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Embracing the digital revolution for conservation in Borneo

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Abstract : The past few decades of land exploitation in the tropics, especially logging and agricultural expansion to induce economic development, have resulted in massive deforestation and severe forest degradation in Borneo. However, digital revolution may provide new means for transforming such exploitative land-based economies to more sustainable modes of development, not only with gradual improvement, but also possibly a total revamp of the existing systems. Here, we explore the potential of digital innovations to enhance conservation efforts such as: 1) improving landscape resilience; 2) enhancing ecosystem service and biodiversity accounting; 3) boosting eco-tourism; 4) elevating the marketing of local products; and 5) enabling self-sufficiency. Ultimately, conservation efforts can be largely enhanced with better accounting of biodiversity, coupled with alternative economic opportunities for rural communities to promote new business models that were not feasible due to technological limitations.

Keywords: digital revolution, conservation, land use, sustainable development

INTRODUCTION

The digital revolution has become a major policy focus in developing countries to ensure these nations can survive and evolve in the face of disruptive changes in the global economy. Digital technologies are perceived as key modular-building blocks for sustainable development in the next few decades (Sachs *et al.*, 2019). In many cases, transformative efforts and initiatives have been made primarily for urban areas, as suggested in concepts like 'smart cities' or 'digital cities' (Yau *et al*., 2016, Jurriëns and Tapsell, 2017, Beschorner *et al.*, 2019). It has only been in recent years that both public and private sectors have started to realise that rural territories, which traditionally rely heavily on agriculture and forestry, are a key strategic area for digital transformation and investment. This is especially important for regions that have undergone severe deforestation and forest degradation due to large-scale land development activities. Ultimately, the digital revolution may enable various transformative strategies to facilitate more sustainable ways of development in these frontiers of environmental degradation (Goh *et al.*, 2020) – this has important implications for biodiversity conservation.

The rapid advances in connectivity and coverage in recent years, accompanied by the confluence of artificial intelligence (AI), Internet-of-Things (IoT), robotics, etc., are poised to redefine conservation strategies . For example, the digital revolution may allow for decentralised but well-coordinated small-scale, grassroots innovations. This is possible owing to wide connectivity and low transaction costs, with tools like real-time, spatially explicit forest monitoring or electronic financing and marketing platforms. More importantly, the convenience offered by digital revolution may redefine urban-rural transition, permitting more sustainable alternative livelihoods and lifestyles for populations spread across rural areas.

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While there are studies that have touched on the various different aspects of digital transformation in agriculture and forestry (Deichmann *et al.*, 2016, Klitkou *et al.*, 2017, Arts *et al.*, 2015), a comprehensive overview of opportunities for conservation brought about by the digital revolution in under-developed regions such as Borneo remains largely missing. How developing, land-reliant regions fare along with the digital revolution, especially in terms of the impacts on biodiversity conservation, will be an important question for researchers in the coming years. Here, we explore how the digital revolution can be potentially adapted for conservation in places that rely heavily on land-based economies, with Borneo as the core example. Borneo was chosen as a case study given our collective experience working in this region, as well as the presence of three national governments, which creates both opportunities and obstacles.

The state of Borneo

Borneo is the third largest island in the world. Located in Southeast Asia, the island is shared by Indonesia, Malaysia, and Brunei Darussalam. In the past five decades, the island has experienced land exploitation on a massive scale due to economic development. The island has experienced rampant timber extraction since the 1970s. Huge amounts of valuable tropical woods has been logged and exported, either as raw logs or plywood, resulting in millions of hectares of deforestation and forest degradation. Approximately 20 million ha of old-growth forests were destroyed from 1973 to 2018, largely due to human activities (CIFOR, 2020).

In the 1980s, the cultivation of oil palm—a lucrative cash crop grown mainly for export—was introduced throughout the Borneo island, bringing about additional and perhaps more devastating forms of land degradation. By 2018, about 22 million tonnes or 12% of the world's vegetable oils was exported from Borneo, compared to 5 million tonnes in 2000 (FAOSTAT, 2021). Although poverty has been substantially reduced, land-based development also considerably increased the risks of immediate local health issues (such as malaria and the Nipah virus outbreak) as well as long-term global climate change to livelihood (Santika *et al.* 2019b, Santika et al. 2019a). The widespread logging and replacement of natural forests with oil palm and other crops in Borneo has resulted in biodiversity loss (e.g. Jonas *et al.* 2017), severe degradation of peatland (mainly in Central Kalimantan, Sarawak, and West Kalimantan) and greatly escalated the risk of fires, especially during periodic long droughts (Santika *et al.* 2020). Repeated peat and forest fire have led not only to enormous carbon stock loss, but also transboundary haze that has exerted detrimental health impacts over the entire region (Zhang and Savage 2019).

There is also evidence that the newly generated wealth from oil palm plantations has been mostly concentrated in the hands of a small group of elites, creating huge wealth gaps among the people. Communities continuing to seek traditional livelihoods (planting dry rice in swiddens, creating rubber, rattan, or mixed fruit gardens, engaging in small-scale mining, hunting, fishing, or collecting forest products)—as well as those working as day labourers on plantations—have found themselves victimized or 'left behind' in this uneven wave of development (Santika *et al.*, 2019b). Today, many parts of the island are plagued by social conflicts, poor governance, corruption, and ineffective law enforcement. The over-reliance on the exports of primary products for fiscal revenues has also exposed Borneo to periodic economic crises due to fluctuations in commodity prices, making incomes unstable and unpredictable. All these drawbacks imply that such a development pathway is unsuitable for continuation into the future. To avoid further environmental degradation and biodiversity loss, while ensuring long-term sustainable development, proper strategies with the right incentives must be put in place to transform the conventional land-based economies (Ogg, 2020).

Digital revolution for conservation

Table 1 lists the key technological vectors based on the framework proposed by Siebel (2019). An important technology vector is the Internet-of-Things (IoT) which can greatly improve the capability of monitoring, on both farm and landscape scale. Furthermore, Big Data comprising, huge, ever-growing, comprehensive databases, can form the basis for generating knowledge for a holistic understanding of the agro-ecological systems. The most intriguing domain is probably artificial intelligence (AI), which can analyse, predict, design, and optimise the operation and maintenance of the landscape. Finally, through digital platforms and cloud computing, communications between rural and urban areas will be greatly enhanced. The platform has the potential to open new doors to the small-scale, highly dispersed rural communities by providing lower-cost access and exchange of information , knowledge, services, and applications that were very difficult or expensive in the past. A combination of these domains can create a powerful land management system to overcome some of the key binding constraints to conservation. The following sections more specifically identify the key technologies applicable to each strategy, with interesting case studies mainly found in Borneo, and if applicable, other regions from Malaysia, Indonesia, and elsewhere.

Improving landscape resilience

Resilience to agro-ecological disturbances has gained more and more attention not only for its environmental implications but also its socio-economic importance. A resilient production system will be able to absorb shocks and stresses like droughts, floods, pests, and diseases while maintaining production. Digital innovations may provide a means to deal with previous challenges in large-scale mapping and monitoring across a multifunctional landscape as mentioned earlier (e.g. www.hutanwatch.com for forest monitoring). These mapping and monitoring efforts can be integrated with climate-smart technologies, such as machine-to-machine (M2M) communication between sensors and robotics that detect and respond to environmental changes. In return, data collected from AI-powered monitoring and feedback systems can contribute to advancing our understanding of extreme climate factors, such as severe droughts brought by El Niño and improving the accuracy of existing land-climate models to evaluate short- and long-term interactions between land-use and climate change (Kwan *et al*., 2014, Chapman *et al*., 2020).

Importantly, real-time, spatially explicit monitoring and forecasting systems with IoT and AI can greatly improve the knowledge and capacity of advanced warning systems for land fire prevention and mitigation in Borneo (Kieft *et al.*, 2016). For instance, Syaufina and Sitanggang (2018) showed that real fire detection for a particular landscape fire in Kalimantan in 2015 was linked to consecutive hotspot occurrences through a spatio-temporal data mining approach. Another study by Sumarga (2017) examined the relationship between human hotspots and human locations such as distance to settlement, river, etc. The precision and frequency of hotspot monitoring can be greatly enhanced by integrating data from satellites, drones, long-range wireless sensors installed in the field (e.g. monitoring water levels) as well as real-time participatory monitoring by farmers and the public through mobile apps (Stolle *et al*., 2010; Yoon *et al*., 2012; Kibanov *et al*., 2017; Aditya *et a*l., 2019; Kadir *et al*., 2019; Widodo *et al.*, 2019). By making data open to public, through government initiatives like 'One map policy' by BIG Indonesia (2020) and non-governmental efforts by Gaveau *et al.* (2022), the impacts can be multiplied as the data can not only be accessed and used but also updated and enhanced by various stakeholders. Another example of this use of open-source big data platforms to provide advanced warning systems is the InfoAmazonia website that can register flood warnings up to 24 hours in advance in almost all regions along the Amazon based on satellite data (Gutierrez, 2019).

Digital technologies also offer complementary solutions to bioremediation of degraded land. Bioremediation can replenish ecosystem services in critical locations through the application of microbial partners, endophytes, and soil enzyme-mediated processes

(Grobelak *et al.*, 2018). Wireless sensor networks can be applied to monitor both above- and below-ground conditions, such as nutrients and water dynamics (Salam *et al.*, 2019). For example, a dam-building equipped with a microcontroller board with sensors can be employed to artificially rehydrate dry peat areas (Hamzah *et al.*, 2018). Integrating these with spatial information of present and historical land-use activities may also help to identify carry-over effects and socio-economic factors underlying land-use changes (Zhou *et al.*, 2019).

The diffusion of digital communication tools empowers the local communities not only through expanding access to information but also by opening up new opportunities for more effective collaboration between different groups of people. This can take the form of increasing communication between groups of people who are affected by transboundary environmental issues but are physically separated. For example, the authors have witnessed growing discussions, debates, and disagreements between Malaysians, Indonesians, and Singaporeans on social media about transboundary haze and environmental issues in Borneo and Sumatra. This was more difficult in the past when people had fewer ways to directly communicate with their neighbours across the South China Sea or the Malacca Straits let alone having (near) real-time discussions. Previously, the regional environmental cooperation among ASEAN countries to address transboundary haze has not been effective (Nguitragool, 2010). It is unclear how social media will transform these relationships, but it likely will affect societal perspectives in these countries and bring new progress in the future.

Enhancing ecosystem services and biodiversity accounting

To facilitate the conservation of natural environments, economists have advocated for the inclusion of environmental goods and services as well as biodiversity in financial accounting. It is argued by these advocates that putting environmental goals explicitly into the economic dimension can help decision-makers in designing and implementing interventions in environmental management. Following on from this concept, monetising ‘nature’ with economic accounting practices has now emerged as a means to address unsustainable land-based economies (Missemer, 2018). Commonly, the term ‘payment for ecosystem services’ is used to describe such strategy. This requires linking natural capital to human benefits on a monetary basis. In any case, the precondition is the development of manageable attributes of natural capital stocks through quantifying environmental services with standard mechanisms (Maseyk *et al.*, 2017).

The application of enhanced monitoring tools like drones, wireless sensors, and shared databases may substantially improve the accounting of ecosystem services (Deichmann *et al.*, 2016). For example, carbon stock data collected from wireless sensors in field measurement, integrated with information retrieved from both optical and radar remote sensing can greatly reduce data uncertainty (Marvin *et al.*, 2016, Langner *et al.*, 2012). The use of a Random Forest Machine Learning algorithm can further enhance regional modelling through better recognition of land cover patterns. This was demonstrated by Asner *et al.* (2018) while examining spatial variation of carbon stock in Sabah by forest use, growth, degradation, and protection status. Other examples include the studies by Cushman *et al.* (2017) and Pfeifer *et al.* (2016) on examining forest degradation gradients and drivers of deforestation, respectively. Monitoring anthropogenic disturbances on aboveground biomass through spaceborne Shuttle Radar Topographic Mission Digital Elevation Model digital surface model and Light Detection and Ranging (LiDAR) digital elevation data helped to pinpoint the role of commercial logging as the main driver for the aboveground biomass changes in Ulu Padas montane forest (Loh *et al.*, 2020). Aerial LiDAR has also been identified as an effective tool for carbon density mapping for accurate measurement and monitoring of the extent of selective logging impacts in the tropics (Ellis *et al.*, 2016). While payments for carbon sequestration can be made through the purchase of forest-based carbon credits, other major types of ecosystem services that have been sold to date include species, habitat, water catchment management services and biodiversity conservation (Treweek *et al.* 2012).

Accurate assessments of wildlife are also essential for the development of conservation projects . In Borneo, Bernard *et al.* (2013) applied a large number of camera traps to obtain useful information on species richness and composition within Imbak Canyon. More recently, camera trap and satellite data helped show that habitat quality was important for the conservation of Sun bears *Helarctos malayanus* (Guharajan *et al.* 2021). Combining camera-trap images and videos can yield large amounts of information to identify various species, capture their distribution, and estimate biodiversity abundance in larger areas through 'deep learning' in artificial intelligence (Christin *et al.*, 2019). In Sabah, the application of drones with thermal infrared sensors to detect the body heat emitted from Bornean Orangutan *Pongo pygmaeus* and Proboscis monkeys *Nasalis larvatus* has helped researchers detect and differentiate the two species based on body sizes and distinct behaviours such as social groups (Burke *et al.*, 2019). Satellite tracking has also been used in conjunction with drones to monitor the latter species (e.g. Stark *et al.* (2018). The use of passive acoustic monitoring has become increasingly popular in the tropics to monitor vocal animals. For instance, Clink *et al.*, (2019) could determine the identity of female Bornean gibbons *Hylobates muelleri* though their calls , using Mel-frequency cepstral coefficients feature extraction and support vector machine classification algorithms. These promising results could help conservation scientists to achieve more accurate estimates of the abundance of an important seed dispersing species for better biodiversity accounting.

The setting up of a global and national digital database, such as the 'One Map Policy' in Indonesia, can also greatly improve transparency in monitoring (Wibowo and Giessen, 2015). A consistent spatial database for clarification of land ownership is vital to resolve various conflicts arising from the implementation of forest carbon credit projects, especially in determining the legal right to benefit from the 'sales' of ecosystem services (Sanders *et al.*, 2017). This can be further enhanced with a higher degree of participation and lower transaction costs with the proliferation of platform technologies. It also improves the reliability and reputation of payments for environmental services schemes like forest carbon credit projects to gain the confidence of (potential) donors and increases the chances of the outcomes being formalised and institutionalized (Salzman *et al.*, 2018).

In terms of credit trading, blockchain technology can assure traceability and connect national registry systems, preventing double counting and ensuring consistency and transparency (World Bank, 2021). One notable initiative is the introduction of VerdePay, a new form of payment method to offset the embodied carbon emissions of any purchases made with carbon credits generated from the Rimba Raya REDD+ project in Central Kalimantan via blockchain (Howson, 2018). In terms of carbon pricing, AI can also be applied in forecasting carbon prices to provide a risk-mitigation mechanism and allow governments to design a more stable market instrument (Hao *et al.*, 2020). Tools like these are important to ensure payments for environmental services adopt models that can remain financially workable in the long run.

Boosting eco-tourism

Conservationists have long realised the importance and potential of binding conservation with service-based livelihood strategies for local communities. For regions suffering from unsustainable land-based development, establishing a prosperous tertiary sector can be a potential avenue for shifting the development pressure away from land exploitation. Traditional tourism businesses in Borneo rely heavily on government efforts for collective promotion, with a few locations being selected and prioritised. With platform technology, businesses can now pursue low-cost marketing strategies, targeting a wider range of customers. Urban youths with more opportunities to explore their own countries, especially due to the availability of budget airlines, are among the targets. This can be a two-way thing, where the gap between consumers and service providers blurs (Buhalis and Sinarta, 2019). For example, a group of young, adventurous tourists on a tour in Borneo may share their stories in the form of words, photos, and more recently, videos including livestreaming, thanks to advancements in connectivity. These may bring greater publicity to places that were below the touristic radar in the past, attracting more young visitors, who will then further spread their experience virtually. Some of these interactions with local guides may also lead to the establishment of new businesses, including making money through ad-revenue on YouTube, Facebook, and other media platforms.

Other tourists may also produce reviews or ratings on various platforms, making the process more transparent and increasing the confidence of potential tourists who have not visited Borneo. Collectively, these data can be analysed by AI, giving service providers unprecedented visibility into tourists' experience, enabling them to improve their business models, including real-time pricing models powered by AI-based on big data (Al Shehhi and Karathanasopoulos, 2020). The 'big data' here include informations collected from flight companies, migration departments, fuel prices, currency exchange, etc., relieving service providers from making raw guesses and adjustment.

IoT can also be applied to promote sustainable tourism, such as estimating fuel emissions along the entire tour, monitoring the situation in national parks with sensors and cameras, connecting climatic data to route planning, etc. It is also possible to view tourists as part of the conservation web rather than being outsiders where communities and tourists can work together to virtually monitor conservation activities. For example, tourist-generated media published on the internet can be harnessed through 'big data' technologies as supplementary to enhance the understanding of wildlife activities, as illustrated in the case of Borneo elephants by Walker (2018) .

In aggregate, platform technologies may create a new form of economic activity in rural Borneo, namely the 'gig economy'. Gig workers are independent contractors who take up jobs through online platforms. The gig economy normally refers to urban applications like Uber, but in the future, it may be formed in the rural areas as well due to the proliferation of smartphones and data connectivity (Robinson *et al.*, 2019). This is not restricted to tourism-related services, but also other environmental-related or knowledge-based jobs. Motivated, self-learning indigenous people may now have opportunities to obtain new knowledge from digital platforms, and forge new collaborations with external organisations or companies, e.g., river and water management, forest rangers, sustainable farming practices, etc.

While it seems to be a wild feat of imagination for that to happen in rural Borneo, local businesses may become digital-based as may be observed nowadays in the urban areas. Furthermore, the availability of other low-cost digital tools to assist local communities, such as smart sensors and mobile apps to detect and manage water quality (Gallagher and Chuan, 2018), will increase the chances of turning such an unlikely scenario into reality. In the past, the concept of a 'smart village' was promoted in Sarawak which aimed to improve living standards and overcome the 'digital divide' for populations in remote areas by providing access to Information and Communication Technology (ICT). It was implemented - though not as impactful as expected - in the Kelabit Highlands town of Bario (e-Bario); in Long Bedian, a remote Kayan logging area 500 km from Miri, (e-Bedian), and in Long Lamai, a Penan village in the Upper Baram (Cheuk *et al.*, 2012, Harris *et al.*, 2018). The more recent impact of mobile phones has led observers to suggest that the 'digital divide' has now been largely bridged so telecentres need to modernize the kinds of services supplied.

Elevating the marketing of local products

Borneo is home to a wide range of natural products with various uses. Many of them are used regularly by local communities, and the hope is that these products may have potential for expansion into medium or high-end markets. The word 'Borneo' itself also represents exotic and mysterious flavours to many foreigners. Ways to leverage this branding and novelty to create new income sources would be a potential strategy for conserving nature. Similar to the aforementioned service sector, digitization may also effectively enable branding and marketing strategies for small farmers which were fraught with high costs and economic uncertainties. Through ICT innovations, real-time inventory tracking and pricing mechanism can greatly facilitate the tracibility of food from farm to consumer, reassuring the authenticity and quality of perishable products which can earn price premiums for the producers (Rana and Oliveira, 2015). This additional income for local producers could in turn alleviate their reliance on forest and biodiversity products to sustain their livelihoods.

Most importantly, the emergence of digital trading platforms and extensive delivery systems grant access to the small farmers' market, connecting them directly with buyers that are physically far away. Financially, electronic banking and trading platforms reduce the cost of transactions via the elimination of intermediaries. These also give small producers more flexibility in making financial arrangements, e.g., quick approval of small loans through e-banking without physical appearance. Supporting policies of governments may also be better executed, e.g., farmers can now apply online for subsidies and access supporting programmes or consultations. This is critical to those located far away from urban infrastructure and have poor access to physical banking or government services. With greater connectivity, farmers can then deploy multiple low-cost strategies to brand, promote, and trade their products using digital platforms coupled with AI and big data which can target potential custormers more precisely. This allows a more flexible, diversified, and demand-based business model as small farmers can continuously adjust their production strategies to changing conditions, e.g., adopting AI-powered price setting, selling on multiple platforms with different labels or certifications, and engaging various distribution channels. This is not something new in the other parts of Indonesia, where collective farm managements and marketings were set up by the Merapi and Merbabu Farmers Association and supported by the dedicated website Tanilink.com (Tanilink.com, 2020). In the long run, this may spur the growth of rural entrepreneurship, especially among the younger populations (Zaremohzzabieh *et al.,* 2016). Interestingly, this may also allow the marketing of traditional knowledge and products which were previously less known. For example, indigenous medicinal produces and perfumes in Sarawak were screened for bioactive compounds and then digitally documented (Yeo *et al.,* 2014). The programme aimed to improve local livelihoods by digitally connecting traditional knowledge and biotechnology, hoping to generate new income sources that can incentivise local communities to help conserve forests.

Enabling self-sufficiency

The concept of self-sufficiency has been frequently mentioned in conservation-related discussions. It is an alternative to the productivity-oriented mentality that essentialises development into economic outputs especially in rural areas, but which requires significant investment in transport infrastructure that is not always available. Therefore, it prioritises food-fibre-fuel security and other provisioning services by maintaining a landscape with agro-ecological and socio-economic diversification (Almstedt *et al.*, 2014). The ‘traditional’ way of living may be emphasised, in hopes of maintaining or regaining health and spiritual benefits through forging a healthy human-environmental relationship as in the past (Dounias and Froment, 2011, Abram *et al*., 2014, How and Othman, 2017).

In terms of food security, self-sufficient farming may be facilitated with the use of digital technologies. In the near future, ongoing changes in the urban-rural gradient may blur the line between urban farming and traditional farming. The former normally occurs in urban and peri-urban areas and enjoys various advantages from the proximity to urban centres (Carolan, 2020). However, with improvement in digital technologies, the incorporation of silicon-based hardware and technologies into small farms scattered throughout the greater rural areas may be further accelerated. In addition, these technological advances may also be applied to address human-wildlife conflicts. For example, Fazil and Firdhous (2018) designed an IoT system to alert residents when elephants are approaching.

The feasibility of applying these technologies at household or village scales remains questionable. Basic infrastructure and subsidies first need to be strategically put in place to make technologies and assets accessible and affordable to rural communitiesThe application of smart farming on moderate scales has been widely discussed and studied. For example, Jo *et al.* (2019) reported a case design of IoT monitoring architecture for smart organic farming at Satoyama Farm 52 in Serian, Sarawak. Mustafa et al. (2016) also reviewed how smart aquaculture can be effectively implemented by an organized fish farming community despite its underlying complexity. Optimistically, the rapid development of digital technologies may further lower the cost of adopting smart farming by rural households.

CONCLUSION

The advances in digital revolution will inevitably be underpinned by advances in two hardware vectors: high-speed internet access and electrical microgrid (see Table 2). Lessons learnt from the implementation of micro hydropower systems in Ba'Kelalan, Sarawak, indicated that the sustainable development of these projects require electrical load distribution management as well as community cooperation (Murni *et al.*, 2013). In other words, the availability of electricity was immediately seized by members of the community to power devices such as computers, which were not originally planned for the initial capacity of the microgrid. The microgrid was initially designed to only support lights and a television set for each household. Future implementations of microgrids in rural Borneo should thus not only seek to supply households with enough power for basic household amenities, but also with enough capacity to run the devices that underpin the various components of the digital information network.

A critical requirement for functional IoT, Big Data, AI and Cloud technologies is reliable and high-speed access to the internet. Most areas of Malaysian Borneo have been reported to have at least partial 3G connectivity (del Portillo *et al.,* 2021), but this is likely a best-case scenario. On-the-ground reports in 2021, specifically on the challenges of secondary school online learning in Sabah, suggested that although the state has a supposed internet penetration rate of 80.7% in 2019 (Gong 2020), low-internet stability is a major problem (Poobalan *et al.*, 2022). In conjunction with better access to electricity, it is possible that in lieu of increased land-based internet infrastructure, rural Bornean high-speed internet connectivity will be facilitated by commercial high-speed satellite broadband (Pachler et al., 2021). While the pricing of such services would probably be initially out of reach for most rural families, a combination of community bandwidth sharing and price competition between Low-Earth Orbit Satellite broadband operators (e.g. Telesat, OneWeb, Starlink, Amazon, etc.) should eventually bring end-user prices down low enough for widespread adoption. When this occurs, we will see an acceleration in the implementation of vectors of the digital revolution to facilitate successful conservation efforts.

Using an oversimplifying broad brush, we have illustrated what could happen if places like Borneo embraces digital revolution, and the implications for future conservation efforts. While socio-economic transitions in Borneo occurred on an unprecedented scale and rate in the past two decades, the digital revolution may irreversibly disrupt the entire system. IoT, big data, AI, and cloud technologies are creating new ways of functioning in Borneo. On the one hand, conventional, highly centralised land-based businesses may gain more control over land with enormous amounts of data retrieved in unprecedented dimensionality and granularity. On the other hand, the possibility to operate in a decentralised mode may revive traditional values in appreciating human-environment relationships and reinvent new ways of living with biodiversity. While both seem to be going to very different ends, they may exist together if proper interventions are put in place, leading to improvement ranging from the reduction of illegal logging and biodiversity loss to the emergence of self-sufficient villages, in the hope of creating a more sustainable Borneo. As successful conservation efforts are likely linked with how food, energy, education, and other services are delivered, top-down interventions can be designed coherently to tap potential synergies generated from the convergence of different sectors. There are a couple of clear common benefits for society through integrating multiple services on digital platforms. First, it improves living standards by making life more convenient and possibly lowering goods prices. Second, digital infrastructure improves governance and allows more participatory systems (Borneo Post, 2020). It may greatly facilitate the efforts of nurturing and empowering rural communities. Third, it creates a basis for bottom-up innovation. Tools and expert knowledge are now available at a much lower cost than ever, with the island observing the mushrooming of bottom-up digital innovation across agriculture, conservation, eco-tourism, etc.

For a digital revolution to develop in Borneo, state governments need to play an active role in establishing a common policy framework that cuts across all sectors , potentially linking land-based sectors with the others in the framework of, e.g., the ‘digital economy’ or ‘digital society’. The ‘digital economy’ development framework introduced by the Sarawak government is a remarkable example (CMO, 2020). The digitizing agenda has been further intensified across all sectors of Sarawak’s economy after the COVID-19 pandemic in 2020. Interestingly, it is placed together with environmental sustainability as the two major policy directions of Sarawak in the future. Strategic investments should be made in key areas like upgrading ICT infrastructure, deploying platform technologies, restructuring financial and regulatory systems, and encouraging domestic research and education (Philp 2020). In East Kalimantan, this has been done in partnership with international organisations, where 1,700 smartphones loaded with various apps were distributed across 160 villages in 2017, to boost community engagement for conservation and livelihood improvement (Hovani *et al.*, 2018). Importantly, attitudes toward new technologies as well as the readiness to exploit these technologies are vital to set the scene.

Conservation in places like Borneo often falls into a trilemma – it is very challenging to find a balance between economic growth, environmental protection, and social participation. Some even suggested that this can only be addressed with either radical degrowth, radical decentralisation, or even uncivilization (Kallis *et al.*, 2012) (Sconfienza, 2019). These options are probably unfavourable or impractical to most of the human population. Can the digital revolution provide a breakthrough for this trilemma? The transformations induced by the digital revolution in regions like Borneo in the upcoming decades may supply new insights into this question. The upcoming decades will be an interesting period of change to be closely observed.

Table 1. Overview of key technological vectors for transformation of land-based economies adapted from Siebel (2019).

Vector	**Functions applicable to land-based activities**
Internet-of-Things (IoT)	● Complex networks of systems consist of sensors and computing devices that permit data flows without human-machine interactions. ● Farm-scale monitoring with wireless network sensors, i.e., various biological, physical, and chemical sensors, controllers, computers, and mobile phones that can be connected through electromagnetic transfer ● Landscape-scale monitoring with remote sensing, i.e., the scanning of the earth by satellite or high-flying aircraft for spatially-explicit mapping and planning. ● Automation with robotics, i.e., intelligent robots that can assist or replace humans in farm, forest, and industrial operations through machine-to-machine communication.

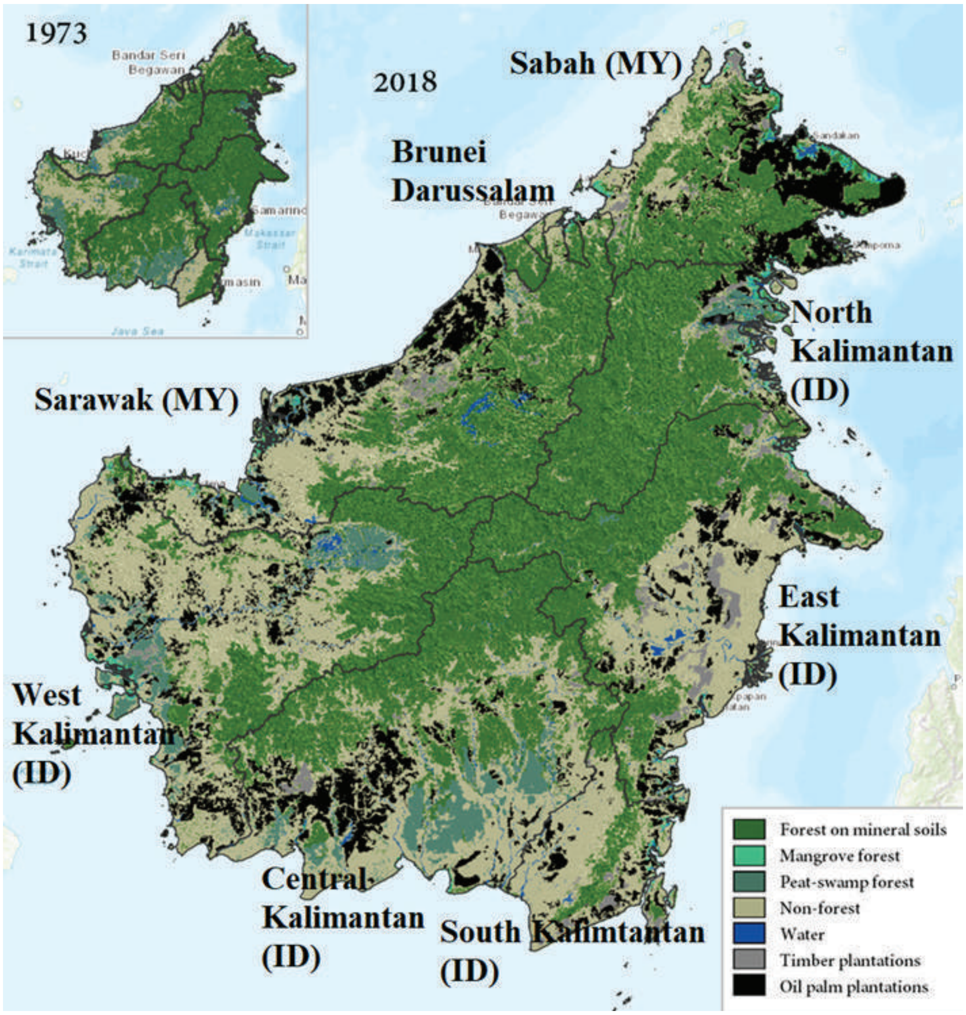
Big data	● Voluminous, ever-growing data collected from IoT platforms in digital formats, including various numerical database, text, still images, audio, video, etc. ● Growing digital libraries that contain, e.g., spatially explicit maps, socio-economic statistics, climatic changes, biological materials, genetic information, enzymatic reactions, etc.
Artificial Intelligence (AI)	● Computers capable of performing tasks that typically require human intelligence but with higher speed ● Improve automatically without human intervention, through machine learning and deep learning with big data fed into the machines ● Analysing digital images or videos, e.g., satellite images, images of individual trees, etc. ● Predicting and optimising complex operation, e.g., 'smart' farming system, landscape management, 'smart' factories, etc.
Cloud technologies	● Provide on-demand data storage, exchange, and computing power without the need of physical possession and management of advanced computer system resources by the users ● Accessing shared pools of data and applications through cloud storage ● Digital platforms for, e.g., trading, product marketing, communications, e-banking

Table 2. Supporting hardware vectors.

Commercial high speed satellite internet	● Widespread availability of satellite internet infrastructure will facilitate the growth of key technological vectors, by enabling remote rural communities access to high-speed internet without intrusive ground-based telecom infrastructure. ● Assist conservation by enabling access to instant information and direct personal communication, thereby reducing the information gap between local conservationists and external actors (e.g. access to legal documents and advice, avoid the prevention of *de facto* action on the ground by bad actors due to slow reporting). ● Assist conservation by enabling the connectivity of rural communities to the global information infrastructure without requiring intrusive expansion of land-based telecoms infrastructure. ● Examples of this can be seen already in the linking of rural Brazilian schools in the Amazon to high-speed internet (Merano, 2022).

Distributed micro-electrical grids	● All software-based technological vectors in the digital economy require electricity. The development of distributed smart electrical grids, based on solar or micro-hydro energy sources will form the bedrock of all digital vectors. ● The establishment of these micro-grids will involve some level of local development (e.g. the rerouting of streams for micro-hydro plants), but conservation efforts in these areas will be boosted by requiring less reliance on national electrical grids, which require long-distance electricity transmissions, and intrusive infrastructure networks. ● An example of this is the provision of 30 kW of energy distributed to 400 people of the Buduk Nur community in Bakelalan , Sarawak (Kuok, *et al.* 2012) for US$ 200,000.

Figure 1. Borneo: Land Cover Map 1973 and 2018 (MY: Malaysia; ID: Indonesia) (CIFOR, 2020)



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