Trends in Biotechnology

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Sustainable Transformation of Land-Based Economic Development in the Era of Digital Revolution

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Biotechnology will play a key role in transforming current land-use systems alongside the digital revolution by using five strategies: enhancing productivity at the farm or plantation level, replenishing degraded land, enabling landscape management for resilience, upgrading and diversifying downstream activities, and creating new value propositions.

A recent paper [1] describes the six key *transformations* within the UN Sustainable Development Goals framework for ensuring sustainable resources for future generations. Transforming the current land-use system (Transformation 4) is one of the major components. Rapid, large-scale land exploitation for economic development, especially in the tropics in recent decades, has negatively affected both society and the environment. Despite this urgency, the progress of transformation has been slow compared with the rate of environmental degradation. Pushing for *transformations* on multiple fronts simultaneously may drive multiple synergies. Among the six transformations, the *digital revolution* (Transformation 6) is regarded as a major force of disruption to the status quo. Digitization forms the foundation for (re)designing land-use systems with wireless sensor networks (WSNs), remote sensing, data analytics with high-performance computing, artificial intelligence (AI), robotics, and communicating platforms. In this sense, biotechnology advancement in land-based sectors can be perceived as a critical approach to forge strong synergies with the digital revolution, potentially redefining land-based economic development on an unprecedented scale. The combination of biotechnologies with the aforementioned digital technologies can potentially be very powerful in realizing the sustainable transformation of land-use systems. Five transformative strategies can be particularly relevant (Figure 1).

Enhancing Productivity at the Farm/Plantation Level

Improving the productivity of existing agricultural land and timber plantations can avoid further expansion onto land areas with high conservation values. Digital technologies can greatly facilitate biotechnology advances in boosting sustainable land intensification in three aspects. First, digitization of laboratory and experiment activities, such as high-performance computing and big data analytics, especially bridging phenomics and genomics, can enhance conventional

(A)

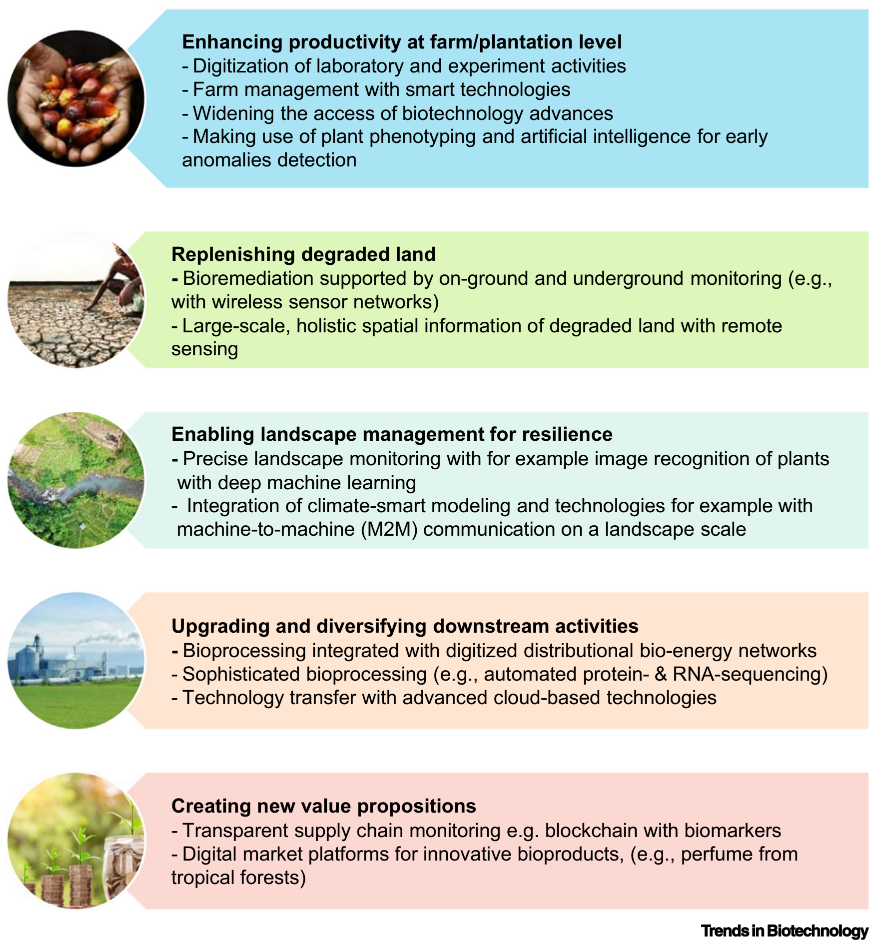

Figure 1. Technology for Sustainable Transformation. (A) Five strategies to accelerate sustainable transformation of land-based development elaborated with some examples. (B) A brief overview of digital technological fields that can be coupled with biotechnologies for transforming land-based economic development.

(B)

Figure 1 (*continued*).

plant-breeding activities. For example, field phenotyping of large populations with WSNs allows researchers to define more ideotypes in a short time-frame [2]. Second, equipping farm, plantation, forest, and landscape management with smart technologies allows large-scale, real-time monitoring and diagnosis. For example, a disease in forests can be diagnosed by integrating drones, hyperspectral image sensors, and machine learning [3]. Third, digitization also potentially widens the access of biotechnology advances to small-scale farmers, especially those located far from cities with less access to the latest technologies and knowledge. In general, highly organized large-scale farming is more productive due to economies of scale. Organizing large groups of farmers through digital platforms such as mobile apps can greatly accelerate collective uptake of technologies and biotech expert advice, enable quick feedback from small-scale farmers (which can be further analyzed with machine learning to understand how to improve their management practices), and facilitate the timely and efficient application of agro-inputs and practices [4]. This was unimaginable in the past, especially in developing regions.

Replenishing Degraded Land

Another strategy is shifting future production away from high-value areas by (re)activating abandoned, degraded agricultural land and timber plantations with the precondition of not incurring additional carbon stock loss or negative ecological impacts. Bioremediation to recover degraded land with breakthroughs in microbial partners, endophytes, and soil enzyme-mediated processes is a major enabler of this strategy [5]. In addition to cropland replenishment, these advances can be applied in reforestation and afforestation as well as recovery of ecosystem services in critical locations. Digital technology, in this case, offers complimentary solutions in terms of monitoring not only on-ground but also underground conditions, such as nutrients and water dynamics, using tools like WSNs [6]. From a large-scale land management perspective, mapping and integrated modeling using remote sensing, airborne technologies, and geographical information system can potentially support bioremediation by providing accurate spatial information of not only geophysical, climatic, and agro-ecological properties, but also present and historical land-use activities of the degraded areas, which are important to understand carry-over effects and socio-economic influences. Advances in remote sensing in terms of hardware, processing technologies and data-sharing have made land surveys not only broader and more detailed but also more affordable. Drone and intelligence-based forest- and landscape-mapping solutions are also being expanded commercially.

Enabling Landscape Management for Resilience

Improving agro-ecological resilience, which is the capacity of the land-use system to endure and adapt to environmental changes, is high on the agenda of sustainable

Box 1. Examples of Land-Use Transformation

Forestry Revitalization and Bio-Energy Deployment in Rural Japan

Deploying a spatially dispersed bioenergy system is an option to strengthen the resilience of energy systems in rural Japan. Reactivating unmanaged monoculture forests across Japan can lead to synergetic effects with local socio-economic and ecological revitalization. An interesting example of forestry and bioenergy development is the Maniwa City Biomass Initiative in Japan (https://www.jlgc.org.uk/en/news_letter/maniwa-city-biomass-initiative/). Maniwa City is sparsely populated (about 5.5 persons per square kilometer) with 80% of its area forested. The initiative aims to improve forest management and leverage untapped forest resources to create value. This is done by keeping the full cyclic supply chain within the city, including valorizing of wood waste. This approach creates numerous small jobs for the residents, such as transporting woody biomass to hotels for heating hot spring baths. A Biomass Lab was set up in 2010 to support research on biomass fuel, training of personnel, and new venture creation, with the support of Japan's New Energy and Industrial Technology Development Organization. While at the moment there has been no significant application of digital technologies, potential applications may include the following.

- Biomass monitoring: using WSNs to support personnel in monitoring biomass quality in real-time and computer vision and machine learning to support to identify forest and biomass conditions (e.g., disease or moisture).
- Supply chain optimization: highly dispersed biomass residues from forestry and agricultural sectors can be optimally channeled to decentralized bioenergy systems through AI-powered logistic planning; with extensive Internet of Things (IoT), biomaterial quality parameters can be automatically tracked and shared among the actors in the value chain, allowing real-time matching and informed decision making.
- Forest management: creating insights and predictive analysis of forest fires, tree diseases, or pests in the forest, through the use of machine learning to monitor and create key insights on forest areas.

Landscape Restoration and Fire Prevention in Central Kalimantan, Indonesia

Central Kalimantan in Indonesia, a province with a vast area of carbon-rich peatland, experienced severe land degradation in the past decades due to the Mega Rice Project in the 1990s and rapid oil palm expansion in the 2000s. The province periodically experiences peat and land fire on a massive scale, causing enormous land emission and serious health issues. Importantly, the entire landscape must be properly restored to avoid further degradation while keeping the livelihood of local communities. There are many ongoing efforts in replenishing the province. Advances in remote sensing in terms of hardware, processing technologies, and data-sharing have made land surveys not only broader and more detailed but also easier and more affordable. This can be greatly enhanced with field measurement connected with IoT and processed with AI, such as image recognition of flora and fauna with deep learning and precise positioning as well as on-ground and underground conditions (e.g., moisture, nutrients, water dynamics, etc.). Changes in biodiversity can also be detected by combining spatial data with camera-trap images or videos and biomarkers.

Analyzing these big data with AI has important implications for landscape planning in Central Kalimantan in the aspects of restoration, such as with bioremediation, fire prevention, and establishing climate-smart and climate-resilient land-based livelihoods for local communities in adaptation to potentially long droughts and fire. The efficiency and accuracy of such an AI-powered system will also evolve with time due to growth in input data and continuous learning. At the moment, the progress is slow. Although individual advances were observed (e.g., remote sensing to map land covers more accurately, or IoT application to monitor fire) at different speeds and coverage, consolidation is very limited. This means that a great advantage of digital technologies for the entire landscape has yet to be tapped. Rethinking the landscape approach in the era of digital revolution may open unprecedented opportunities for conservation.

development in the face of climate change. The landscape approach has been advocated as a more resilient and sustainable form of land-use compared with monoculture and intensive agriculture. It advocates designing and maintaining a mosaic of land-use consisting of forest, cropland, settlements, and other ecosystems that is creatively optimized for economic, social, and ecological resilience [7]. However, it has been challenging to measure and manage the interactions between different land-uses at a landscape level. Digital innovations in biotechnology may revolutionize the technical constraints of precise large-scale mapping and monitoring across the entire landscape that have hindered the implementation of the landscape approach. For example, combining image recognition of plants with deep machine learning [8] and precise positioning, imaging using wireless devices [9] can be keys to optimize spatial planning of such a multifunctional landscape. The resilience of the landscape can be further strengthened by integrating climate-smart modeling and technologies in climate change adaptation to potentially severe long droughts and floods. For example, machine-to-machine communication can facilitate autonomous interactions among machines, from sensors to robotics, in detecting and responding to landscape-scale climate changes.

Upgrading and Diversifying Downstream Activities

A long-term solution to shift away from inefficient and unsustainable land exploitation would be a structural economic transformation that opens up new income sources, particularly for emerging countries that are stuck in the middle-income trap. Investing in digital-biotechnological innovation in the downstream supply chain is a strategic move in this sense. This is not limited to sophisticated bioprocesses like the automated operation of protein- and RNA-sequencing [10], but also low-hanging fruits that can potentially be applied in developing regions on a larger scale. For instance, through digital connectivity, advanced bioprocessing can be integrated with digitized distributional bioenergy networks in rural areas, enabling the optimal use of bio-waste streams like biomass residues from forestry and agricultural sectors. Biomaterial quality parameters can be automatically tracked and shared among the actors in the value chain, allowing real-time matching and informed decision making [11]. One commercial example is Inray Fuel Control (http://inray.fi/en/home/), a firm that can measure and share solid biofuel quality in real-time through sensor-based X-ray analyses of moisture, foreign substances, and energy content. Furthermore, the expanded use of advanced cloudbased technologies will redefine the modes of technology transfer and research collaboration between developed and developing regions, upstream and downstream, buyers and suppliers, as well as different sectors [12].

Creating New Value Propositions

Sustainable branding of agricultural and forestry products with market premiums is widely employed as an instrument to promote sustainable production. Certifications like the Forest Stewardship Council and Roundtable for Sustainable Palm Oil are prominent examples that provide incentives for companies to adopt sustainable practices instead of forest conversion. In this setting, the use of smart technologies and blockchain allows more transparent and effective monitoring of the entire supply chain [13]. Biotechnology can be a useful complement to enhance the traceability of food and bio-based materials, such as the use of biomarkers [14]. A synergistic combination of technologies can reduce transaction costs, allowing more uptake of various certifications by smaller players in developing regions, who are often blamed for their inefficient and unsustainable land-use practices. Interestingly, the advancement of connectivity between suppliers and potential buyers through digital marketing also permits marketing new, novel biomaterials that are difficult to access due to logistical constraints. A noteworthy example is the digital documentation of indigenous medicine and perfumes through screening of bioactive compounds extracted from tropical forests in Borneo [15]. Digital market platforms can further contribute to the creation of new markets for such products, creating new income sources from conserving tropical rainforests.

These five strategies are important in addressing the critical question of how to support growth, not only without causing further environmental impacts, but also repairing damage done in the past. The digital revolution, coupled with biotechnology, opens up more possibilities to reconcile economic development and conservation. The *Six Transformations* framework marks the importance of crafting and adopting technologies for improving people's lives, prosperity, and wellbeing in the context of sustainable development. Nevertheless, it is crucial to recognize that technological innovation in the land-use system requires much deeper thoughts on implementation and business models that fit well in specific local contexts. While interdisciplinary collaboration between different scientific communities is imperative, working closely with stakeholders on the ground to effectively design, execute, and manage the strategies is key for realizing the *Six Transformations*. The examples shown in Box 1 may shed some light on such on-ground efforts. This paper offers initial implications of synergies between biotechnologies, land-use systems, and the digital revolution, which may hold important prospects both in academia and among practitioners in driving sustainable development.

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