies to predict accurate scenarios, select feasible methods, and create supposedly cost-effective interventions that shape restoration activities (Table 2). The 'Atlas of Forest and Landscape Restoration Opportunities',[1] 'Framework for Ecosystem Restoration Monitoring' (FERM),[2] and 'Vegetationmap4africa'[3] platforms are especially indicative of attempts to mobilize scientific knowledge to optimize restoration. These digital innovations often aim to optimize restoration operations and maximize resources to respond to ambitious international restoration pledges. Many of these emerging digital platforms seek to identify supposedly vacant degraded lands for selection of geographical areas and financial investments for large-scale restoration (e.g. Crouzeilles *et al.* 2020). These approaches are the result of aerial views of landscapes generated through remote sensing, big data, algorithms, and other digital processes that facilitate scientific assessments (de Almeida *et al.* 2020). For instance, as part of the Bonn Challenge initiative the

Table 2. Overview of selected digital platforms categorized as four different drivers of technological developments for forest landscape restoration (FLR).

Drivers of technological developments for FLR	Main functionality	Restoration activity	Examples of digital platforms
Scientific expertise	Technical operations guided by scientific expertise that aim to maximize resources and optimize restoration practices	• Landscape assessment	Earth Engine (Google); The Restoration Atlas (WRI); Tree Canopy Insights (Google); Trees and health app (SUPRlab); SEPAL forest restoration planning tool (FAO); Global Forest Watch (WRI).
		• Planning and implementation	Africa Tree Finder App; CliMate change in East Africa; Terraformation; App Rural Legal!; CostingNature; WePlan-Forests; InVEST
		• Monitoring outcomes	TreeMapper; Restoration Observatory; The Framework for Ecosystem Restoration Monitoring (UN)
Capacity building	Global networks that interconnect stakeholders to exchange experiences and facilitate access to resources	• Gathering data, databases, and communication channels	Restor; Restoration Implementers Hub (UN); The Regreening Africa App
		• Training, seminars, and capacity building	Restoration Resource Center (SER); GLFx (Global Landscapes Forum)
		• Access to investments and funding support	The Land Accelerator (WRI); Terramatch (WRI); Crowdfunding platforms
Digital markets	Commercial platforms that encourage global restoration supply chains, tree planting	• Creating global restoration markets • Establishing supply systems and business models	FLRchain; Alipay; Cultivo; Farm-Trace; Thuru; Plant for the Future; Klima – Live carbon neutral; Plant for the Planet; Ecosia; Reforestum; TreeApp
Community participation	Grassroots practices shaped by participatory processes with the aim to meet local or place-specific needs and demands	• Internal communication channels	WhatsApp; Messenger; Signal; Google meets; Skype; Zoom
		• Sharing local knowledge online	Instagram; Twitter; Facebook
		• Co-development practices with local communities	Redário

Atlas of Forest and Landscape Restoration Opportunities was first launched in 2011 as an online management tool financed by transnational environmental non-governmental organizations (NGOs) to map global restoration opportunities and to better inform political decision-making processes (Minnemeyer *et al.* 2011). This digital map revealed an unprecedented global land assessment by identifying two billion hectares of land as potential sites for FLR, mostly in tropical regions of Asian, South American, and African countries (WRI 2014).

Digital technologies and platforms become tools that legitimize and include (often expert) knowledge and practices (Büscher 2016). For example, in the case of WRI's FLR Atlas, the developers adopted biophysical variables combined with population density datasets to map current and possible forest distribution on earth. This technique addresses the need for restoration interventions in a particular site as inversely proportional to population density (Laestadius *et al.* 2011). These arbitration land-use planning metrics disregard complex territorial dynamics, including regional land-use practices, development and economic pressures, and diverse sociocultural perspectives. In response to criticism about the disastrous impacts of large-scale afforestation initiatives (Bond 2016), the WRI Atlas researchers highlighted how this tool is a platform for global land assessment, rather than planning and implementation (DeWitt *et al.* 2016). However, such a statement can depoliticize knowledge-making processes by neglecting how scientific knowledge mobilizes and shapes actions.

This analysis shows how the WRI Atlas was not produced to support restoration as an on-the-ground practice. Instead, it contributed to a scientific narrative that responded to international agreements such as the Bonn Challenge. By optimizing responses within designated restoration areas, the Atlas legitimizes and promotes global-scale restoration targets and programs. Here, abstract scientific expertise and the development of digital platforms coalesce to sustain international development policies, often at the exclusion of the more complex dynamics of ecosystems that may diverge or converge from this evidence.

Digital technologies that mobilize scientific expertise can thus directly influence how powerful actors respond to multilevel policies. Standardized digital land-monitoring processes are now aligned with international restoration programs for measuring the progress of projects through consistent and replicable scientific methods. The United Nations Decade on Ecosystem Restoration brought together 277 specialists to implement a global monitoring framework to measure and report how worldwide restoration would reach its established goals by 2030 (UN 2021). For example, the recently launched FERM is a geospatial platform for scientists and policymakers to identify and monitor restoration actions to achieve the UN Decade on Ecosystem Restoration goals. This sophisticated digital system includes several scientifically grounded indicators to measure the progress of member countries in implementing restoration across scales in varied ecosystems. Member countries will be encouraged to use this system to track restoration progress and demonstrate how local projects implement the SDGs and multilateral environmental commitments, including the Paris Agreement.

While some platforms entangle scientists with global restoration politics, others demonstrate how scientific expertise can support local and community decision-making processes. For instance, several digital tools for plant species identification and selection adopt scientific taxonomies and technical guidelines, which identify particular trees and their ecological functions for achieving pre-designed restoration goals. One example includes a collaboration among scientists associated with a scientific center for rural development, the International Council for Research in Agroforestry (ICRAF). This initiative designed the Vegetationmap4africa as a digital vegetation map for seven eastern African countries, which involved planning scenarios of natural resource management and conservation. By accessing these maps on smartphones and computers, users can identify the spatial distribution of 1,022 plant species across 48 vegetation types to support landscape restoration decisions, such as selecting the right tree for the right place (Breugel *et al.* 2015).

Such plant selection platforms can help to identify reference ecosystems and design restoration plans based on plant species distribution. However, these tools can neglect other (often local) knowledge about species and locations that offer a more place-specific understanding of different landscapes. For example, Laikipia Maasai and Samburu Indigenous peoples in Kenya follow community rituals and advice from elders to select relevant species for restoration (Kaunga and Johnson 2017). The incorporation of local practices to identify and select plant materials suitable for recovering degraded lands is widely recognized as a core component of successful restoration projects (Sacande and Berrahmouni 2016). However, because digital platforms tend to generalize approaches and work primarily with scientific expertise, which can lead to the exclusion of perspectives for planning restoration that are crucial for successful restoration projects.

The examples in this section show that while scientific evidence could help to optimize resources and effectively assess and plan FLR, platforms informed by these parameters typically rely on partial perspectives, limited data, and power inequalities, which drive large-scale forest restoration decisions. These digital platforms could theoretically accomplish restoration targets but fail to implement locally viable and ecologically sound restoration initiatives. When decisions regarding land assessment, monitoring, and planning restoration activities are made with these digital platforms, FLR practitioners can potentially overlook local knowledge and more complex dynamics that ensure the longevity of restoration projects. Scientific expertise coded into digital restoration platforms could then exacerbate inequality in pursuit of restoration targets. Under the influence of digital platforms, the environmental politics of FLR could become more disparate and distanced from the people most influenced by restoration decisions.

Driver 2: digital networks for building global restoration capacity

Digital platforms can form networks that connect multiple stakeholders in practices of gathering data, exchanging resources, and communicating experiences. They can provide a wide variety of digital resources, such as online libraries and project management systems to create channels among stakeholders and facilitate learning processes (Table 2). Emerging and established platforms can transform restoration processes through decentralized information flows that remake collaboration, funding support, and project implementation. These digital networks often emerge through multisectoral partnerships across tech corporations with universities, development agencies, and NGOs often located in the Global North.

Practices for building capacity to implement restoration actions can also reflect powerful stakeholders' interests and their roles in negotiating plans and supporting projects, such as the Restor initiative.[4] This Swiss Digital Network is a prominent planning and managing system that connects practitioners and organizations who are running restoration actions worldwide. Restor was co-developed by ETH Zurich and Google. A few months after its release in 2020, the Restor platform registered 70,000 restoration sites. This platform offers technical input, including as site-specific geospatial analyses of biophysical conditions, monitoring, and managing restoration projects, and sharing information and data about project outcomes on varied landscapes (i.e. forests, wetlands, grasslands) through scientific datasets and models. Users provide the geospatial location of their sites combined with other types of data, such as their restoration intervention type and the year of implementation. They can adopt tools to make important decisions, including by identifying potential areas for restoration, selecting local plant species, and quantifying soil carbon storage. Moreover, this digital network helps with managing projects by adding field data (e.g. photos and notes) and creating connections with other initiatives globally to share experiences and build partnerships.

While these platforms can facilitate capacity building, they also can extract data from restoration users, plans and projects, which can be applied for a variety of other interests. According to their privacy policy, the Restor platform states that users' data can be used by Crowther Lab at ETH Zurich, Google, and other partners to develop research and new scientific insights. Researchers have recently questioned the ethical and scientific implications of harvesting user data to understand conservation issues (Jarić *et al.* 2020). Importantly, the use of such data can result in ethical issues and misinterpretation of realities associated with data biases, validation problems, inconsistency in data quality, and reinforcement of assumptions (Enni and Herrie 2021). Environmental data justice issues also potentially arise when information can exert political and economic influence over communities and conservation relations, such as data on Indigenous peoples and their lands (Pritchard *et al.* 2022).

Other digital platforms connect donors and investors with local stakeholders who either run or plan restoration projects. With a major international presence in shaping the FLR strategies, WRI also leads the Terramatch[5] and The Land Accelerator[6] initiatives. These digital platforms seek to transform local aspirations into entrepreneurial opportunities for initiating tree-planting actions and transformative social mobilizations in African, Latin American, and South Asian regions. For example, The Land Accelerator encourages local restoration initiatives to access restoration supply chains through business opportunities. On this platform, restoration entrepreneurs in the Global South are invited to join an annual training program by first answering an online questionnaire that specifically asks about economic opportunities for restoration. Selected participants then engage with a digital network of Global North experts and business mentors through several capacity building sessions. Rather than a centralized government initiative, these digital platforms create spaces for local stakeholders to present their initiatives and learn business strategies while potentially accessing funding directly from international foundations and investors. In this way, the restoration finance markets are reorganized through comparatively decentralized systems that link local stakeholders with international donors and funders.

However, such business programs also exhibit power dynamics that are common within development strategies, including unequal knowledge sharing between the Global North-South divide. To exemplify this issue, after one year of training in The Land Accelerator, four African participants from Kenya, Uganda, Kenya, and Niger pitched their potential restoration initiatives during an online live streaming session in May 2021. As feedback to one of the participants, a business mentor based in Seattle, United States, indicated:

> The typical investor audience doesn't care who you are until they care what you do [. . .] Your pitch needs to start with something like – "the forests in Uganda are in peril"; with the pictures of forests being cut down and even something stronger than that [. . .] The problem in Uganda is not farmers; you don't start with farmers; you start with the problem. The problem here is that we are losing the forests in Uganda.[7]

While here the U.S.-based mentor attempts to share entrepreneurial tactics for attracting global investors, this business expert also draws on common imaginaries of environmental collapse (Yusoff and Gabrys 2011), which can be more influential in mobilizing private sector engagement than documenting how people struggle with degraded lands. These strategies frame a 'right way' to think, plan, communicate, and act upon site-specific problems by universalizing narratives and perspectives within FLR (Osborne *et al*. 2021). Such approaches to tackling degraded lands further overlook how environmental impacts are often the consequence of ongoing structural injustices.

Through several examples, this section shows that digital platforms contribute to FLR capacity-building processes. At the same time, they present risks through partial data use and potential impacts to forest restoration practices. Furthermore, restoration platforms contribute to distinct environmental politics through the commercialization of data, investment of financial resources, and sharing of stakeholder benefits. These dynamics can create and exacerbate unequal power dynamics among investors and local stakeholders in networks across the Global North and Global South.

Driver 3: 'click to restore the planet' with digital tree-planting markets

Digital technology further transforms restoration processes by producing new channels for requesting and offering tree planting as part of a global green economy (Table 2). Tree-planting initiatives, such as Plant for the Planet,[8] TreeApp,[9] and Klima[10] offer carbon-offset services to individuals, companies, and foundations. These emerging digital operations have been instrumental in creating restoration finance markets by linking stakeholders in search of carbon offsets in the Global North with organizations and local groups (often in the Global South) responsible for managing and implementing restoration actions (Figure 2). Unprecedented multi-sector collaborations among platform developers, environmental campaigns, international brands, and non-profit organizations have resulted in online spaces that manage finances for tree-planting schemes. At the same time, the fragmented nature of these operations can complicate the roles, responsibilities, and rights between individuals, companies, tech enterprises and communities.

Tree planting through smartphone apps and webpages has become an emblematic way to express individual and corporate environmental responsibility (Jepson and Ladle 2015). Users can request and pay for ecosystems services in areas often remote from them through digital platforms. As part of the supply side of the tree planting production chain, tech entrepreneurs build connections with environmental non-profits that identify and select local stakeholders, particularly in the Global South, who have the capacity to facilitate the practical restoration operations, from tree seedling production and planting to ecosystem monitoring.

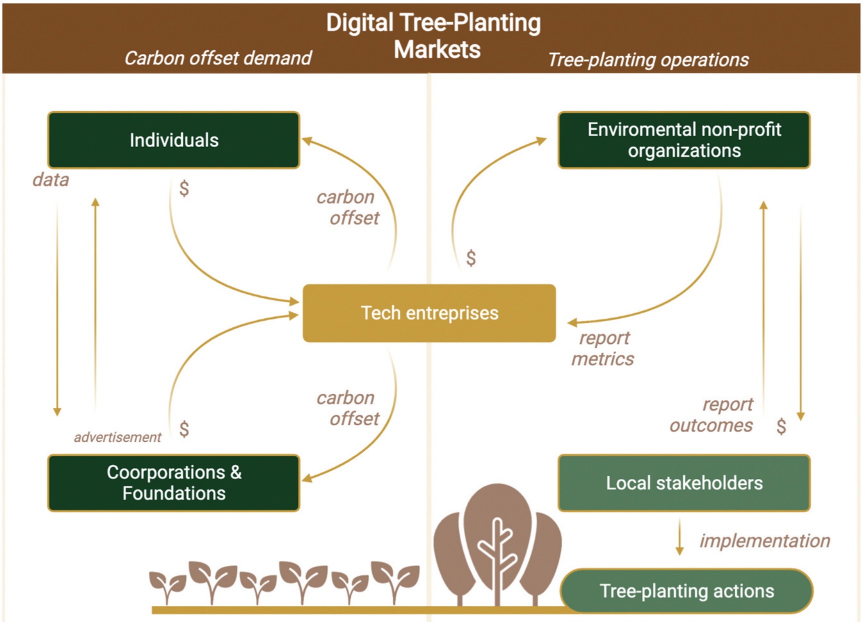

Figure 2. Large-scale tree-planting operations through digital platforms, connecting international carbon offset demands with restoration actions at the local level.

These dimensions become clearer through an analysis of the TreeApp. This British digital restoration platform is responsible for linking tree-planting market demands with on-the-ground initiatives through a smartphone app that drives and reports the planting of hundreds of thousands of trees yearly. As a business model, this app establishes partnerships with international lifestyle brands that pay for tree-planting activities from income created through app users' engagement with advertisements and commercial surveys. With these commercial partnerships in place, the TreeApp encourages individual users of the app to engage with advertisements from several brands in order to generate credits for tree planting across 14 different projects in the Global South, including initiatives in Madagascar, Mozambique, Tanzania, Indonesia, Peru and Brazil. Users can also decide to fund more trees through casual or monthly purchases of as little as £1 GBP per tree on the app. Hence, these digital operations for restoration markets can interconnect both supply and demand for recovering degraded lands, while also joining up the speculative and actual aspects of restoration as a practice for environmental change.

As part of TreeApp's engagement strategies, the aesthetics of tropical biodiversity and charismatic animals interconnect with community participation to illustrate how tree planting could address complex environmental

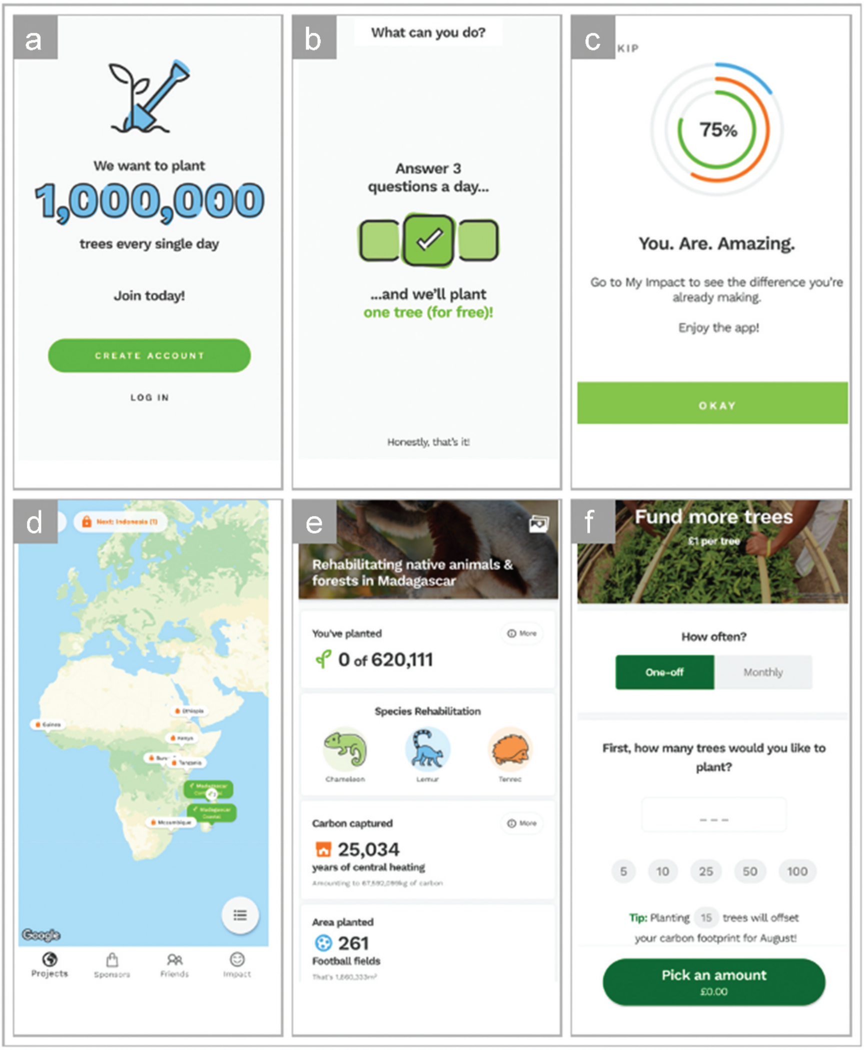

Figure 3. TreeApp screenshots illustrating different digital aspects of tree-planting markets: (A, B, C) narrative strategy to stimulate user's engagement with the application; (D) map illustrating the distribution of restoration projects across the world; (E) Example of Eden project's page reporting outcomes in Madagascar in terms of the number of trees, area planted and carbon capture; (F) tree purchasing page with recommendations of a number of trees to offset individual carbon footprint.

problems in the developing world (Figure 3). The visual and narrative components of these digital systems can capture and facilitate public involvement (Verma *et al.* 2015). The TreeApp adopts several strategies for maintaining users' commitment with the platform. Each user has a personalized impact profile to track the progress on the number of trees planted to offset individual carbon footprint, which is quantified through WWF's Footprint Calculator.[11] The app also sends daily notifications to motivate users to click and digitally plant forests, such as 'Make a difference and plant now' and 'Help to rejuvenate our planet.' These notifications further stimulate the emotional involvement of users and suggest that their actions will have an impact on FLR.

Tree-planting platforms use indicators to report outcomes to users and demonstrate how significant their actions are for improving environmental and social conditions. On the TreeApp, ecological outcomes are represented as collections of aesthetically pleasing photos and videos from the restoration sites, and simplified quantitative indicators, such as number of trees planted, size of areas under restoration, and the volume of carbon stored (Figure 3). While there are international principles and standards for monitoring areas under restoration (Gann *et al.* 2019), these digital tools tend to adopt generic metrics without in-depth methodological descriptions. For example, the American nonprofit Eden Reforestation Projects[12] operated several of the TreeApp's restoration projects. In August 2021, Eden's projects planted 411 million trees across 147 species using the TreeApp. Between 2019 and 2020, this non-profit organization reached financial growth of 275% ($18,288,923 USD), mostly as a result of partnerships with twelve corporations and access to grants from three foundations.[13] Such platforms benefit from the growing popularity of digital environmentalism to make profits as part of a global green economy (Sullivan 2013).

While such platforms remake environmental politics as a contribution that seems to be only a click away, they can be simultaneously disengaged from local forest livelihoods. While international brands and digital platforms offer new types of engagement with the forest restoration economy, they can be disconnected from actual restoration practices. They can also overlook the importance of tangible livelihood improvements, and fail to secure long-lasting jobs or stable household income in restoration locations. By promoting attention toward quantifying tree planting metrics, these digital platforms often neglect labor issues and benefit sharing associated with planting interventions. Local communities in the Global South typically play a central role in implementing restoration actions through their labor, local capabilities, and knowledge practices (Erbaugh *et al.* 2020). Eden's tree-planting approach, for instance, concentrates on hiring community members to implement restoration actions in low-income regions. According to Eden and TreeApp, tree planting creates 'consistent income' and transformative social change to reduce poverty levels. However, 'workdays created' is the only indicator reported by these organizations to measure how this international market impacts complex local socioeconomic realities.

These uneven power dynamics between who controls market demand and who is responsible for delivering the ecosystem services demonstrates the potential proliferation of inequalities in FLR.

Emerging digital restoration platforms, such as tree-planting apps, can overcome barriers forindividuals and companies interested in offsetting their carbon emissions or contributing to FLR activities. However, by using simplified metrics, commodifying restoration practices, and narrating FLR through attractive imagery that sells tree planting, these platforms can be disconnected from the locations where FLR actions take place. The performance of environmental politics by privileged consumers can contribute to less viable forest livelihoods for the people living with the consequences of click-based environmentalism.

Driver 4: community participation in digital restoration

While digital technologies are being advanced in forest science and policy arenas, digital platforms are also being adopted, adapted, and co-developed to enhance grassroots restoration and communication processes by local stakeholders (Table 2). Over the last few decades, community-led networks have created restoration planning and actions from the bottom-up by including local knowledge practices to address place-specific land-use issues (Urzedo *et al.* 2020). Our analysis of digital restoration platforms reveals how local restoration techniques also operate through the emergent use of social media (e.g. Instagram), smartphone applications (e.g. WhatsApp), and the co-production of digital developments from the bottom up.

Due to widespread mobile connectivity in forests, smartphones are now becoming popular technologies to support and deal with daily environmental management activities from data collection to social and political transformations in diverse community contexts (Skarlatidou and Haklay 2021). The most popular smartphone applications, including instant messaging technologies, such as WhatsApp, Telegram, or Signal, have supported internal knowledge sharing and negotiations in community restoration networks. These digital platforms connect online and offline political debates at the community level by mobilizing visions, stories, and experiences (Hendriks *et al.* 2016).

Indigenous peoples, smallholders, and urban residents in remote regions commonly use WhatsApp as a tool to organize logistics, share experiences, and identify species. For example, during the ongoing COVID-19 pandemic, the Xingu Seed Network,[14] a community-based seed supplier in the Brazilian Amazon digitalized their management activities with 600 seed collectors, including plant species selection, seed collection planning, and delivery logistics (Urzedo *et al.* 2022). Here, digital communication platforms became a primary means of organizing social and productive activities to coordinate the supply of about 25 tonnes of native seeds yearly for land restoration while maintaining social distancing practices (Schmidt *et al.* 2019). Such platforms offer ways to communicate in community groups by recording voice messages, videos and sending pictures. By using existing messaging technologies, seed collectors benefit from self-organizing their communications, rather than having systems imposed on them. On the other hand, community groups often do not have the benefits of financial and political power that app-makers operating from the Global North enjoy. While big tech companies impose particular ways to use these applications and manage data, communities also rely on these platforms to mobilize their capabilities at the local level. These power asymmetries expand to other generalized platforms that can enable communication between community members and a broader public.

Local restoration groups are also active on social media platforms sharing practices, lessons, and struggles on popular platforms, including Twitter, Facebook, Instagram, and TikTok. Public engagements with community restoration projects contribute to the recognition of local knowledge and actions, which further drives new possibilities for influencing policies and funding allocation. For instance, Cerrado Pé Association[15] is a community-led organization able to supply around 10 tonnes of seeds from more than 80 native plants for neotropical savanna restoration projects in Central Brazil (Sampaio *et al.* 2020). On their Instagram page,[16] more than 8,500 followers can access interviews, field experiences, community information, environmental campaigns, and training courses through several hundred audiovisual files produced over the last four years. By sharing these materials, this community-led organization presents several unique local seed production practices, from species identification to seed storage. Their account has given broad visibility to grassroots actions that co-create supply chains from the bottom-up and include community groups to generate local livelihood opportunities. Consequently, this seed network has attracted public media coverage, including broadcasting news on national and international television, which directly legitimizes their practices, consolidates commercial demands, and facilitates access to funding (Schmidt *et al.* 2019).

Community-led digital development can also transform how technology is planned, designed, and used in restoration actions at the local level. The co-creation processes of digital platforms and tools can incorporate local practices, knowledge, and place-specific needs, rather than a universal approach to restoration. A recent collaboration between several community-based seed suppliers in Brazil resulted in Redário[17] – a national network to assist the expansion of restoration networks in Brazil. Redário has implemented an online seed supply management platform for seed production data management to coordinate commercial operations of seed suppliers. The incorporation of technologies focuses on applying common standards for seed supply, quality control, and commercial practices, respecting the diverse organization modes across different community groups.

Beyond the development of digital platforms for FLR, local communities self-organize and use commonly available communication tools and social media to collect and share local restoration practices. When communities have a direct role in the co-creation of digital technologies and remain involved in political and economic decisions, restoration practices can be more viable and responsive to local conditions. However, the co-creation of participatory technologies can be an asymmetrical political process that might not always include the diversity of local values, interests, and financial goals from different stakeholders (Radil and Anderson 2019). Hence, community-led digital restoration platforms can also lead to local conflicts that cannot be resolved through a singular participatory process.

Conclusion

Recent digital transformations have significantly remade how FLR practices and policies are formulated and implemented across scales. Digital platforms can influence restoration activities, while also shaping power relations between stakeholders and decision-making processes. In this paper, we demonstrate how four different drivers of technological developments influence restoration projects through the formation of scientific expertise, network relations, commercial systems, and knowledge practices that impact restoration outcomes globally.

We argue that it is vital to understand the digitalization of FLR as it addresses environmental challenges. Such an analysis draws attention to how scientific expertise is coded into the politics of platforms, the growing influence of the private sector in restoration actions, and the socio-economic inequalities that can arise when implementing restoration initiatives within communities. These digital platforms are not neutral tools but instead influence power dynamics, political decision-making processes, and socio-environmental outcomes. Because of the prominent role played by digital technologies in remaking environmental politics, this analysis expands beyond human and institutional actors as the primary political agents shaping restoration policy-making systems (Baker *et al*. 2014). This research shows how the configuration and use of digital technologies also exerts political power. Digital platforms influence knowledge practices, organize networks, and distribute resources (Hendriks *et al*. 2016). They further transform organizational systems and restoration interventions.

Our examination shows how digital platforms developed and backed by powerful stakeholders can shape conventional ideas of restoration resources, techniques, and investments. These transformations often involve power inequalities among stakeholders, which materialize through unequal access to and influence over technologies and development processes across the Global North and Global South. This analysis draws attention to how these technological developments can remake environmental politics (Howson 2019). It further argues for the importance of ensuring that restoration platforms and actions do not overlook benefits sharing, worker protections, sound living conditions, and community engagement (Erbaugh *et al.* 2020). Additional research is required to identify how these digital systems affect place-specific practices and social-political worlds, especially through the implementation of large-scale restoration programs that seek to accomplish global environmental pledges and objectives.

Notes

1. Atlas of Forest and Landscape Restoration Opportunities: https://www.wri.org/data/atlas-forest-and-landscape-restoration-opportunities.
2. Framework for Ecosystem Restoration Monitoring (FERM): https://data.apps.fao.org/ferm/.
3. Vegetationmap4africa: https://vegetationmap4africa.org/.
4. Restor: https://restor.eco/.
5. Terramatch: https://www.wri.org/initiatives/terramatch.
6. The Land Accelerator: https://thelandaccelerator.com/.
7. The Land Accelerator workshop session: https://www.youtube.com/watch?v=Q3d0O4y2AM4.
8. Plant for the Planet: https://a.plant-for-the-planet.org/.
9. TreeApp: https://www.thetreeapp.org/.
10. Klima – Live carbon neutral: https://klima.com/.
11. WWF footprint calculator: https://footprint.wwf.org.uk/.
12. Eden Restoration Projects: https://edenprojects.org/.
13. Eden's annual reports: https://www.edenprojects.org/financials.
14. The Xingu Seed Network: https://www.sementesdoxingu.org.br/.
15. Cerrado de Pé Association: https://www.cerradodepe.org.br/.
16. Cerrado de Pé Association's Instagram account: https://www.instagram.com/cerradodepe/.
17. Redário platform: https://redario.sementesdoxingu.org.br/.

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Appendices

Appendix A.

List of keywords used when searching digital technologies and forest landscape restoration (FLR).

Keywords associated with 'FLR'	Keywords associated with 'ecosystems'	Keywords associated with 'digital technologies'
Restoration	Forest(s)	Satellites
Reforestation	Woodland(s)	Sensors
Recovery	Savanna(s)	Lidar
Rewild	Grassland(s)	Internet of Things (IoT)
Rehabilitation	Mangrove(s)	Machine learning
Seeding	Rainforest(s)	Algorithm
Planting	Bush	Robotics
	Land(s)	Artificial Intelligence (AI)
	Landscape(s)	Precision
	Indigenous lands	Drones
	Community forestry	Machinery
	Protected area(s)	Automation
	Forest fire(s)	Application (App)
	Tree(s)	Big Data
	Seed(s)	Citizen science

Appendix B. List of web-based and mobile digital platforms applied to forest landscape restoration activities

Digital platform	Developer	Website
#Quantoé? Plantar floresta	Instituto Escolhas	http://quantoefloresta.escolhas.org/
8 Billion Trees	Save & Plant Real Trees	https://play.google.com/store/apps/details?id=com.billiontrees.trees
Africa Tree Finder App	World Agroforestry Centre	https://www.worldagroforestry.org/output/africa-tree-finder
Alipay	Alipay Ant Forest	https://medium.com/alipay-and-the-world/alipay-gallery-ant-forest-tree-planting-spring-2019-dc4e0578cc7c
Atlas of Forest and Landscape Restoration Opportunities	WRI	https://www.wri.org/data/atlas-forest-and-landscape-restoration-opportunities
CostingNature	King's College London, AmbioTEK, UNEP-WCMC	http://www.policysupport.org/costingnature
Crowdfunding platforms	Crowdfunding platforms	https://www.gofundme.com/f/airseed-30000-trees-reforestation-project?qid=e1334e2a30ed751c036e6f6851fccfd1

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Digital platform	Developer	Website
Cultivo	Cultivo	https://cultivo.land/
Drylands Restoration Monitoring Platform (DRIP)	FAO	http://www.fao.org/in-action/dryland-restoration-initiative-platform/en/
Earth Engine	Google	https://earthengine.google.com/
Ecosia	Ecosia	https://info.ecosia.org/?tt=fa7e1292
Facebook	Meta	https://www.facebook.com/
Farm-Trace	Farm-Trace	https://farm-trace.com/
FLRchain – a blockchain-based application for FLR	Gaiachain and IUCN	https://www.iucn.org/news/forests/202103/blockchain-forest-landscape-restoration-flrchain-marries-two-brilliant-concepts
Framework for Ecosystem Restoration Monitoring (FERM)	FAO	https://data.apps.fao.org/ferm/
Global Forest Watch	WRI	https://www.globalforestwatch.org/
Global Landscapes Forum	Global Landscapes Forum	https://www.globallandscapesforum.org/
Instagram	Meta	https://www.instagram.com/
InVEST	Stanford University	https://naturalcapitalproject.stanford.edu/software/invest
Klima – Live carbon neutral	Climate Labs GmbH	https://klima.com/
Leafsnap	Leafsnap	http://leafsnap.com/
Lifesnap	Plant Identifier	https://plantidentifier.info/
MoreTrees	THG	https://moretrees.eco/
Pl@ntNet	Pl@ntNet	https://plantnet.org/en/
Plant for the Planet	Plant for the Planet	https://a.plant-for-the-planet.org/
Redário	Brazil's Seed Network	https://redario.sementesdoxingu.org.br/
Reforestum	Reforestum	https://app.reforestum.com/
Restaura Mata Atlantica	EMBRAPA	https://www.embrapa.br/busca-de-solucoes-tecnologicas/-/produto-servico/6051/aplicativo-restaura-mata-atlantica
Restor	ETH	https://restor.eco/
Restoration Ecosystem Service Tool Selector (RESTS)	IUCN	https://www.fs.fed.us/psw/publications/documents/psw_gtr262/psw_gtr262.pdf
Restoration Implementers Hub	UN	https://implementers.decadeonrestoration.org/submit-initiative/info
Restoration Observatory	Climate Observatory	https://observatoriodarestauracao.org.br/app/home
Restoration Resource Center	SER	https://www.ser-rrc.org/
Right Plants	ITCRC	https://apps.apple.com/gb/app/right-plants/id1361626912
Root	IUCN and Stanford	https://naturalcapitalproject.stanford.edu/software/root
Rural Legal	Atrium Assessoria Florestal	https://apps.apple.com/us/app/rural-legal/id1419889077

(*Continued*)

(Continued).

Digital platform	Developer	Website
Seed collecting/banking	Terraformation	https://www.terraformation.com/solutions/software
SEPAL forest restoration planning tool	FAO and collaborators	https://servir.ciat.cgiar.org/sepal-webinar-june2021/
SisCar	Brazil's Forest Service	
Terramatch	WRI	https://www.wri.org/initiatives/terramatch
The Land Accelerator	WRI	https://thelandaccelerator.com/
The Land Degradation Surveillance Framework (LDSF)	World Agroforestry Centre	http://landscapeportal.org/blog/2015/03/25/the-land-degradation-surveillance-framework-ldsf/
The Regreening Africa App	World Agroforestry Centre	http://landscapeportal.org/documents/2972
Thuru	Thuru	https://thuru.lk/app/
Tree Canopy Insights	Google	https://insights.sustainability.google/labs/treecanopy
Tree Plant	Tree Plant	https://treepla.net/
Tree-nation	Tree-nation	https://tree-nation.com/plant-citizens
TreeApp	The TreeApp	https://www.thetreeapp.org/
TreeMapper	Plant for the Planet	https://a.plant-for-the-planet.org/treemapper/
Trees and health app – Urban Canopy Assessment – PSU	SUPRlab	http://map.treesandhealth.org/
Trees for the future	Trees for the future	https://trees.org/
Vegetationmap4africa	World Agroforestry Centre and the University of Copenhagen	https://vegetationmap4africa.org/
Vitrine da Restauração	SOBRE	https://www.sobrestauracao.org/mapa/
WePlan-Forests	IIS	http://weplan-forests.org/index.html
WhatsApp	Meta	https://www.whatsapp.com/