Frontier Technologies for Securing Tenure

A REVIEW OF CONCEPTS, USES AND CHALLENGES

IFAD
Investing in rural people

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Abstract

The International Fund for Agricultural Development (IFAD) and the Food and Agriculture Organization of the United Nations (FAO) seek to improve the livelihoods of small-scale farmers and customary land rights-holders. Many projects funded by international finance institutes, such as IFAD, have few or no standalone land-tenure projects, but they touch upon tenure issues, especially in rural development. Examples include irrigation, improved natural resource management, rural infrastructure development, climate change adaptation, afforestation, and forest management. Tenure issues need to be assessed and, if necessary, addressed to achieve positive long-term impact for small-scale producers and mitigate risks. Inadequately addressing tenure issues carries the risk of overlooking the needs of vulnerable groups, or the project not being effective/sustainable. In some cases, there is also the risk of conflict. Improving land tenure security is hence an important component of these investment projects, and frontier technologies offer opportunities for improvements in this regard.

We interviewed 13 knowledgeable experts, hand-picked by the research team for their knowledge of and experience in developing and implementing innovative solutions to address tenure security, particularly in developing and customary land rights contexts. We also reviewed 20 relevant publications, including peer-reviewed journals, conference proceedings, and reports. This qualitative dataset was synthesized and several themes emerged, focussing on the range of technologies available and their uses, and the benefits and challenges of using frontier technologies for land tenure. Finally, recommendations are made based on the lessons learnt.

While close to **20 different technologies** were mentioned in the interviews and literature, the most prominent were the following:

- mobile devices (smartphones and tablets),
- image-based solutions (including satellite-based remote sensing and unmanned aerial vehicles or UAVs),
- distributed ledger technology (such as blockchain),
- machine learning and artificial intelligence for automated feature extraction and big data analytics, and
- software solutions such as geographic information systems (GIS).

We found that technologies are rarely used in isolation and combinations of technologies are favoured. We also found that participatory approaches are crucial for project success.

Close to 20 **benefits of using frontier technologies for tenure** emerged from the data. We grouped these under four headings:

- saving time and money,
- managing disputes,
- information access, and
- allowing new approaches.

One of the main motivators for development and adoption of new technologies is to reduce cost and improve efficiency. Adopting participatory approaches supported by frontier technologies helps to reduce land-related disputes. Through the use of land data dashboards and cloud-based services, access to land-related information can be improved. And one of the biggest benefits of frontier technologies is that they open up new opportunities that can be tailor-made to address context-specific requirements, which is very important for customary contexts where there is no one-size-fits-all approach.

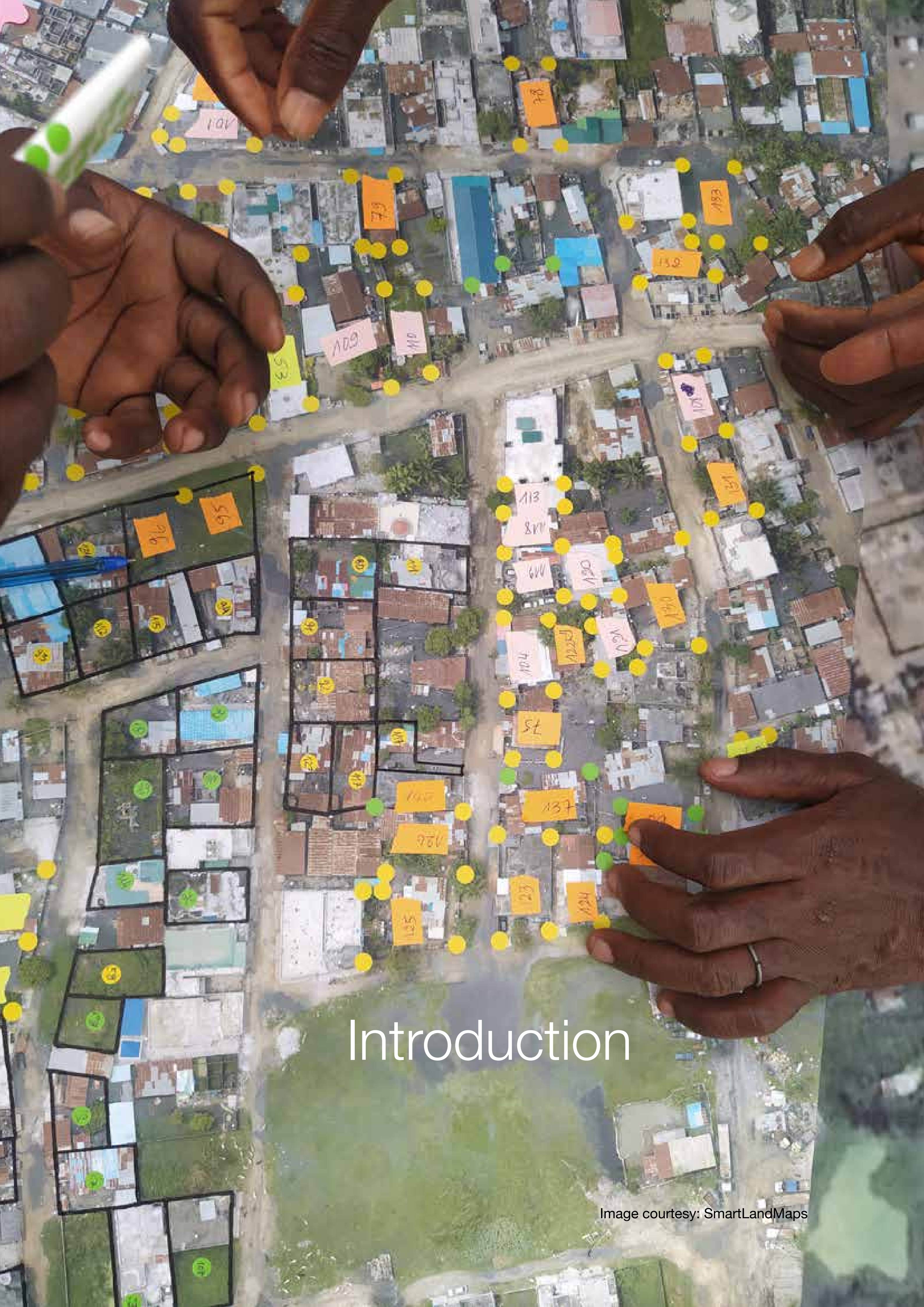
Over 20 challenges were identified in the data, which are grouped here under six headings.

1. There is the need for **capacity development** to ensure sustainability of technology use. Capacity extends to administrative, financial, political and legal spheres.
2. There must be a **supportive political and legal environment**. Well-intended projects have been hampered by over-restrictive or non-existent regulations and a lack of political will.
3. **Cost and quality** can be inhibiting factors. While frontier technologies can save time and money, there may be initial cost implications requiring donor support to get projects up and running. Saving costs may mean a reduction in the quality of the data gathered or the service provided, and fit-for-purpose solutions need to be carefully designed to balance these aspects.
4. There is the **challenge of the hype** surrounding some frontier technologies, which have been touted as cure-alls for land tenure and land administration. Users also have high expectations of what can or should be delivered. These expectations need to be carefully managed.
5. **Resistance to change** is another challenge to overcome. While frontier technologies offer new opportunities, there is some inertia to overcome in land administration institutions that have established and sometimes legally prescribed ways of doing things.
6. Finally, and especially pertinent in developing and customary land rights contexts, mapping customary land rights is a challenge that requires innovative and sensitive approaches. The **involvement of the beneficiaries and relevant communities** and government agencies is crucial for success.

We conclude with three common-sense recommendations:

1. **Taking an integrated approach regarding technologies, data and methods is strongly advocated**. Frontier technologies allow for integration of data sources, creating opportunities for enhanced data analytics. And technologies should be used in partnership with the communities and beneficiaries they are intended to support. The use of participatory approaches is strongly recommended, especially in contexts involving customary land rights mapping.
2. **There must be a focus on sustainability**. Technical, financial and institutional capacity need to be addressed before implementation. Without a supportive legal, political, and institutional environment, land tenure projects will face many challenges that cannot be addressed using technology.
3. **The focus should be less on the technologies and more on ensuring an enabling environment**. The focus should also be on choosing the most appropriate technology for the task and context, bearing in mind that this might not be the latest, most advanced solution.

Contents



Introduction

Image courtesy: SmartLandMaps

1 Introduction

1.1 BACKGROUND AND MOTIVATION

Secure land and natural resource rights are a key ingredient for rural transformation, social inclusion, and the realization of many of the Sustainable Development Goals (SDGs), especially in the developing world. FAO & IFAD (2022) identify SDGs 1, 2, 5, 11 and 15 as applying particularly to land-related targets with a focus on land access and tenure security. Many rural communities in the developing world access land and the associated natural resources through a diverse range of tenure regimes from across the land tenure continuum (UN-HABITAT, 2015). In many cases these rights are not formally recorded or registered, and very often statutory land administration systems are inaccessible to rural communities (Hornby *et al.*, 2017). As a result, land transactions are often not recorded in formal systems, people's ability to leverage finance through their proof of tenure security is restricted, and more fundamentally, their ability or incentives to invest in sustainable land management and land-based economic activities is undermined.

The rapid development of geospatial technologies and systems, combined with participatory methods for social empowerment, have contributed significantly to addressing these challenges (FAO & IFAD, 2022) and in developing fit-for-purpose land administration / land recordation systems, including for related processes in land and natural resource use, management, planning and payment for environmental services (Koeva *et al.*, 2019). Spatially enabled land administration can form the basis for improved tenure security and provide improved services and information for a variety of uses from land management and planning to environmental monitoring and climate action (Stanley and Törhönen, 2013). Frontier technologies create opportunities and potential benefits in the development of affordable and accessible fit-for-purpose systems.

Specific opportunities and benefits include inter-alia:

- monitoring and ground-truthing changes in land and natural resource use,
- recordation of land and natural resource rights, including collective, familial, individual, and multiple (sometimes overlapping) user rights,
- facilitating land transactions in emerging land markets,
- enabling systems for payment for environmental services, and
- using proof of ownership or tenure security for improving access to finance.

There are, however, various challenges and risks associated with the use of frontier technologies that need to be identified and for which safeguards and mitigation measures need to be developed. Paramount amongst these measures is the empowerment of rural communities in the use of technologies. Without regulatory oversight to ensure security of data and protection of privacy, technology can foster exclusion, authoritarianism and social control, rather than inclusion and empowerment (UNCTAD/TIR, 2021).

There are a wide range of government, private sector and civil society organizations that are pioneering new innovations in the use of technologies and methods that promote land tenure security. Each have different areas of expertise and important roles to play in developing innovative approaches to securing land tenure. FAO and IFAD are thus interested in partnering with various stakeholders across all sectors and disciplines. There is hence need for a systematic review of the various experiences in the use of frontier technologies combined with social empowerment in land recordation and land governance systems more broadly to map out the potential benefits, opportunities, challenges, and risks in relation to FAO/IFAD's and their partners' specific interests, as well as the key stakeholders involved with whom FAO/IFAD could strengthen collaboration. Consequently, this report sets out to review, in broad terms:

1. The range of available and innovative geospatial tools and frontier technologies, and how they have been used for securing land tenure, especially in developing contexts,

2. The benefits and challenges associated with the use of frontier technologies for securing land tenure, and the prevailing principles governing such use,
3. Recommendations for application of frontier technologies for securing land tenure.

In addressing the abovementioned points, we drew from published literature (conference proceedings, peer-reviewed journal articles, as well as 'soft' literature) and interviews with experts from academia, international organizations, and solutions providers. We found a wide range of frontier technologies that are being used in land tenure / land administration projects, from the Internet of Things and Artificial Intelligence through to high-resolution satellite images, drones and mobile devices. The report begins with some definitions of key terms and a description of the methodology used, before drawing together the results of the analysis to address each of the objectives listed above.

1.2 DEFINITIONS

Frontier technologies

Frontier technologies offer potential for combatting current global challenges such as poverty and climate change while disrupting and displacing existing processes (Ramalingam *et al.*, 2016). Manyika et al. (2013) refer to such technologies as having "the potential to disrupt the status quo, alter the way people live and work, rearrange value pools, and lead to entirely new products and services." Such technologies have the potential to assist in the global drive for sustainable development, with the caveat that they also have the potential to widen existing inequalities or create new ones as technologies may be quickly adopted by some, leaving others behind (UNCTAD/TIR, 2021).

Ramalingam et al. (2016) identify five characteristics of frontier technologies:

1. They can address large-scale economic, social, or political opportunities or problems,
2. They are characterised by rapid technological development,
3. They have the potential for broad impact across diverse fields,
4. They have potential for displacing existing technologies and bypassing expected technological pathways, and
5. They involve considerable uncertainty, largely due to their adoption outstripping regulators' and policymakers' ability to set standards for their use (Kambria, 2019).

Typical examples of frontier technologies include (but are not limited to):

- artificial intelligence (AI), machine learning, distributed ledger technology (DLT, such as blockchain),
- 'drones' (Unmanned Aerial Vehicles – UAVs),
- satellite-based imaging sensors (generally referred to as 'remote sensing' or 'Earth observation'),
- the Internet of Things (IoT),
- big data,
- Global Navigation Satellite Systems (GNSS, such as the Global Positioning System, GPS), and
- mobile device / smartphone applications.

See Table 2 in the Appendix for brief definitions and uses of these technologies. This report will briefly relate these technologies to opportunities for improving land tenure security and inclusiveness in developing contexts.

Land tenure security

For understanding land tenure security and identifying the intended beneficiaries of land tenure projects, the following definitions of associated terms are provided:

Land rights: rights held by people or communities over land, including rights of access, occupation, and resource use, as well as the right to transfer those rights to others and exclude others from exercising those rights over the land in question.

Land tenure: refers to the way in which land rights are held and recognised (whether through written policies and laws or unwritten customs and practices), including the associated terms and conditions.

Land tenure security: "the legal and practical ability to defend one's ownership, occupation, use of and access to land from interference by others" (Weinberg, 2015).

Tenure systems: the mechanism by which societies regulate access to land, fisheries and forests.

Customary land tenure systems are noted to exhibit the following characteristics (Chitonge *et al.*, 2017; Cotula, 2007; Cousins, 2007; Freudenberger *et al.*, 2013):

1. Land rights are socially embedded, overlapping, and nested. They mirror the social and cultural values of the community and gain legitimacy from the trust a community places in the institutions governing the system.
2. Rights are derived from accepted *membership* of a social unit (kinship ties), either through birth or acquired allegiance.
3. They allow multiple uses (e.g. farming, fishing, occupation) and users (e.g. farmers, migrants, herders, residents) of resources.
4. Rights are both individual (the holding) and communal (the commons).
5. They are dynamic and evolve in response to external or internal change. Boundaries are flexible and negotiable.

Small-scale farmers are defined by their context and their characteristics, both of which vary widely. Generally, it is accepted that 'small-scale/smallholder farmers' are those farming on 2,0 ha or less, though this is a rough measure given the different potential of land vis. soil quality and rainfall (IFAD/UNEP, 2013). "Overall, smallholder farmers are characterized by marginalization, in terms of accessibility, resources, information, technology, capital and assets" (*Ibid.*: 10).

Frontier technologies can support projects aimed at improving land tenure security for small-scale farmers and customary land rights-holders in a variety of ways. For example, high resolution remotely-sensed or drone-based imagery can be analysed using AI and machine learning to automatically extract land parcel boundaries (Koeva *et al.*, 2017, 2019). These can be verified through participatory processes involving GNSS-enabled smartphones (Eilola, Käyhkö and Fagerholm, 2021) and recorded in the cloud. Land-based transactions can be secured using distributed ledgers such as Blockchain (Panfil *et al.*, 2019). Thus, a combination of technologies and procedures can (and should) be used to record land rights. Further details are given in Section 3.

'Going digital'

In the context of frontier technologies and their impact on land administration processes and land tenure security, many innovations are aimed at 'going digital'. To understand what this means, it is necessary to distinguish between three distinct terms that are often, and incorrectly, used interchangeably: digitisation, digitalisation, and digital transformation. According to Gupta (2020), Hapon (2020) and Asite (2021):

- **Digitisation** is the creation of a digital copy of an analogue or physical object or attribute, i.e. converting something that is not digital into a digital representation or artifact. Examples include scanning a paper document and storing it as a digital document (e.g. converting to pdf or image) or moving a paper-based administration process online (without changing the process).
- **Digitalisation** cannot occur without digitisation. It is the use of digitised information to improve business processes. Examples include collaborating on documents shared online. This increases productivity and reduces costs by enhancing access to digital data and processes.
- **Digital transformation** involves organizational change to leverage the opportunities made possible by digitisation and digitalisation. It requires a rethink of the way things have been done in the past, taking advantage of the possibilities afforded by new technologies to radically increase productivity and creativity.

These phases of 'going digital' loosely correspond to the Land Information System (LIS) generations identified by Bennet, Pickering and Sargent (2018). Generation 0 LIS is identified as the pre-digital phase of paper-based systems, with Information Technology (IT) possibly playing a supportive role. Generation 1 LIS corresponds loosely with digitisation: standard data collection tools and processes are still used, but some data and analysis is occurring digitally. Generation 2 LIS corresponds loosely with digitalisation: the creation of "tools that [are] more rapid and cheaper to apply, broadening the constellation of definable land interests, and utilizing alternative [frontier] technologies" (*Ibid.*, 5). Digital transformation occurs when Generation 3 LIS emerge: "These entrepreneurial approaches seek to transcend conventional institutions, technologies … and methods" (*Ibid.*). The disruptive and opportunistic nature of frontier technologies allows organizations to leapfrog generations, by-passing established technologies that may be more expensive, less efficient, or of inferior quality (Ramalingam *et al.*, 2016). This is a considerable opportunity for less developed contexts to accelerate development.

1.3 IMPLEMENTATION PRINCIPLES

Challenges and considerations for adopting frontier technologies

UNCTAD/TIR (2021) identifies five challenges developing countries face when it comes to adoption of frontier technologies:

1. *Demographic changes*: The world's population is projected to grow to 9,7 billion by 2050, with the biggest changes taking place in lower-middle-income countries. This means that these countries will have a surplus of available labour and many youth requiring employment, depressing wages and reducing the incentive for innovation.

2. *Lower technological and innovation capacities*: There are several technology-related gaps between low- and lower-middle-income countries as compared to other country groupings. If these gaps are not closed, the developing world will keep falling further behind as their more developed counterparts push forward with increased technological innovations.

3. *Slow economic diversification*: Many developing countries exhibit a dependence on commodities over manufacturing. Manufacturing drives innovation, while commodities offer fewer opportunities for diversification.

4. *Weak financing mechanisms*: Developing countries lack the public or private finances to fund technological innovation.

5. *Stringent intellectual property (IP) rights*: Most frontier technologies are developed by a few companies and countries. These innovations are protected through IP rights such as patents, trade secrets, trademarks, and copyrights. These create hurdles for the diffusion of technology, reinforcing the divide between developed and developing countries.

Hence, it is important for development agencies such as FAO and IFAD to support communities and individuals in developing contexts to leverage frontier technologies to address their context-specific challenges. The UNCTAD/TIR report also identifies five considerations for ensuring that people and communities can access frontier technologies while avoiding negative unintended consequences (Figure 1): availability, affordability, awareness, accessibility, and ability. They note that:

> **"… technology is rarely a solution on its own… [It] is neither inherently good nor bad; it is a means to an end. Technology … needs to be used carefully if it is to help rather than hinder"**
>
> (Ibid.: 71).

Taking this caution into consideration, in the context of land tenure, FAO (2012) provide ten guiding principles for the implementation of projects aimed at improving tenure security (Table 1). These relate generally to recognition of human rights and good governance principles and should be adhered to in the context of the implementation of frontier technologies.

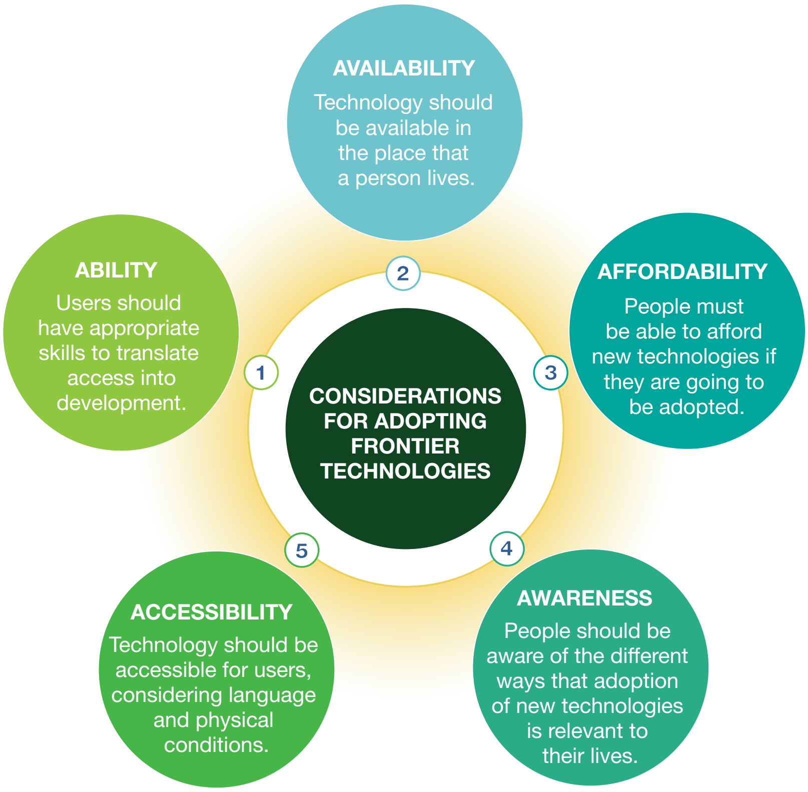


Figure 1 The five A's of technology access (UNCTAD/TIR, 2021)

Table 1 **Ten guiding principles for the implementation of projects aimed at improving tenure security (FAO, 2012)**

Principle	Description
Human dignity	Recognizing the inherent dignity and the equal and inalienable human rights of all individuals.
Non-discrimination	No one should be subject to discrimination under law and policies as well as in practice.
Equity and justice	Recognizing that equality between individuals may require acknowledgment of individual differences and taking positive action to promote equitable tenure rights for all.
Gender equality	Ensure the equal right of women and men while acknowledging their differences, taking specific measures to improve equality when necessary.
Holistic and sustainable approach	Recognizing that natural resources and their uses are interconnected, requiring an integrated and sustainable approach to their administration.
Consultation and participation	Ensuring that all legitimate tenure-rights-holders are engaged prior to decision being taken and responding to their contributions, considering existing power imbalances.
Rule of law	Adopting a rules-based approach, acknowledging all national and international laws and agreements.
Transparency	Having clearly defined and widely publicized policies, laws and procedures.
Accountability	Holding individuals, public agencies and non-state actors responsible for their actions and decisions according to the principles of the rule of law.
Continuous improvement	States should improve mechanisms for monitoring and analysis of tenure governance in order to develop evidence-based programmes and secure on-going improvements.

Figure 2 Country-level fit-for-purpose implementation approach (after Enemark and Mclaren, 2017)

Frontier technologies and fit-for-purpose approaches

Linking with the principle of continuous improvement, and drawing from human rights principles, the International Federation of Surveyors (known as FIG) has drawn up fit-for-purpose land administration (FFP LA) guiding principles (Enemark, McLaren and Lemmen, 2015). These 12 principles are divided equally into three frameworks – the spatial, legal and institutional frameworks (see Table 2) – to help ensure that strategies aimed at improving a country land administration system are designed in a way that is participatory, inclusive, flexible, and focused on citizens' context-specific needs (Enemark *et al.*, 2014).

The adoption of frontier technology to secure tenure should follow the above-mentioned principles to ensure that their use is successful and sustainable. To this end, Enemark and McLaren (2017) have suggested a seven-step implementation process that begins with an analysis of the country context, identifies gaps in the existing spatial, legal and institutional frameworks, develops strategies for addressing those gaps (which could include adoption of frontier technology for securing tenure), followed by capacity development and benefits analysis (see Figure 2). The process is cyclical because intervention changes the context, thus there must be a re-assessment to ensure that the implemented intervention is still fit-for-purpose (Barry, 2018).

Table 2 **The key principles of a fit-for-purpose approach to land administration**
(after Enemark, McLaren and Lemmen, 2015)

Spatial framework	Legal framework	Institutional framework
Visible (general) boundaries	Flexible, administrative	Good land governance
Aerial imagery	Continuum of tenure	Integration
Accuracy for purpose	Flexible recordation	Flexible ICT approach
Updating, upgrading, ongoing improvement	Gender equity	Land information: transparent, affordable, accessible

Generalised steps for systematic land registration

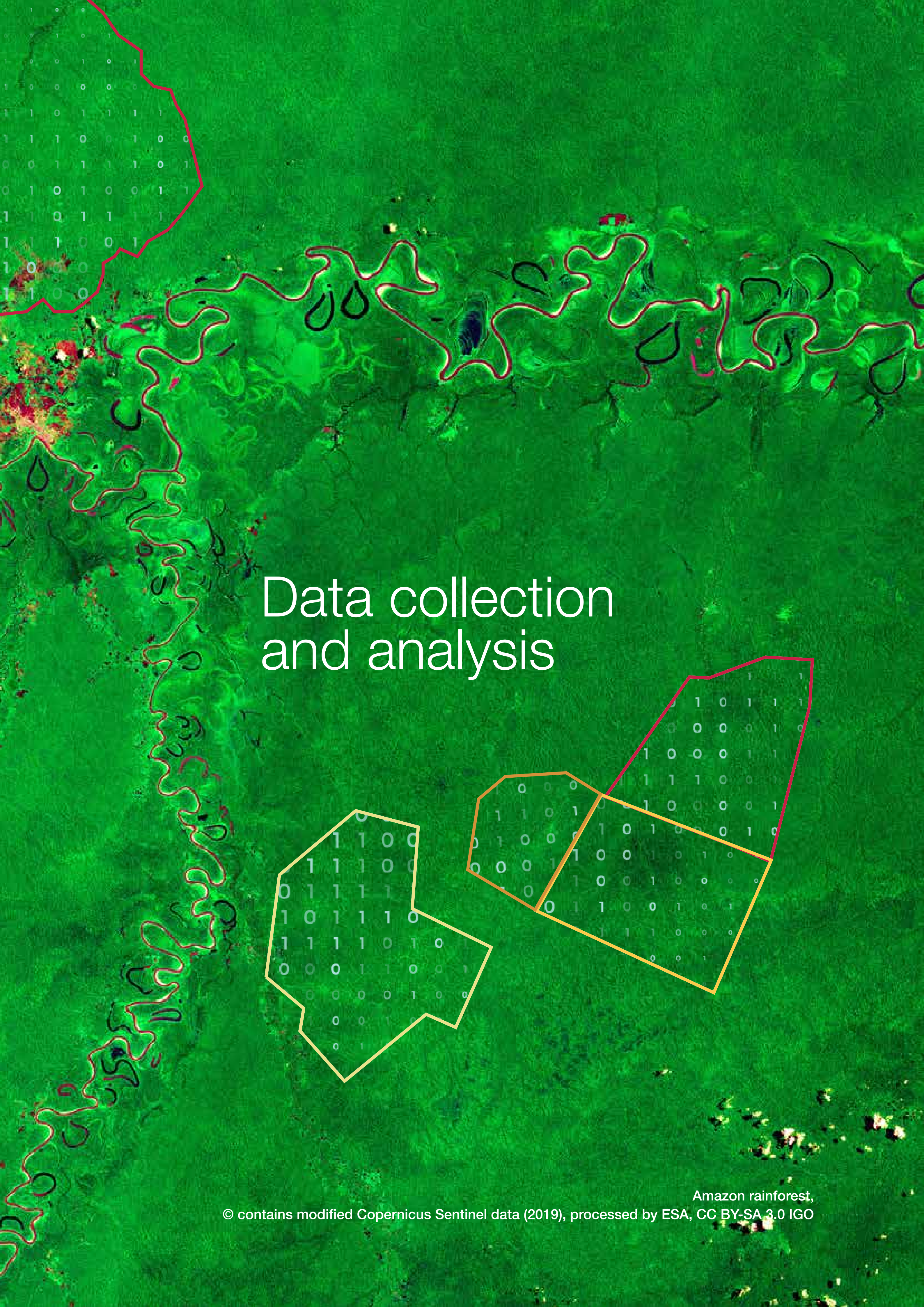
Systematic registration is generally a top-down process whereby every land parcel is registered across a country or region relatively quickly, whereas sporadic registration is generally a bottom-up process whereby land rights-holders apply for registration when they feel the need. In the long-term, sporadic registration is more expensive than systematic registration, yet for pro-poor land administration it is recommended that a sporadic approach be implemented at first until there is sufficient support for systematic land registration (FAO, 2017; Zevenbergen *et al.*, 2013).

Stanley & Törhönen (2013) have proposed 10 steps grouped into four phases for systematic land registration. They note that the steps, and their order, vary from region to region based on contextual differences, but these steps and phases are nonetheless a useful guide for systematic registration programmes. Similarly, FAO (2017) has identified seven steps for systematic land registration. The importance of context is again highlighted. The two descriptions are similar and, for simplicity, are summarised here under the four phases of Stanley & Törhönen (see also FAO & IFAD (2022) for a detailed description of the activities associated with each phase):

1. **Preparation.**
    a. Developing an inventory of existing spatial and legal datasets, setting project targets, defining adjudication areas, and developing a schedule for a phased implementation.
    b. Identifying and mapping vulnerable groups.
    c. Implementing a public awareness programme.
2. **Technical work.**
    a. Investigation of parcels, holders and rights.
    b. Demarcation of boundaries and cadastral parcel mapping.
    c. Collection of evidence and adjudication of claims.
    d. Preparation of documents and quality checks.
3. **Verification and resolution.**
    a. Public display of land records.
    b. Facilitating appeals and dispute resolution.
4. **Legal registration.**
    a. Formal adjudication and registration.
    b. Issuance of titles / certificates.

Frontier technologies can be used throughout these four phases. The developed recordation system must allow for validation and updating as the situation changes, which makes this a cyclical process in line with the fit-for-purpose process described above.

Data collection and analysis



Amazon rainforest,
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2 Data collection and analysis

2.1 DATA COLLECTION

The research team comprised of an external consultant and two members each of the land tenure teams at FAO and IFAD. The team conducted a review of relevant literature as well as several interviews with 'knowledgeable experts'. Sampling was hence purposive in that the research team identified suitable experts and pertinent literature based on their own experiences in the field of land tenure and administration. Some experts also provided the team with relevant literature to support the content shared via interview.

We sent invitations to 14 knowledgeable experts, 13 of whom agreed to be interviewed. We are exceptionally grateful to each of them for giving of their time so willingly. Each interview was conducted online using either MS Teams or Zoom, and each interview lasted an hour. Interviews were conducted in English from May to June 2022 and were recorded with the consent of the interviewees. See the Appendix for the full list of interviewees, who all gave consent for their names to be disclosed. Six interviewees were female and nine were male (in two cases a man and a woman were interviewed together). Interviewees were drawn from a broad base of expertise, including representatives from academia, international organizations, and solutions providers:

- International organizations included groups such as the International Federation of Surveyors (FIG), FAO, World Bank, USAID, and Ordnance Survey International.
- Solutions providers are companies / organizations that offer a tool or platform for land administration / land rights recording such as Cadasta, Meridia, Medici, and Terra Firma.

It is important to note that these distinctions are quite blurred: several interviewees wore multiple hats (e.g. academics engaged in private consultancy and sitting on boards or committees of international organizations), and several interviewees have moved between different roles and reported on their experiences broadly. Overall, four interviewees represented academia, four represented solutions providers, and seven represented international organizations.

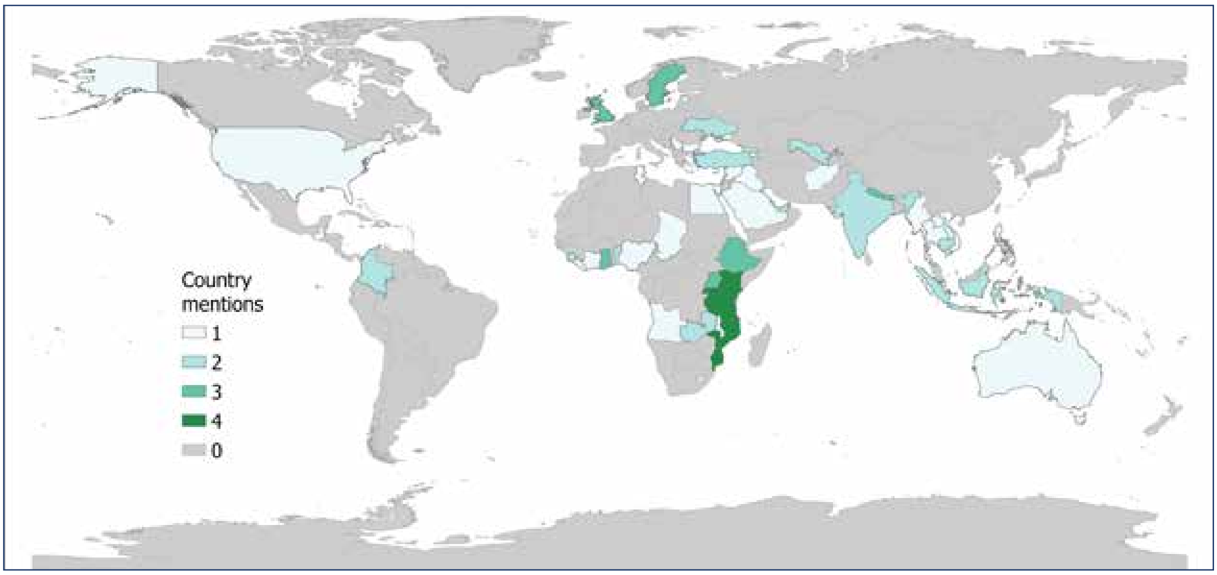


Figure 3 Countries mentioned by interviewees where frontier technologies have been applied for land tenure

The breadth of the interviewees' collective experience is illustrated in Figure 3, which identifies all countries mentioned by the interviewees as locations in which they are applying frontier technologies for land tenure security. Overall, 55 countries were mentioned (some by more than one interviewee), from Tonga and Samoa in the Pacific, through Africa to Oceania.

The interviews were transcribed and shared with the interviewees for verification that their contributions had been faithfully recorded. We used the automated transcription services available in both MS Teams and Zoom.[1] Transcription and editing involves some interpretation on behalf of the researcher, which is why it is important that the transcriptions are shared with interviewees for verification before proceeding to analysis. Interviewees were also afforded the opportunity to make corrections or elaborations as they deemed appropriate.

The full list of questions (see the Appendix) was shared with the interviewees before the interviews but note that these were used as a guide only and the emphasis in each interview was on creating a *conversation* around frontier technologies for land tenure. The most commonly asked questions related to:

1. understanding interviewees' interest and involvement in land tenure projects,
2. their experiences with frontier technologies,
3. their biggest challenges and successes, and
4. where they see the future for land rights mapping.

The research team also identified relevant publications for review (see Table 5 in the appendix), and in some instances, these were received from the interviewees as additions to the information shared in the interviews. We note that this is not an exhaustive list and much has been published on this topic over the last couple of decades. It is not possible to review everything, and we have focused on 20 publications from the last 10 years (as a 'manageable' number to review (Çağdaş and Stubkjær, 2009; Silva and Stubkjær, 2002), with emphasis on the most recent publications.

1 On average, it took about three hours per one-hour interview to edit the transcript. This includes re-listening to the interview at 1,5x speed after editing to correct any mistakes that the automated transcription made.

2.2 DATA ANALYSIS

The transcribed interviews and shared publications were reviewed using Atlas.ti version 8 computer-assisted qualitative data analysis software (CAQDAS). This involved open coding of the qualitative dataset (Holton, 2007), focusing on identifying the different types of frontier technologies used, the purposes for which they are used, the different approaches adopted, and the associated benefits and challenges. This yielded an initial list of over 120 codes and a high level of saturation[2] for the dataset. These were then reviewed and refined, starting with the codes with the lowest groundedness.[3] Part of the challenge with qualitative, grounded theory-based data analysis is that the researcher does not know, at the outset, what concepts may emerge from the data (Barry and Roux, 2013). Hence, s/he may create a code for something that appears interesting, only to find that it is rarely repeated in the data. Such a code would have a low groundedness. Codes that occur frequently have a higher groundedness.

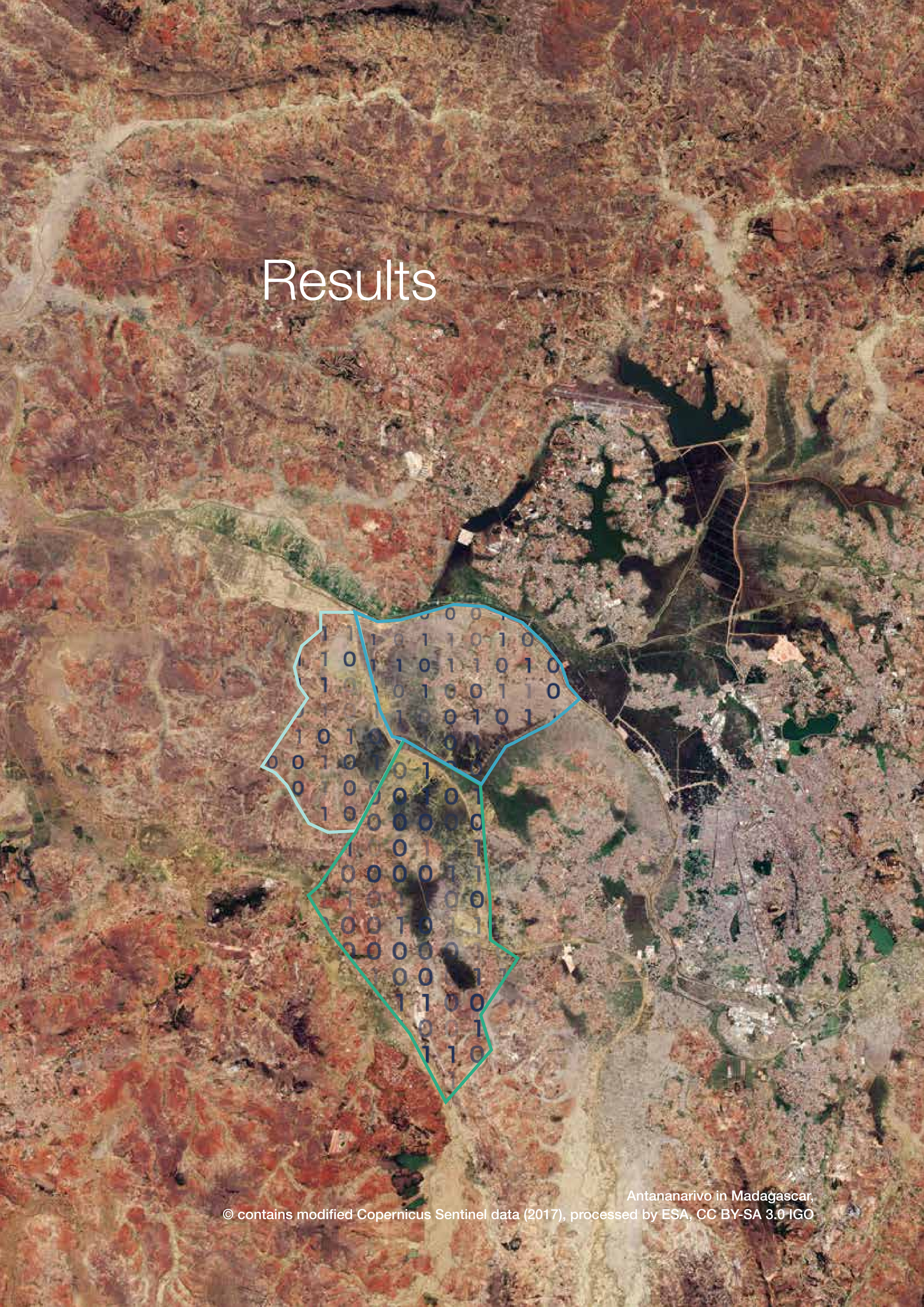
In some instances, the researcher may realise that the code had been overlooked in the first round of coding. Using CAQDAS, a quick search through the documents and transcripts can be done to increase the code's groundedness. In other instances, the researcher may find that the same concept has been coded more than once using different words. The software allows for such similar codes to be merged. Similarly, the researcher may find several codes that can be grouped together under a different name. In this way, the total number of codes was reduced to 90 that were grouped as follows:

- 14 related to different *approaches* used,
- 18 related to *benefits* of frontier technologies,
- 22 related to *challenges* to be addressed or related to the use of frontier technologies,
- 17 related to the *purpose* for which frontier technologies were used, and
- 19 related to different types of *technologies.*

Atlas.ti allows the researcher to interrogate the codes through code co-occurrence and code-document tables. The former identifies instances in which codes overlap, for instance artificial intelligence co-occurs with machine learning, cloud computing and automated feature extraction. The code-document tables cross-tabulate the numbers of codes per document (or interview), which allows the researcher to identify the dominant concepts per document. In the following section, we present the findings from this qualitative data analysis exercise.

2 Saturation occurs when the researcher finds no new codes emerging from the dataset (Holton, 2007).
3 Groundedness refers to the number of times a code appears in the dataset (Hull, Babalola and Whittal, 2019).

Results



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3 Results

The objectives for this report are to review, in broad terms:

1. The range of available and innovative geospatial tools and frontier technologies, and how they have been used for securing land tenure, especially in developing contexts,
2. The benefits and challenges associated with the use of frontier technologies for securing land tenure, and the prevailing principles governing such use,
3. Recommendations for application of frontier technologies for securing land tenure.

Linking these objectives to the code groupings listed in the previous section, the range of tools and technologies corresponds with the *approaches* and *technologies* groups. The range of uses of tools and technologies corresponds with the *purpose* group. The recommendations for application are derived from the *challenges* and *benefits* groups.

Figure 4 Enumerator collecting ownership information from landowner with family looking on (image courtesy: Medici Land Governance)

3.1 RANGE OF TECHNOLOGIES AND USES

Figure 5 illustrates the range of technologies mentioned in the interviews and literature, arranged according to their groundedness. It is clear that modern, image-based solutions (remote sensing and UAVs), coupled with mobile devices and GNSS, are receiving the most attention whereas the Internet of Things (IoT) and Semantic Web feature rarely. However, technologies are rarely implemented on their own (Hay, 2016): the Semantic Web features prominently with cloud-based computing and big data analytics; the IoT features in discussions involving web-based solutions and mobile devices; whereas UAVs and remote sensing feature alongside automated feature extraction (AFE) and machine learning. Note also that Figure 5 only illustrates groundedness and does not imply that any technology or tool is more beneficial or important than another. For example, blockchain (DLT in Figure 5) has a high groundedness due to its somewhat controversial adoption / rejection. The tools and technologies identified in Figure 5 are briefly described below.

Software solutions

Several 'software solutions' have been developed to address land tenure and administration challenges. These include:

- SmartSkeMa (Chipofya, Jan and Schwering, 2021; Koeva *et al.*, 2021),
- the 'its4land' toolbox (Koeva *et al.*, 2019),
- the 'Ubutaka App' developed by Medici Land Governance for the Rwandan Land Management and Use Authority (Hughes *et al.*, 2022),
- USAID's Mobile Application to Secure Tenure (MAST) (USAID, 2017),
- LADM[4]-compliant software packages developed using the open-source 'Go' programming language (Galić and Vuzem, 2020),
- the Solution for Open Land Administration (SOLA) suite of open-source software (Rizzo, pers. comm., 2022),
- Meridia's tailor-made software solutions (Vernin, pers. comm., 2022), and
- software to assist with managing staff and devices in large-scale projects (Norfolk, pers. comm., 2022).

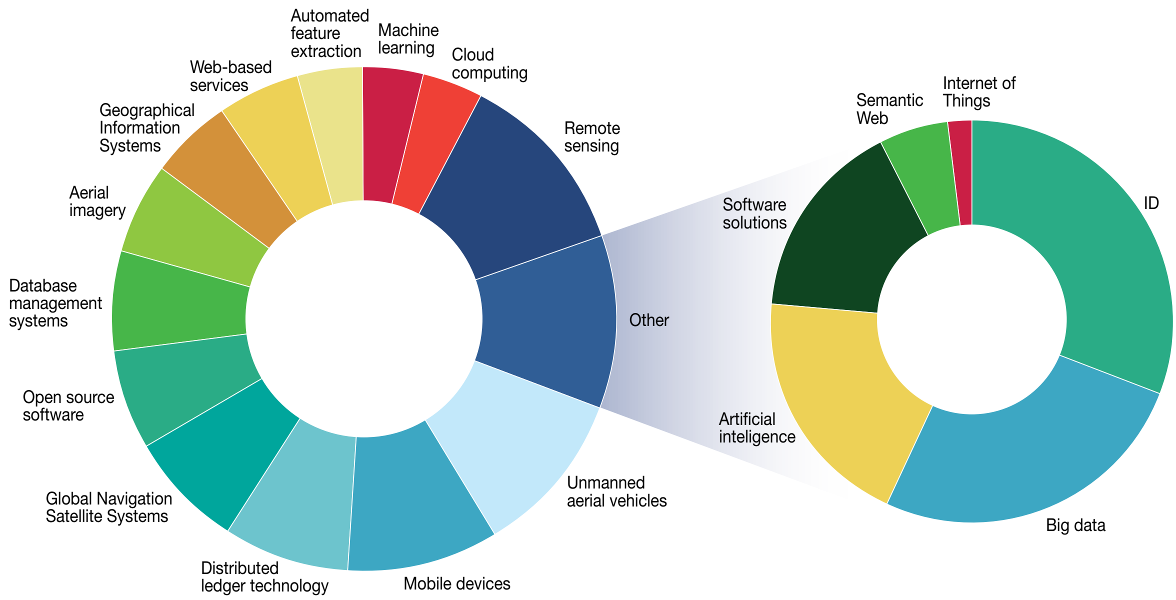


Figure 5 Range of technologies mentioned, arranged according to groundedness

4 LADM – the Land Administration Domain Model, an ISO-standard that is "a conceptual model which supports the modelling of social relations with land articulated through *rights*" (Beck, 2022).

Figure 6 Digitised, annotated hardcopy map showcasing community-drawn land parcels (image courtesy: SmartLandMaps)

It is noted that new software developments create opportunities "for more cost-effective, efficient and participatory ways to register the boundaries of land rights" (UN-HABITAT, IFAD and GLTN, 2016).

Software solutions are always applied with other technologies, such as mobile devices, UAVs, high-resolution satellite images, etc.

Geographic Information Systems

GIS is more than just software – see Table 3 in the appendix. It is a system of hardware, software, procedures, data and people for the analysis, modelling, and management of spatial data. GIS is highly useful as a repository for a wide range of data linking people to land, e.g. georeferenced data on features and land uses, photographs of people, places and events (TerraFirma, 2017). It is also useful for georeferencing hardcopy maps, often including annotations by communities, and can be used to link qualitative data, captured via online or hardcopy forms, with spatial data about land rights – see Figure 6. It thus facilitates the use of participatory mapping of land rights and natural resources (UN-HABITAT, IFAD and GLTN, 2016). Certificates of land rights can be produced, e.g. using the Social Tenure Domain Model (STDM) plug-in to the open-source QGIS software (Babalola and Hull, 2019; UN-HABITAT, IFAD and GLTN, 2016).

As geospatial information improves in terms of scope, accuracy, availability and affordability, GIS is growing in importance as a means of managing, modelling, and mapping spatial data in support of land governance and natural resource management (UN-HABITAT, IFAD and GLTN, 2016). For example, GIS is used in:

- **Madagascar**: for the participatory mapping of customary ownership rights and the development of local land occupation plans and issuance of certificates of occupation;
- **eSwatini**: in the planning and management of irrigation projects for improved decision-making on the best use of irrigated lands;
- **Zambia**: using georeferenced satellite imagery for mapping land use capabilities, existing and proposed land uses, infrastructure and facility management, and participatory mapping;

- **Mozambique**: in support of community-based participatory mapping of existing and planned land uses;
- **Kenya**: using georeferenced satellite imagery for natural resource management and in support of project monitoring and evaluation.

Bell (pers. comm., 2022) noted that many investments in GIS only scratch the surface of what GIS has to offer, e.g. as "a tool to visualize spatial data and produce maps" (Norfolk, pers. comm., 2022). Yet GIS offers many opportunities for advanced data management and analysis, as well as inclusion of land rights-holders, both individuals and communities, in the land rights mapping process.

GIS technology, if driven by community members themselves, could be a powerful tool because it empowers people to better analyse the issues, identify options to resolve them, and to facilitate dialogues within the community and with the related government authorities and other stakeholders.

(UN-HABITAT, IFAD and GLTN, 2016)

Open-source solutions

Most interviewees promoted the use of open-source software, such as QGIS, Open Computer Vision libraries (OpenCV), Open Data Kits (ODK), Open Drone Map (ODM), MAST, and SOLA. The notable exception is Cadasta, who have taken a proprietary approach (Coughenour and Molina, pers. comm., 2022). There are pros and cons to both approaches, which are briefly outlined here.

Open-source software is software that is released under a Creative Commons licence in which the copyright holder grants users the rights to access, use, change, and distribute the software and its source code. The emergence of open-source technologies is a driver for Generation 2 LIS (Bennett, Pickering and Sargent, 2018). Beck (pers. comm., 2022) refers to Creative Commons licence frameworks as "empowering" due to the availability of the software and associated data. Sagashaya (pers. comm., 2022) noted that proprietary software can be very expensive, both for initial purchase and ongoing maintenance. It is this concern that drove the development of open-source machine learning algorithms for AFE in the its4land project: "We know that there are commercial possibilities that can be offered by many companies, and they of course are very good, but it also depends who can afford them, how they can be implemented in the country" (Koeva, pers. comm., 2022). Bell (pers. comm., 2022) noted that he has seen governments investing in proprietary software at great cost, but only using a fraction of what the software has to offer. A real problem occurs if these costs become unsustainable and users risk losing access to their data. The Technical Register Under Social Tenure (TRUST) and MAST were both developed as open-source solutions to avoid licensing fees while allowing for easy updates, maintenance, and reduced cost (Sullivan *et al.*, 2019).

The flip side is that proprietary software comes with technical support which is often lacking in open-source solutions (Sagashaya, Coughenour and Molina, pers. comm., 2022) – users of open-source software must rely on communities of experts via online forums for assistance. It is also very important to note that open-source software is not 'free' – there is always a cost (Molina and Rizzo, pers. comm. 2022). The software may be free to download and use, but the expenses of maintenance and upkeep, and the lack of technical support or warranty, may result in future costs (Zhao, 2012).

Coughenour and Molina (pers. comm., 2022) note three reasons why Cadasta moved away from an open-source to a proprietary software solution:

1. It takes a lot of resources to build a new technology; using proprietary software, requests for improvements can be sent to the software developers, who develop and test the solution before rolling it out. Thus, the user is always assured that the software works as desired and that there is support for bug fixes.
2. The focus on technological development detracts from the need for sustainable, community development. By handing over the technical side, Cadasta is able to focus on community support and analytics.
3. Land is a sensitive topic in most regions, but especially post-colonial, developing contexts where much land rights mapping is taking place, and people and communities are nervous of privacy and security breaches with open-source tools.

The decision to use open-source solutions in the development of SOLA was driven by the need for flexibility. SOLA is intended to be adaptable to any legislative and social framework, in any language, and an open-source approach facilitates such adaptability. "We wanted to create something that is not the product that we have to sell, but it's something for developing countries, which is not expensive, that is open source" (Rizzo, pers. comm., 2022). The philosophy behind the development of SOLA was to provide the basic building blocks of a land administration system that can be developed for particular country contexts. This has been successfully done in Myanmar, Angola, Sierra Leone, Nigeria, Nepal and elsewhere. User support is provided through user guides available online.

Machine Learning and Artificial Intelligence

According to Galić (pers. comm., 2022), machine learning is a subset of Artificial Intelligence (AI). These two technologies will hence be discussed together. Machine learning can be used to automatically extract property boundaries from aerial imagery, assist with property valuation, and help automate registration processes. For example, Ordnance Survey International have developed:

> **… an automated feature extraction platform. It's essentially a digital mapping solution based on top of a suite of different machine learning and artificial intelligence algorithms to extract digital map features and land classes, including potential cadastral units.**
>
> (Beck, pers. comm., 2022)

They are implementing this technology in Lusaka, Zambia, to automatically extract detailed base maps from aerial imagery (Wilson *et al.*, 2022). By automating labour-intensive processes, machine learning can save time and money. It can also reduce human subjectivity and error in mapping and valuation.

> **By automating multiple components of the property mapping, documentation, and transaction process, machine learning can vastly increase the scale and speed of property rights delivery, resource management, and land use planning.**
>
> (Panfil et al., 2019)

Machine learning is highly useful in the context of Automated Feature Extraction (AFE) from images captured by UAVs or remote sensing. AFE is used for the automated identification of land parcel boundaries from images (Tembo and Sagashya, 2022; World Bank Group and T&I Lab, 2021) or hand-drawn sketch maps (Chipofya, Jan and Schwering, 2021). Machine learning is also useful in the analysis of big data.

However, the outputs are not 100% accurate. Bell (pers. comm., 2022) estimates that the AFE success rate currently sits at around 50 – 70%, but notes that this means potentially half of the workload is solved through AFE. Nonetheless, ground truthing by knowledgeable, local experts is required. This is especially relevant in linking the land parcel to the rights-holder/s and documenting the relationship between them (tenure rights). Thus, for "purposes of property registration, machine learning must be paired with other methods" (*Ibid.*), such as are described below.

Automated Feature Extraction

With their high spatial resolution, drone images can be used as a basis for land administration or participatory mapping of land rights. In Zambia, Medici Land Governance is using a fleet of drones to capture imagery with 5 – 10 cm spatial resolution (Sagashaya, pers. comm., 2022). They are using machine learning to analyse these images and automatically detect parcel boundaries in urban areas, where the existence of fences and walls makes automated boundary detection possible (see also Tembo and Sagashya, 2022). Similarly, Koeva et al. (2019) reported that they used "high-resolution UAV images, geocloud services, … sketch maps and automatic techniques for boundary delineation … to improve existing land recording processes" in Ethiopia as part of the its4land project.

AFE is not limited to UAV imagery, however, and can be applied to high-resolution satellite or aerial imagery as well (Koeva *et al.*, 2021; Bell, pers. comm., 2022). Koeva (pers. comm., 2022) mentioned that a current limitation of AFE is that the output is in raster format.[5] At the University of Twente, they are researching how to extract parcel boundaries in vector format, which would allow for improved accuracy and integration with other platforms. She also suggested that improvements in satellite imagery and machine learning for AFE could lead to continuous updating of parcel boundaries, which is important for land tenure security in dynamic tenure environments (such as riverine borders, seasonal variation and nomadism). Such innovations are driving the Generation 3 LIS.

Bell (pers. comm., 2022) noted that the use of high-resolution imagery with AFE is significantly reducing the workload for parcel identification and recordation. Despite the use of machine learning for AFE being described as an emergent technology (World Bank Group and T&I Lab, 2021), it appears to offer much promise for improving the efficiency of land parcel mapping (Bell, pers. comm., 2022). However, Norfolk (pers. comm., 2022) raised an important caution: the need for ground truthing (Panfil *et al.*, 2019) can limit the effectiveness of automation. Automation can also result in job losses, which is particularly undesirable in contexts of high unemployment.

> **I'd rather give the opportunity to 20 interns from the university who are doing GIS courses to earn a bit of money on the side through digitizing 100 parcels a day for a week than to throw the money at an algorithm … The conclusion that we came to [when trialling automated parcel boundary extraction from UAV imagery in Mozambique] was that the initial parcel fabric would require you to verify and check and that would take almost the same amount of time that it would take to digitize the parcel from points that were provided by field workers.**
>
> (Norfolk, pers. comm. 2022)

Big data analytics

Machine learning also goes together with big data management and analytics as an emerging land administration technology. "The combination of cloud computing, big data analytics, Semantic Web technologies and mobile devices offers interesting new opportunities for the advancement of land registry and cadastral information systems implementation, theory and practice" (Hay, 2016). Similarly, Bennett, Pickering and Sargent (2018) note that:

> **[p]ossibly the greatest untapped opportunity in the big data space for land administration is in land tenure security provision – particularly in developing contexts … [B]y bringing together … data – from a myriad of official and less official sources – there lies the potential to apply descriptive machine learning techniques in order to reverse-engineer 'land tenures' through the identification of patterns in social and spatial data.**

Yet Bennett, Pickering and Sargent caution that the challenge remains as to whether machine learning and data mining can indeed extract meaning from multiple, diverse, unstructured data sources for land tenure verification. Panfil (pers. comm., 2022) reported on a project underway by New American that is embracing that challenge.[6] By drawing together data from, for example, Google Maps location history, rideshare receipts, and social media posts, it is possible to create a bundle of evidence for someone's claim to occupation or ownership of a location. McLaren (2016) notes that the IoT, using data gathered from smartphones and other devices (passively monitored patterns of movement), can assist in crowd-sourcing evidence of land and resource rights. This can be used in post-disaster or post-conflict scenarios where all such formal evidence has been destroyed, such as following Cyclone Idai in Mozambique or the war in Ukraine.

5 In raster format, data is stored in a pixel-based grid. In vector format, data is stored as points, line and polygons.
6 https://www.newamerica.org/future-land-housing/project-visible-using-tapestry-credentials-prove-where-we-live/

> **[The] idea is that we can weave together a 'tapestry credential', this tapestry of proof points, that each one isn't in itself dispositive, but together they create a pretty compelling picture of an ownership or occupancy right. And one that's difficult to fake because it's retroactive.**
>
> (Panfil, pers. comm., 2022)

In addition, Dlodlo, Mofolo and Kagarura (2012) note that IoT can be used in enhancing sustainable rural livelihoods by improving land and water resource management, food security, rural infrastructure and services, agricultural logistics, disaster and risk management, public health and education, and eco-management. And with the increasing penetration of smart mobile devices into rural areas, Panfil (pers. comm., 2022) predicts that a significant portion of the global population will soon be able to take advantage of the opportunities that IoT and big data analytics offer for land tenure security.

This challenge of gleaning land tenure information from big data via machine learning is partly being addressed through the emergence of new approaches to database management systems (DBMS): "Unstructured data, non-relational databases, distributed databases (including blockchain technologies), and big data analytics potentially change the landscape for land data creation, management, and dissemination" (Bennett, Pickering and Sargent, 2018). The IoT plays a role here too in the prolific provision of structured, semi-structured and unstructured data – including from social media, smart sensors and mobile devices – and how this has affected the evolution of DBMS (Bennett, Pickering and Sargent, 2018; Galić and Vuzem, 2020). The Semantic Web[7] offers opportunities for interrogating such unstructured data. "These technologies can be combined with cloud and mobile technologies in order to address issues associated with the meaning of highly schema variable data" (Hay, 2016). The Semantic Web is hence highly valuable in the digitalization of digital data and the analysis of big data. It allows for less structured recording of land administration-related information than traditional systems, potentially enabling the creation of more agile, adaptive land administration systems (Bennett, Pickering and Sargent, 2018).

Galić (2021) notes that traditional relational DBMS are not meeting the challenges posed by distributed, data-intensive applications, including big data. He suggests that the time for digital transformation of DBMS is upon us, and yet scaled uptake of new DBMS offerings (such as NoSQL and NewSQL) is noted to be slow (Bennett, Pickering and Sargent, 2018; Galić, 2021). Galić (2021) further cautions that NewSQL DBMS "should not be considered as a panacea for building LIS and other relevant data-intensive applications and systems in the [land administration] domain." New systems should be designed for resilience, scalability and sustainability (*Ibid.*), including the use of data lake houses[8] for both transactions and analytics (Galić, pers. comm., 2022).

Distributed Ledger Technology

One technology that offers the potential to meet these requirements is DLT, and specifically blockchain. "Incorporation of blockchain into a land registry's database system architecture can help alleviate issues related to corruption, lack of trust, inefficient services, insecure data, and vulnerability to cyberattacks" (Panfil *et al.*, 2019). The strength of DLT comes from its decentralised nature, removing the need for centralised authority. This translates into lower costs, improved scalability, and faster time to market (World Bank, 2017). Because the same database is replicated over numerous computers, there is greater transparency and easier auditability. Management and maintenance are dispersed across the network, decreasing the potential for fraud and further reducing costs. The system also lends itself to automation and programmability so that pre-agreed actions may be automatically executed under certain conditions. The built-in redundancies mean the system is less likely to fail. It is also very difficult to tamper with the data because all users verify new data through consensus and all data is assigned a unique identifier to ensure integrity. Users can view and track the same data in real time, which also discourages fraud.

7 The Semantic Web relates to technologies that address the meaning of data on the World-Wide Web through their implementation in Internet protocols.
8 https://www.databricks.com/glossary/data-lakehouse.

However, there are some pre-requisites to a blockchain-based solution that many developing countries will struggle to meet. These include a functioning information and communication technology (ICT) infrastructure, identity system, accurate digitised records, and a trained, competent, and professional community. There may also be a lack of political will or public support leading to too few users for the system to work (Panfil *et al.*, 2019). The systems also lack maturity and there are concerns over their robustness and resilience, especially for large volume transactions. Scalability and transaction speed are also noted concerns. Other technological concerns relate to the interoperability and integration of different DLT systems with existing systems, cybersecurity and governance.

Norfolk (pers. comm., 2022) noted that, for land administration, blockchain does not offer anything that a classical, centralised relational database would not be able to offer. Bell (pers. comm., 2022) concurs:

> **The interesting thing is that some things that blockchain claims it can achieve through DLT, you can achieve through good database technology using multifactor authentication, completely under the control of the responsible government.**

Beck (pers. comm., 2022) highlights that blockchain offers potential for deeds-based registration systems, but is not as useful for title-based systems:

> **As a ledger system, it works well with deeds, because deeds represent atomic levels of change. Title represents state, and I can't yet see how blockchain as a ledger works for the state-driven system.**

Sagashaya (pers. comm., 2022) reported that Medici Land Governance is working with the Government of Rwanda to introduce blockchain for registering land transactions:

> **In Medici Land Governance, we are only using it for transactions and storage and distribution of land registration systems... Right now, we don't use it for land tenure regularisation, but it can be used when doing the 2nd and 3rd transactions from the data we have captured. We have also seen that blockchain can be used to secure the data that has been captured during the land tenure registration.**

Bell (pers. comm., 2022) cautioned that digitalization, and even digital transformation, need to precede the adoption of blockchain and distributed ledgers for land tenure security. If the land administration system is paper based, then blockchain is not a useful technology. Norfolk (pers. comm., 2022) is likewise sceptical of the way that blockchain has been punted as a panacea for land registration, "because you cannot get away from the hard slog of first-time registration. You have to do that and the blockchain is not going to solve that in any way." Panfil (pers. comm., 2022) predicts that blockchain has a future in land registration, especially around decentralisation and fraud prevention, but Bennett (pers. comm., 2022) noted that blockchain challenges the sovereignty of land administration systems – their data and mandates – because in many jurisdictions around the world, land administration is still a state-sanctioned activity. Also, it requires more than merely a technological solution:

> **You must have the legal part, you must have the partnerships part, you must have a sound business model, you've got to have controls around your data, and you must have standards in place.**

Image-based solutions

The application of remote sensing (both satellite and aerial) in land administration has a lengthy history. It has recently found renewed application due to the recommendation in the guiding principles for fit-for-purpose land administration (see Table 2) for the use of general, visible boundaries and aerial/remotely sensed imagery (Enemark, McLaren and Lemmen, 2015). This is the approach taken for the identification of parcel boundaries in, for example, Mozambique (TerraFirma, 2017), Zambia (Tembo and Sagashya, 2022), and Benin (Stöcker et al., 2022b). While some approaches make use of hand-drawn sketch maps (Koeva et al., 2017, 2021; Stöcker et al., 2022b) or delineation of land parcels on remotely-sensed images (Eilola, Käyhkö and Fagerholm, 2021) – see Figure 7 – recent improvements in spatial resolution paired with machine learning allow for automated parcel boundary extraction. "Today, in any projects that require geospatial information remote sensing is essential" (UN-HABITAT, IFAD and GLTN, 2016).

Remote sensing is often used with GIS. In Tanzania, the Village Land Use Plan guidelines specify the use of GIS and satellite imagery for the preparation of village maps and participatory delineation of land parcels (Eilola, Käyhkö and Fagerholm, 2021). In Madagascar, GIS and remote sensing (including both satellite images and orthophotos) have been used for participatory rural appraisal (UN-HABITAT, IFAD and GLTN, 2016). Remotely sensed images also provide an excellent platform for participatory, community-based mapping of land rights (Chipofya, Jan and Schwering, 2021; Eilola, Käyhkö and Fagerholm, 2021; Stöcker *et al.*, 2022a) that can be digitally recorded using GIS.

Figure 7 Identification of land parcels on remotely sensed images (image courtesy: SmartLandMaps)

Rapid developments in ICT have presented new opportunities to establish computerized management information systems and the integration of GIS and remote-sensing tools and applications; this permits more effective information management in support of project operations and monitoring, evaluation and learning (ME&L). The repetitive nature of satellite data capture creates an excellent opportunity for monitoring changes in land use and land cover and evaluating the impact on the environment.

(UN-HABITAT, IFAD and GLTN, 2016)

The combination of community-based mapping with remotely sensed images helps enhance a common understanding of land and natural resource rights. For example, in Peru, communities are mapping threats to rainforests, such as fires and illegal logging. They upload this data to Cadasta's online platform where it is integrated with satellite data in the Global Forest Watch Threat Monitoring API (Cougenour, pers. comm., 2022). In Mozambique, satellite images are used as backdrops to community area maps. Updating the imagery reveals trends in resource use and land degradation, providing community associations with valuable information for future use and conservation of natural resources (TerraFirma, 2017). In Tanzania, the use of remotely sensed data also empowers otherwise disadvantaged people (such as the elderly or disabled) who may find it difficult to investigate land parcels on the ground. Using up to date high resolution aerial or satellite images, they can take part in land rights mapping exercises (Eilola, Käyhkö and Fagerholm, 2021).

Sketching on maps has proven to be useful during participatory mapping activities in various contexts such as urban planning or environmental protection… It allows an increased stakeholder engagement, and transparency and represents one of the easiest and cheapest ways to co-create spatial data with citizens.

(Stöcker et al., 2022b)

Drones (or UAVs – see Figure 8) are relatively inexpensive with low maintenance costs and the ability to be quickly deployed. They can be used to map large areas quickly and cheaply when compared to traditional land surveying, with highly accurate results. "Use of drones at the local level, through community mapping initiatives, diminishes reliance on central mapping authorities, while empowering citizens, NGOs, and small, informal networks" (Panfil *et al.*, 2019). Stöcker et al. (2022a) consider UAVs to be a revolutionary addition to the land administration toolset, given their ability to quickly and accurately capture high-resolution imagery of small to medium-sized areas, which can be used "to derive insights on land use, land development, land value or land tenure, either during participatory mapping activities … or as input data for automatic scene understanding procedures and machine learning". UAVs offer opportunity for innovative approaches due to the variety of different sensors that can be employed (e.g. GNSS, multispectral cameras, LiDAR, RADAR) (*Ibid.*) and are considered to be an enabling technology for Generation 3 LIS (Bennett, Pickering and Sargent, 2018). However, Bennett (pers. comm., 2022) notes that drones are not yet ubiquitous in the land administration sector, though they are finding much application in the agricultural and urban development sectors. Evtimov (pers. comm., 2022) reported that drones have been used in Uzbekistan for monitoring of land use and crops. However, Galić (pers. comm., 2022) mentioned that drones have been trialled in Kosovo for first registrations of land rights, though widespread adoption has not yet followed.

Figure 8 Examples of UAVs used to map land rights (images courtesy: (left) SmartLandMaps and (right) Medici Land Governance)

Bell, Bennett and Cheremshynskyi (pers. comm., 2022) noted that combinations of remotely sensed satellite imagery and aerial / drone-based imagery should be used in contexts where variable mapping accuracies are required / permitted. It may also be necessary to resort to ground-based methods (classical surveying, or GNSS-based measurements) in situations where the project area might not be clear enough in the image (UN-HABITAT, IFAD and GLTN, 2016). Koeva (pers. comm., 2022) reported that this is the approach being taken in Rwanda for updating the cadastral database.

There are some significant limitations to drone use, however, not least of which are the regulatory limitations imposed by national governments (or the absence thereof) as reported by several interviewees (Bennett, Koeva, Sagashaya, and Stöcker, pers. comm., 2022). Battery life is also a significant limitation, as is the need for survey-accurate ground control. The costs associated with processing of acquired data can also be prohibitive. The technology is currently still in an innovation phase and facing resistance to widespread adoption that is limiting its usefulness for land administration and tenure security. It is recommended that alternating top-down (through e.g. passing appropriate legislation) and bottom-up (through e.g. awareness-raising and research) approaches be employed to shift it from niche market to widespread adoption (Stöcker *et al.*, 2022a).

Mobile devices

The improvement and increasing wide spread of GNSS-enabled mobile devices has made a big impact on participatory land rights mapping – see Figure 9. "The increasing location and measurement accuracy of mobile technology has the potential to change the practice of land surveying by enabling the possibility for non-surveyors to conduct and submit surveys using these devices" (Hay, 2016). Norfolk and Panfil both commented on the ease with which local youth could be trained to use smartphones for mapping land rights in Mozambique and Tanzania respectively (pers. comm., 2022) – see also Sullivan *et al.* (2019) and Chipofya, Jan and Schwering (2021). Panfil additionally commented on how empowering this can be for people, who gained confidence and were able to transfer their mapping skills to other employment opportunities. Vernin (pers. comm., 2022) commented on Meridia's approach:

> **The idea is really to be able to give those [mobile devices] to people of the communities, train them for a week or two, depending on the complexity of the work they have to do, and then those agents would be able to go to the field, collect information as a paralegal, or doing some surveying of a parcel … but the equipment is simple to manage and everything is digital, so you are not afraid to actually lose data along the way.**

Rizzo (pers. comm., 2022) noted that the Open Tenure tool was the pioneer of such a participatory, mobile-based approach for the collection of both spatial and qualitative data in the field. On the qualitative side, Hay (2016) suggested that crowd-sourced information contributed using mobile devices can include narratives and oral histories in support of land claims (see also the 'Talking Titler' approach (Barry, Molero and Muhsen, 2013; Bennett, Pickering and Sargent, 2018)). Qualitative data can also be

Figure 9 Certifying Sustainable Supply Chains in South Sumatra, Indonesia (image courtesy: Cadasta)

captured via mobile devices using questionnaires (Norfolk, Panfil and Stöcker, pers. comm., 2022); (Stöcker *et al.*, 2022b). By integrating participatory approaches into data capture, community validation of the mapped land parcels is ensured as part of the process, reducing land-related disputes (Rizzo, pers. comm., 2022) – see also Sullivan *et al.* (2019) and Chipofya, Jan and Schwering (2021).

Many mobile solutions make use of cloud- or web-based services for storage and access of data. Meridia allows for the offline collection of data on mobile devices in situations of low mobile connectivity, and the later upload to a server platform when connectivity is restored (Vernin, pers. comm., 2022). The its4land toolbox includes a 'Publish and Share' platform for the integration and sharing of the outputs from various data sources (Koeva *et al.*, 2021). SOLA follows a similar approach (Rizzo, pers. comm., 2022).

Mobile devices can also be used in low-tech ways to assist with land registrations, as reported by Cheremshynskyi (pers. comm., 2022). He noted that, in Mozambique, Tanzania and Uganda, SMS messages can be sent to customers to inform them about the status of their land registration. He suggested that the trend of development is towards mobile applications installed on smartphones to facilitate feedback and communication between customers and land registration offices. He envisages that these applications may also allow for the submission of documents.

3.2 BENEFITS

The ranges of benefits and challenges mentioned in the interviews and literature are illustrated in Figure 10 and Figure 15 respectively, arranged according to groundedness. The most common benefits of frontier technologies are improved speed and cost and the opportunity for new approaches. The most common challenges relate to capacity issues and political and legal concerns. In this and the following sections, the benefits and challenges are presented in relation to the frontier technologies described above.

Saving time and money

GIS and remote sensing have a good track record of improving efficiency and reducing costs of land rights mapping (UN-HABITAT, IFAD and GLTN, 2016). Coupled with advances in machine learning, drone-based imagery and automated feature extraction, these frontier technologies are changing the landscape for land tenure security, as the following examples attest.

One of the objectives of the its4land project and its successor, SmartLandMaps, is to make land rights mapping faster, easier and more secure (Koeva and Stöcker, pers. comm., 2022). The use of frontier technologies such as UAVs, GIS and remote sensing allows for quick and reliable digitization of annotated orthophotos, reducing human error in interpreting parcel boundaries (Chipofya, Jan and Schwering, 2021). Automated processes also ensure consistency in outputs that are machine-driven, with less influence on individual operator's decisions (Wilson *et al.*, 2022).

In Benin, 50 land parcels were mapped per day using a participatory process that required minimal training (Stöcker *et al.*, 2022b). Similarly, using GIS and aerial / remote sensing imagery in a participatory process, Medici Land Governance improved the time taken to map land parcels in Rwanda (Sagashaya, pers. comm., 2022). In Indonesia, millions of land parcels are being mapped every year following a similar approach (Bennett, pers. comm., 2022). In India, Cadasta's integrated technology approach is also speeding up land rights mapping (Coughenour, pers. comm., 2022) – see Figure 11, while in Tanzania, georeferenced satellite imagery has made the process of mapping land parcels less tedious and quicker than the traditional, ground-based approach (Eilola, Käyhkö and Fagerholm, 2021). Ordnance Survey reported that their automated process was able to generate a new base map of a portion of Lusaka in one tenth the time it would have taken using manual techniques (Wilson *et al.*, 2022).

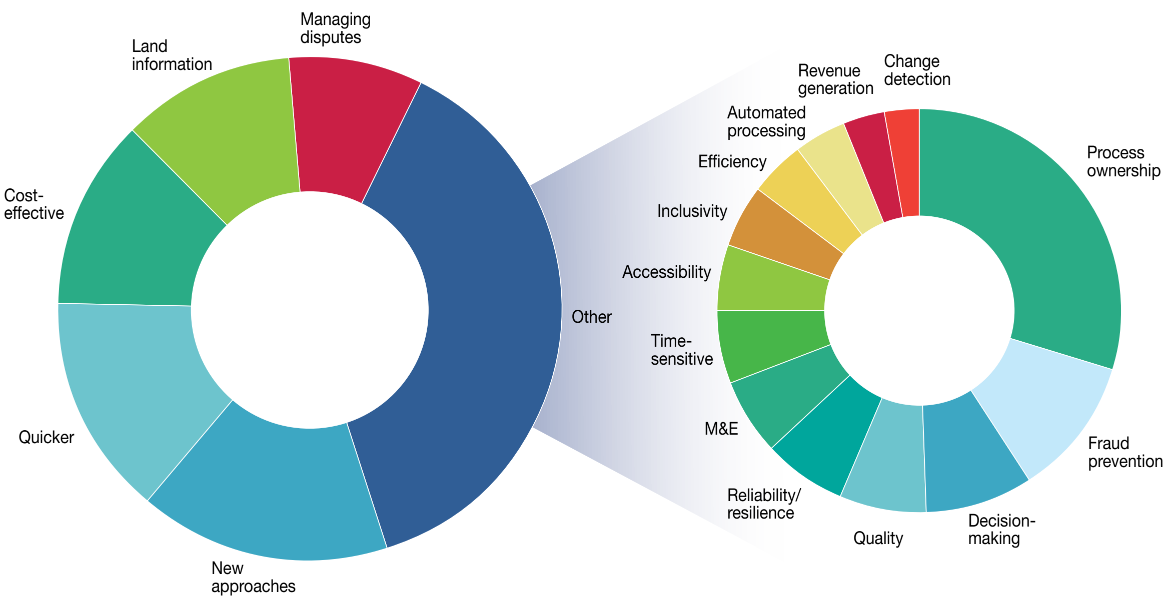


Figure 10 Range of benefits mentioned, arranged according to groundedness

Figure 11 Providing tools to help women, families and communities establish forest rights in Odisha, India (image courtesy: Cadasta)

New technologies for AI-based automation, mapping and geospatial data capture have the potential for making land rights registration faster, more affordable, and accessible than ever before by reducing the amount of field work to a required minimum.

(World Bank Group and T&I Lab, 2021)

Where land parcels cannot be identified in aerial or satellite imagery, ground-based methods must be used. Advances in GNSS technology have improved ground-based mapping – in Mozambique, surveyors make use of new, lightweight GNSS receivers to map 20 000 to 30 000 plots per month with sub-metre accuracy (Cheremshynskyi, pers. comm., 2022). Handheld GNSS receivers can be connected to mobile devices using the ODK to collect qualitative information (photographs and text) about parcels and households (TerraFirma, 2017). Such technology provides fit-for-purpose mapping solutions that reduce the time taken to survey, which also reduces the cost of land regularization or certification.

It is not only on the data collection side that time and money are being saved. Using cloud-based services offers the potential for developing nations to improve quality and efficiency and reduce the cost of land administration. Cloud computing, big data analytics, Semantic Web technologies, and mobile devices offer opportunities for cost-effective provision of services, improved availability of geospatial information, and quicker transaction times through automated processing. Thus, the sustainability of land administration systems and the faithful representation of land tenure may be assured (Hay, 2016). In Kenya, this has led the government to embark on a process of digitalization of land records, with the aim of reducing corruption and improving efficiency of services (Bennett, Pickering and Sargent, 2018).

New technologies are speeding up land transactions too. The Ubutuka App in Rwanda speeds up the land transaction process, from seven days down to one or two days (Hughes *et al.*, 2022). The App saves users time and money through reduced trips to the district office and removes the need to print and submit paper-based documents. Similarly, the use of DLT such as blockchain is said to increase the speed of land transactions while reducing transaction costs (Bennett, Pickering and Sargent, 2018).

Another area of cost savings is in fraud prevention. The Ubutaka App is designed with fraud prevention in mind. Both buyers and sellers of land can confirm each other's identities using the app, including photos and biometrics, which prevents double selling of land and identity fraud. The app also registers the transaction using blockchain, providing "a permanent, independently verifiable, and tamper proof record of the time and details of the transfer for all involved" (Hughes *et al.*, 2022). This immutable nature of information in the DLT is said to reduce fraud, and blockchain has hence earned a reputation as a 'silver bullet' for land administration (Sullivan *et al.*, 2019). However, while DLTs may assist in preventing some types of fraud, research shows that it does not prevent all fraud (Bennett, Pickering and Sargent, 2018).

Another area in which blockchain may be able to assist is in revenue generation / rewards to communities for positive actions (Norfolk, pers. comm., 2022). In Mozambique, community associations are responsible for the protection and conservation of natural resources on their land (TerraFirma, 2017). If they are making positive contributions to shared global assets, such as effective natural resource management or reforestation, blockchain may be able to provide a means of recognising their contributions and ensuring that financial rewards reach the right people. Additionally, frontier technologies such as remote sensing, GIS and LiDAR can be used to calculate carbon credits and should be used to support the local people from whose land carbon credits are being sold (Coughenour, pers. comm., 2022).

Managing disputes

Phase 3 of the systematic land regularisation process relates to verification of land rights mapping and dispute resolution. Frontier technologies are being developed to assist with these processes, but there remains need for reliance on public displays of printed maps for community verification – see Figure 12. Medici Land Governance, Cadasta and SOLA have in-built capabilities for flagging disputes raised during community verification (Sagashaya, Coughenour and Rizzo, pers. comm., 2022). These software solutions facilitate the adjudication of disputes by designated committees, relevant government agencies or community leadership processes.

Ultimately, we want to support the delivery of a socially acceptable and coherent … suite of practices, which results in as minimal number of disputes as possible. It's also about trying to strike a balance between the needs of the range of different engaged stakeholders.

(Beck, pers. comm., 2022)

The use of mobile devices and remote sensing images integrated into a participatory process helps to prevent land-related conflicts in Tanzania (Eilola, Käyhkö and Fagerholm, 2021). By involving members of the Village Adjudication Committee and community leaders in the mapping process, using MAST, land-related disputes are reported to be as low as 0,5 % of total parcels demarcated (Sullivan *et al.*, 2019). Inclusivity is also improved by using women and youth as 'trusted intermediaries' in the data collection process. Panfil (pers. comm., 2022) reported that, in Tanzania, by including women and youth in this way, the number of women holding customary land certificates improved considerably, marking a paradigm shift in women's land rights. Participatory processes also help to create 'process ownership' among relevant stakeholders, be they the Ministry of Lands in Sierra Leone (Rizzo, pers. comm., 2022) or communities and land rights-holders in Tanzania (Eilola, Käyhkö and Fagerholm, 2021). Process ownership is important for ensuring smooth project delivery and reducing conflicts between stakeholders.

Figure 12 Public display of land parcels mapped on aerial imagery (image courtesy: SmartLandMaps)

In Ghana, GNSS-equipped mobile devices with positional accuracy of 1 – 5 m were used to map parcel boundaries. Although the accuracy of the boundary positions is low, there were few reported disputes, possibly because all neighbours were present during the mapping process (Asiama, Bennett and Zevenbergen, 2017). In Rwanda, the Ubutaka App requires verification at different steps before transferring and buying land, and these prevent future disputes arising from conflicting claims to the same land (Hughes *et al.*, 2022).

In this process is also an integrated dispute prevention mechanism, because going into the field with the mobile application and having this kind of multi-stakeholder approach in the collection of information, has also resulted in a way to prevent disputes over the land, or whenever some dispute has been raised during the exercise, it has been possible to complete the exercise, flag the dispute and then adopt a kind of mediation or conciliation, including the disputant and also the mediator, in order to get to an agreement, and most of the time that was solved.

(Rizzo, pers. comm., 2022)

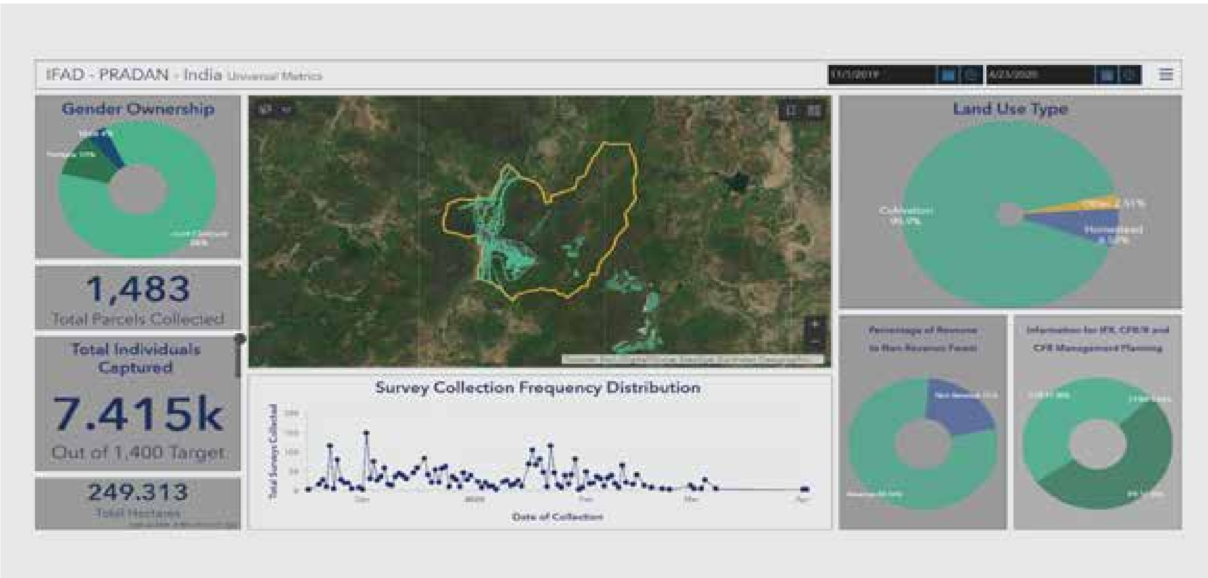


Figure 13 Cadasta dashboard for providing tools to help women, families and communities establish forest rights in Odisha, India (image courtesy: Cadasta)

Access to information

Globally, governments are facing challenges due to increased urbanisation, climate change, and population growth. Access to geospatial information is crucial in meeting these challenges because it links different datasets through their shared location. Up-to-date, accessible geospatial information is necessary for policy- and decision-makers to monitor, measure, predict and adapt effectively (Wilson *et al.*, 2022).

In Kenya, the its4land project aimed to improve geospatial information through the use of UAVs, participatory sketch maps, and AFE (Koeva *et al.*, 2019). In Rwanda, Kenya and Tanzania, UAVs were used to acquire up-to-date imagery for land rights mapping. The currency and high resolution of the images was highly useful for identifying boundaries (Stöcker, pers. comm., 2022). Still in Kenya and Tanzania, shared geospatial information from remotely sensed images helped communities and investors reach common understanding on boundaries and the consequences of land-based decisions. The use of remotely sensed images also improved inclusivity of decision-making because whole neighbourhoods could gather around the printed image and contribute to the discussion (Eilola, Käyhkö and Fagerholm, 2021; UN-HABITAT, IFAD and GLTN, 2016).

Having fit-for-purpose and up-to-date, timely data is crucial for effective policy and decision-making (Wilson *et al.*, 2022). Hence, Cadasta works with their clients to produce an online dashboard that makes available land-related indicators – see Figure 13 and Figure 14. This helps project managers to track progress, provides vital information for monitoring and evaluation, and helps communities to understand the land-related issues they face. Dashboards can also shed light on issues such as gender inequality, distribution of plot sizes, donor coordination and agricultural productivity (Coughenour, pers. comm., 2022).

Hay (2016) promotes the use of cloud-based services for making available geospatial information from a range of sources (UAVs, remote sensing, mobile devices, etc.):

> **Making these data available together with official cadastral and land registry information and, knowing that all information about land and individual properties can be reliably and conveniently retrieved is a difficulty in many jurisdictions. A real-time up-to-date inventory of all land in a jurisdiction or country is a need that is often not met in even the most developed nations.**
>
> (Hay, 2016)

Figure 14 Cadasta dashboard for certifying Sustainable Supply Chains in South Sumatra, Indonesia (image courtesy: Cadasta)

Utilising cloud-based environments for the storage and sharing of geospatial information helps to meet this need and improves the accessibility of geospatial information. In Zambia, Ordnance Survey were able to address the need for up-to-date, accurate geospatial information through the automated creation and sharing of a basemap (Wilson *et al.*, 2022). The basemap was used for locating informal settlements, assessing transport infrastructure and population density, predicting changes in informal settlement patterns, to support land registration, for integrating future census data, and in support of land administration functions. It is hoped that this will lead to "a more agile and iterative approach to land management in terms of policy formation and decision making" (Beck, pers. comm., 2022).

Allowing new approaches

Digital transformation (Section 1.2.4) involves reimagining processes based on the opportunities that new technologies bring. Frontier technologies can disrupt the norm by challenging existing limitations and allowing new possibilities (Hay, 2016). Instead of rigid, standardised approaches, it is now possible to develop agile, context-specific, tailor-made solutions. Both open source (SOLA) and proprietary (Cadasta) software solutions allow for the development of tailor-made solutions to embrace these new opportunities. The philosophy behind SOLA is to provide a basic, open-source building block that can be the catalyst for a brand-new land administration system, or the digital transformation of previously paper-based land administration processes (Rizzo, pers. comm., 2022). The Cadasta dashboard example above makes information available for analysis that may create new insights that lead to new approaches or strategies for addressing previously unnoticed problems (Molina, pers. comm., 2022). "The idea is configuration and integration of appropriate technology based on the need" (Coughenour, pers. comm., 2022).

Advances in database technology, including DLT and blockchain, are also creating opportunities for new approaches to land transactions, as well as entirely new land-related services (Bennett, Pickering and Sargent, 2018). Galić and Vuzem (2020) maintain that the next generation of LIS should be built on NewSQL DBMS to ensure resilience by leveraging the opportunities that distributed databases bring. Such systems should be designed with resilience, scalability and sustainability in mind (Galić, 2021).

3.3 CHALLENGES

The biggest challenges identified with respect to the use of frontier technologies for securing land tenure are around capacity, the political and legal context, cost and sustainability. Managing expectations, overcoming resistance to change, and grappling with the complexities of mapping customary land rights are challenges that will also be addressed in this section. Many of the other challenges illustrated in Figure 15 will be addressed alongside these.

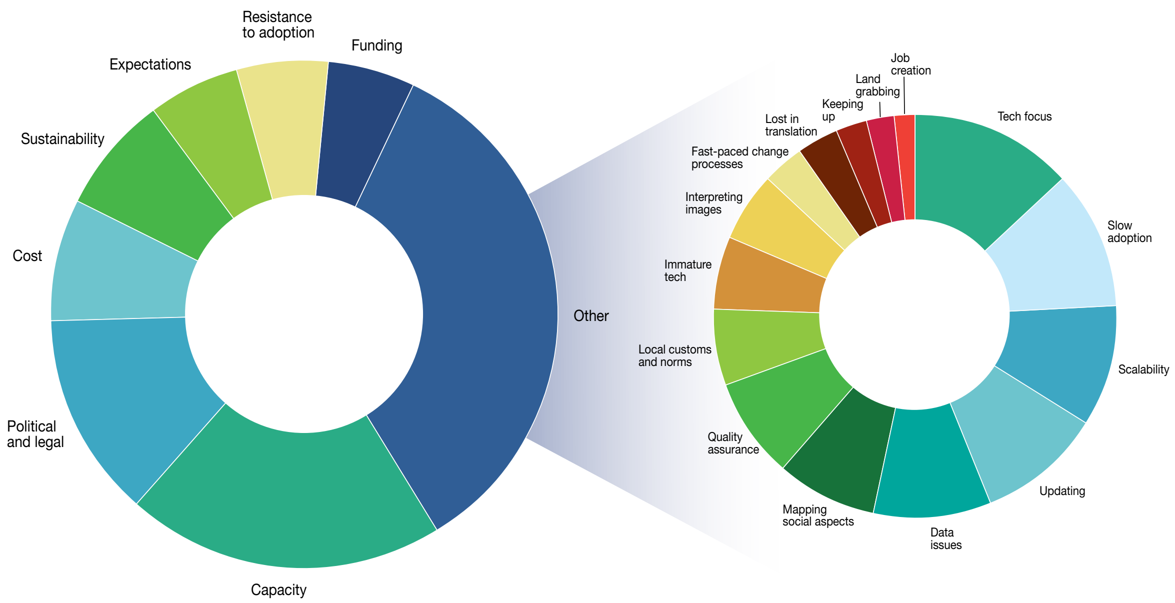


Figure 15 Range of challenges mentioned, arranged according to groundedness

Building capacity for sustainability

Capacity for adopting frontier technologies is the biggest challenge identified in the interviews and literature. This is in keeping with the challenges noted by UNCTAD/TIR. Without the capacity to adopt and maintain frontier technologies, the sustainability of land tenure projects is compromised.

For example, in Rwanda, the systematic land regularization programme saw the number of registered properties jump up from 8 000 to 8 million, with over 600 000 transactions to process every year. The institutional capacity to maintain the system and process the transactions was missing – people were not sufficiently trained, resulting in bottlenecks and missed opportunities (Sagashaya, pers. comm., 2022).

A further challenge is that, once people are trained, they become skilled and often move on to more profitable employment because governments cannot pay competitive wages (Bennet, pers. comm., 2022); hence training should be on-going (Hughes *et al.*, 2022). Stöcker (pers. comm., 2022) suggests adopting a 'train-the-trainers' approach to ensure a sustainable pool of skilled personnel. The same approach is adopted by Cadasta and SOLA (Coughenour and Rizzo, pers. comm., 2022). If technological solutions are kept simple for the user, this reduces the amount of training required for participatory mapping. Thus, the initial focus can be on a small pool of key personnel who are trained by the development team, and they can pass on their training to others. Sagashaya (pers. comm., 2022) suggests that this initial pool should be drawn from people used during project pilots, and that they should be employed as staff in the various district offices.

Training and capacity building is necessary through the entire range of professions involved in land tenure (Cheremshynski, pers. comm., 2022). Hence, in Rwanda, there was support for two people per district to study towards a Masters degree in land administration. A similar recommendation was made by the Presidential Advisory Panel on Land Reform and Agriculture in South Africa (Mahlati, 2019), though this has not been implemented. In some countries (such as Bulgaria, Kenya, Kosovo and Nepal), UAV-related educational courses are being built into existing geomatics curricula (Stöcker *et al.*, 2022a), while in Tanzania there is a noted need for GIS education and on-the-job training (Eilola, Käyhkö and Fagerholm, 2021). There is also a dearth of skilled geospatial experts to support land tenure projects. The responsibility for overseeing land transactions post-registration falls on village leaders. They, too, are insufficiently trained in the required processes and find the system difficult to access. As in Mozambique and Rwanda, the default is then for land transactions to take place off-register, threatening the sustainability of the land administration system.

It is not sufficient to provide the technical means to process post-registration transactions without ensuring that capacity to use the tool is strengthened at all levels, that the process is simple, and that the costs to the user are not prohibitive.

(Sullivan *et al.*, 2019)

In Rwanda, the cost of accessing and using the land administration system was also leading land rights-holders to transact land rights off-register, challenging the system's sustainability (TerraFirma, 2017). Other challenges include low digital literacy, low electricity penetration, low mobile device and internet penetration, and high costs of data and mobile devices. Similar challenges are experienced in Tanzania, where the problems associated with poor ICT infrastructure and low digital literacy limit the effectiveness of digital solutions (Eilola, Käyhkö and Fagerholm, 2021). In Rwanda, these limitations restrict the adoption and use of technology solutions such as the Ubutaka App:

With these challenges in mind, use of Ubutaka App and similar technology-based initiatives needs to be paired with investments in digital literacy at all levels, consistent training and support to users, access to the internet, and quality equipment.

(Hughes et al., 2022)

Mozambique faces similar challenges. The Terra Segura programme aimed to document over 5 million land parcels, yet the institutional capacity to maintain the resulting land records is lacking:

> **[M]illions of newly-titled DUATs,[9] representing rights awarded in perpetuity and transferable on death, will require updating over time and the responsibility for this is currently located within institutions that are weak, unresponsive and far removed from the holders of these rights.**
>
> (TerraFirma, 2017)

Norfolk (pers. comm., 2022) highlighted internet connectivity and data costs as limiting factors to realising the full potential that frontier technologies have to offer. An opportunity has recently arisen with the launch of the Starlink system of low orbiting satellites that can provide data access, and Mozambique has signed up for this. To address the issue of low or no internet connectivity, tools such as Meridia's land rights mapping software allow for data collection offline with later upload to a cloud-based server once connectivity is restored (Vernin, pers. comm., 2022).

Bell (pers. comm., 2022) noted that land tenure projects have succeeded in contexts where the technical and financial capacity to sustain the technology have been built up. But where such capacity is lacking, the technology 'dies' once donors withdraw. The technical readiness of countries should be assessed before new approaches are proposed (Koeva, pers. comm., 2022). Hence, Stöcker (pers. comm., 2022) advises that the focus should not be on the latest technology, but rather on the context-specific needs pertaining to land tenure security, and then investing in appropriate technology for which the necessary financial and technical support is available. Blockchain is one such technology that was being promoted to – and adopted by – governments that lacked the capacity to take it on (Cheremshynskyi and Panfil, pers. comm., 2022). Galić and Bell (pers. comm., 2022) caution that clients are often supplier-driven, seeking applications for new technologies and approaches, rather than looking for appropriate technological solutions to existing challenges.[10]

Community orientation is another important aspect of capacity building. In Mozambique, after the publication of the new Land Law in 1997, a thorough community orientation programme was employed to educate people about their land rights (Norfolk and Bechtel, 2013). Similarly, in Tanzania, USAID invested considerable time and effort upfront in educating communities about the new Land Law of 1999 (Panfil, pers. comm., 2022). Such interventions are crucial for helping land rights-holders to understand potential benefits of land tenure projects, including gender equality in land registrations. They are thus better incentivised to engage with proposed solutions.

Political and legal environment

Political will and an enabling legal framework are crucial for successful and sustainable land tenure projects. By way of example, Bennett, Koeva, Sagashaya and Stöcker (pers. comm., 2022) all mentioned the lack of clear legislation and regulations around the use of UAVs as a limiting factor (see also Stöcker *et al.*, 2022a). Even in Rwanda, where legislation was in place, the regulations were updated every year and it took two and a half years to navigate the legal requirements and get flight permission (Stöcker, pers. comm., 2022). To truly scale up the use of UAVs in land administration from a niche market to widespread application requires enabling laws and policies and a supportive political environment (Stöcker *et al.*, 2022a).

Thus, Sagashaya (pers. comm., 2022) proposes that the first challenge that needs to be addressed for land tenure projects is political will and second is the policy and legal frameworks in a country, including how these pertain to the use of ICT and technology. He suggests that both political and technical reforms need 'champions' to get the necessary political support, including passing legislation through parliament and clearing red tape that impedes implementation. For example, if the law requires wet signatures on land transactions, such as in Armenia (Bennett, pers. comm., 2022), then blockchain and other paperless innovations cannot be adopted. Eilola, Käyhkö and Fagerholm (2021) noted that, in Tanzania, policies on data security, quality and access to information are outdated, restricting the use of participatory land rights mapping. In Zambia, it took three years of

9 DUAT – *Direito de Uso e Aproveitamento dos Terras* or right of use and benefit of land.

10 The caveat, of course, is that frontier technologies allow for new applications and create new opportunities such as digital transformation (Section 1.2.4) of systems and processes. There needs to be a balance between forcing a new technology onto an existing problem and using innovative thinking to apply new technologies in previously unconsidered scenarios.

lobbying before a law was finally passed allowing the use of electronic signatures on land documents – see Figure 16. Thus, Sagashaya says:

> **Before talking about any large scale land tenure project, countries … need to have policies in place. Then that land policy needs to go hand in hand with policies allowing the use of tech. It doesn't mean anything if you say you are going to use a tech in a country where e.g. you can't get cell data. ... Tech is not a solution, it is an enabler. It enables people to do well what they intend to do. But if there is no intention / political will, tech doesn't mean anything. You will get frustrated with good gadgets and applications, but at the end you can't produce a result because the law won't support it or there will be too much red tape to get a result.**

Norfolk (pers. comm., 2022) is facing such frustration. He reported that, in Mozambique, the government is actively blocking the rollout of the community cadastre. They are questioning the competency of community associations to do land rights mapping and produce certificates, despite evidence that such participatory approaches (as have been described above) are very beneficial and largely successful. Ironically, the commission that is overseeing the current revisions to the land policy and legal framework is in support of the participatory, community-based approach, but the National Land Directorate is not.

Even when such approaches are permitted to go ahead, there can be problems with legal support. In Uganda, after participatory, community-based mapping using SOLA was completed, the government could not come to agreement on how to incorporate the land rights mapped into the national land information system developed under a World Bank project. The records were hosted on a server, the administration of which was handed over to the Ugandan government, but this data has not been used (Rizzo, pers. comm. 2022). Part of the challenge, says Bennett (pers. comm., 2022), is that these new technologies and approaches are challenging government sovereignty around land administration. National governments have a mandate to administer and secure land rights

Figure 16 A woman receives an electronically signed certificate of tenure (image courtesy: Medici Land Governance)

on behalf of their citizens, and innovations such as blockchain and community-based certification challenge that mandate.

Conversely, in Ukraine, Panfil (pers. comm., 2022) reported that the government is currently developing legislation for how properties will be returned to citizens, and how restitution will happen, post-conflict possibly leveraging the 'tapestry' approach mentioned above. In Tanzania, the government made a public commitment to deliver millions of customary land tenure certificates, which facilitated the adoption of MAST as a practical means of meeting this commitment. The Ministry of Lands Task Force has put forward guidelines for the adoption of digital land registration and transaction processes, including acceptance of scanned signatures on prescribed forms. They are also making allowance for land records collected by village residents using MAST to be incorporated into the Integrated Land Management Information System (Sullivan *et al.*, 2019), contrary to the Ugandan experience with SOLA mentioned above. The new Land Policy in Rwanda, passed in 2019, calls for "the simplification of land registration processes, facilitation of easy access to land administration services, and promotion of ICT-based solutions to land administration services" (Hughes *et al.*, 2022). And in Zambia, recently passed legislation and amendments to existing laws and regulations allow the use of electronic signatures for land title certificates (Tembo and Sagashya, 2022). Strong political will and an enabling legal environment support the adoption of new approaches and technologies for securing land tenure.

Cost and quality

Although frontier technologies can save time and money, there are still cost considerations that limit their adoption. The classic trade-off is between cost and quality, as explained in the fit-for-purpose guidelines (Enemark, McLaren and Lemmen, 2015): it is not possible to have high accuracy at low cost. Choosing high accuracy solutions simply because the technology is available will result in expensive surveys that take a long time and require complex maintenance (Beck, pers. comm., 2022).

Cost is a major determinant in the decision to adopt open-source or proprietary solutions, as mentioned above. Proprietary solutions require an initial cost and often include maintenance fees, whereas open-source solutions appear to be free or low cost. Most interviewees and literature reviewed in this study pointed towards the use of open-source solutions as being preferable, though strong arguments were also made in favour of proprietary solutions.

The scale of a project is a determinant on the choice of tool. For example, UAVs are proven to be useful for up-to-date and accurate data collection of small areas, but for country-level projects it is more cost-effective to use aerial or satellite imagery (Koeva and Stöcker, pers. comm., 2022). And even though UAVs are characterised as a relatively low-cost alternative to field surveying, cost is still a barrier to large-scale adoption. After initial purchase, there are maintenance and licencing fees to consider (Stöcker *et al.*, 2022a).

The scale of adoption is another factor impacting on cost. Ideally, cadastral and land administration systems should be self-sustaining (Kaufmann and Steudler, 1998). Norfolk (pers. comm., 2022) suggests that the cost of first registration should be subsidised by the government or donor driven, because "first-time registration of land creates a public good" – see Figure 17. Subsequent transactions can be fee-based or designed with cost recovery in mind. This is a current challenge in Rwanda, where the land administration system is not generating enough fee income to be self-sustaining (Bennett, pers. comm., 2022). At the early stages of land registration, there may be only a few hundreds or thousands of people using the system. The cost per transaction to maintain the system will be high and users are disincentivised to engage. But once the system gains traction and public support and the number of users rises into the millions, the cost per transaction will come down (Norfolk, pers. comm., 2022). Similarly, when technologies are new, there are few providers and less market competition, which drives up costs. But as technologies mature, so the costs of products come down (Eilola, Käyhkö and Fagerholm, 2021). This is a significant barrier to early adoption for lower income countries, as highlighted in Section 1.

Figure 17 A Zambian family proudly displaying their certificate of tenure (image courtesy: Medici Land Governance)

Funding is another important cost factor. Most of the solutions mentioned above were made possible with funding from donors. Sometimes, projects are funded by multiple donors, or multiple donors are funding multiple projects in the same area. Donor coordination can become challenging (Bennett, pers. comm., 2022). This was the situation in Liberia, where there were several NGOs and civil society organizations all working to demarcate and collect land data as part of a customary land formalization programme. It became difficult to know what areas had been mapped by whom, so Cadasta developed a community land monitoring tool using cloud-based services to help the Liberian government manage the process (Coughenour, pers. comm., 2022). Bennett (pers. comm., 2022) predicts that funders are moving away from simply funding land tenure projects and towards the pressing issues of our time: climate change, SDGs, food security, disaster response, carbon monitoring, etc. All these issues involve land tenure and future projects seeking donor support need to be aware of the need to contribute to these broader societal concerns.

Managing expectations

> **User expectations are driven by the elegant experience they have when interacting with [social media platforms], and the transparency, ease and speed that [online shopping] platforms … provide for the carrying out of transactions. Users expect clear and transparent access to data, and the ability to make decisions for themselves.**
>
> (Stow, Hill and Beck, 2022)

Balancing expectation and reality can be a challenge for implementers and adopters of frontier technologies. There is a general expectation that all digital services should be integrated and automated; this is proving a challenge for many government agencies. Part of the challenge is in secure, digital party identifiers: without the ability to identify people securely, systems aimed at improving land administration efficiency are hampered (Beck, pers. comm., 2022).

Blockchain is one such technology that has experienced much initial hype, followed by disillusionment, as predicted by the Gartner Hype Cycle.[11] Following its initial success in Bitcoin, blockchain service providers began promoting it as a solution for land administration. Its reported immutability was touted as a means of overcoming the rampant corruption in the land administration industry. By doing away with paper-based land administration systems, it was also promoted as a means of increasing efficiency (Bennett, pers. comm., 2022). However, others have evaluated these claims and decided that blockchain is not a suitable solution for land registration (Bell, pers. comm., 2022). Thus, Medici Land Governance have opted to use it only for transactions, storage and distribution of land registration systems, not first registration (Sagashaya, pers. comm, 2022). In Uzbekistan, the cadastral agency was interested in pursuing blockchain, but after running a pilot project, they decided against it (Galić, pers. comm., 2022).

Despite the hype surrounding blockchain, there are many trade-offs, issues and challenges that remain to be solved (Galić, 2021). Bell (pers. comm., 2022) notes several challenges associated with blockchain in land administration. One of the problems, especially for lower income countries, is that blockchain requires a digital environment. If the country land information system is still at Generation 0 or Generation 1, i.e. if the existing system is paper-based or even if it is digitised, blockchain cannot work. There needs to be an element of digital transformation in place. Another challenge is that it is not designed to handle spatial data, and a third challenge is its immutability, because land data is dynamic and changing all the time. A further challenge that has been alluded to previously is that of sovereignty – blockchain takes land administration out of the purview of the responsible government. Blockchain aims to address the corruption issue, but it is not as immune to corruption as advertised.

Others echo these sentiments:

> **I'm skeptical, more of the way it's being sold as the panacea. Because you cannot get away from the hard slog of first time registration. You have to do that and the blockchain is not going to solve that in any way, whereas a lot of people are saying this is the solution to land registry – not necessarily.**
>
> (Norfolk, pers. comm., 2022)
>
> **Blockchain is not very niche anymore. As of 2019, it felt that blockchain was being pushed by Western companies and governments onto developing country governments that didn't necessarily have the capacity to take it on, but were jumping at the 'shiny thing' that was being presented, in some cases as a bit of a panacea.**
>
> (Panfil, pers. comm., 2022)

Another frontier technology that is working its way along the hype cycle is UAVs. Stöcker *et al.* (2022a) evaluated the use of drone technology in land administration using the Framework for Effective Land Administration (FELA) (UN-GGIM, 2019) and the Gartner Hype Cycle. They found that experts estimate UAV technology to be in the 'trough of disillusionment', where innovation needs to overcome unmet expectations before widescale adoption can happen. Part of the disappointment around UAVs is due to the restrictive legislation and regulations, or lack thereof, governing their use. Another disappointment is around the apparent ease of use of UAV technology. While it is true that modern drones can autonomously follow predetermined flight paths at the push of a button, there is still need for surveying proper ground control, processing the images, and analysing the results. These tasks require experienced and educated personnel. Like with

11 https://blogs.gartner.com/avivah-litan/2022/07/22/gartner-hype-cycle-for-blockchain-and-web3-2022/

blockchain, there were reports of service providers over-selling their product, claiming that drones were a viable product for surveying a region of hundreds of thousands of square kilometres (Cheremshynskyi, pers. comm., 2022). As mentioned previously, for such large-scale projects, aerial or satellite imagery is a better option.

Resistance to change

There is a tendency in land authorities to avoid change, particularly when it comes to new technologies. This restricts the potential for innovation and new service offerings. For example, the land administration domain has been slow to adopt data warehousing and big data analytics (Bennett, Pickering and Sargent, 2018). Instead, change should be seen as the norm to accommodate changing social and technological needs (Stow, Hill and Beck, 2022). Winning over the relevant authorities can take time and patience. For example, before MAST was piloted in Tanzania, there was a long, slow, low-pressure period of winning over the land authorities, both at national and local government levels. In that way, they became allies and bought into the whole process (Panfil, pers. comm., 2022).

Another area of concern relates to accepting lower positional accuracies, as derived from handheld GNSS receivers or interpreted from aerial or satellite images, as opposed to standard surveying techniques. This is a big motivation for the fit-for-purpose land administration approach: the best accuracy is not always the best solution. "Choosing high accuracy surveys … because the technology allows it will result in very expensive surveys that will take a long time to collect and will become more complex to maintain" (Beck, pers. comm., 2022).

Others resist new approaches because they think it will replace them and they will lose their job (Stöcker *et al.*, 2022a). In such cases, people need to be shown how new technologies can help them to become leaders and managers in their field (Koeva, pers. comm., 2022). Of course, as was mentioned previously, automated processing can do tasks that would otherwise be done by humans. Especially in contexts of high unemployment, such as in sub-Saharan Africa, there must be balance between creating employment and learning opportunities on the one hand, with better, more efficient systems and processes on the other.

Mapping customary land rights

When we consider land tenure projects on customary land, there is a strong belief that land is best held in discrete, individualised ownership secured by a land title, whereas the reality might be much more complex and interesting (Hay, 2016). Individualised titling serves to "dismember all of those parcels from the broader community holding … locking people into a national system that [in Mozambique] is fundamentally dysfunctional and inaccessible" (Norfolk, pers. comm., 2022). Individualised titling is only one option and there should be consideration of the full range of options available for securing land tenure (TerraFirma, 2017). Land titling projects involving customary land rights will challenge, and be challenged by, existing customs and norms (Tembo and Sagashya, 2022).

> **I've seen too many projects led by Western consultants go completely wrong because people are dropping in with no context, no knowledge, trampling over the existing systems and imposing their approach, and it's either rejected outright or as soon as they leave, everyone goes back to doing what they had been doing before. I'm a big believer in locally led solutions.**
>
> (Panfil, pers. comm., 2022)

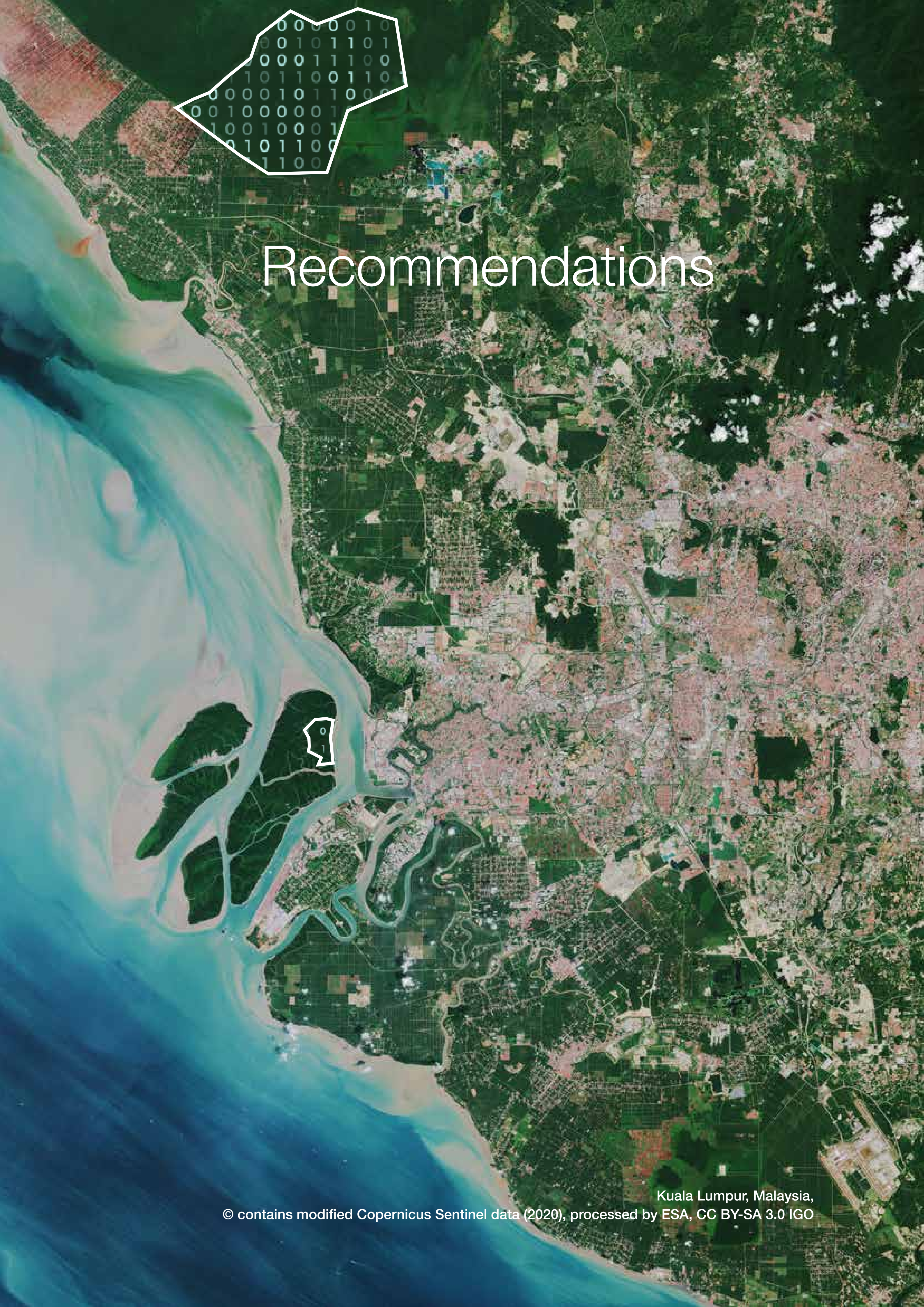
The approach behind SOLA, combining a participatory methodology with geo-technologies, serves to find a suitable solution for communities that want recognition and protection of their land rights (Rizzo, pers. comm., 2022). Similarly, SmartSkeMa seeks to model existing land tenure concepts as closely as possible. It is not only the spatial aspects that need to be mapped, but tool developers should consider how to map the social and legal aspects as well. Hence, the SmartSkeMa approach attempts:

> **… to support both the legibility of customary land tenure to government authorities and the preservation of the customs within which tenure relations operate. Preserving customary rights to land requires also preserving customary ways of allotting, negotiating, and exercising those rights. Otherwise, the entire notion of customary land tenure itself becomes a shell or a cover for replacing customary tenure with statutory tenure.**
>
> (Chipofya, Jan and Schwering, 2021)

When it comes to mapping customary land rights, people can be suspicious of new technologies and approaches, being fearful that they will be used to appropriate their lands (Eilola, Käyhkö and Fagerholm, 2021). Chiefs may see a land tenure project as an attempt to divest them of land and hand it over to individuals – who are no longer obeisant to their chiefdom – or to the government. In Malawi, this challenge was addressed by first mapping the extent of the chiefdom areas. Using satellite imagery, chiefs were able to settle disputes between their territories. This demonstrated the usefulness of the technology. Next, the same process was used to map out family holdings within chiefdoms and certificates were issued that linked families and individuals to the chiefdoms – see for example Figure 18. "If you frame it in that way, they understand you are not taking their powers of land administration away, but you are giving them a tool to manage the land that is under their chiefdom" (Sagashaya, pers. comm., 2022). Hence, it is important to understand cultural norms and make every effort to accommodate them before embarking on systematic land titling (Tembo and Sagashya, 2022).

Figure 18 Issuing Certificates of Customary Occupancy by the Ministry of Lands in the Namutumba District, Uganda (image courtesy: Cadasta)

Recommendations



Kuala Lumpur, Malaysia,

4 Recommendations

Three dominant themes that have arisen from the data are presented as recommendations for project developers and others seeking to embrace frontier technologies in land tenure projects. The three themes – an integrated approach, focus on sustainability, and 'it's not about the tech' – are over-arching concerns raised in the interviews and literature. These are not ground-breaking revelations and both experienced and novice practitioners will see the sense in these recommendations. These recommendations represent a 'common-sense' approach to land rights mapping, focusing on the basics without being distracted by the 'shiny things'.

4.1 AN INTEGRATED APPROACH

Technologies are most effective when used in combination (Cheremshynskyi, pers. comm., 2022). A typical example of this is a smartphone: it integrates GNSS, a compass, inertial positioning, connection to the internet, high-resolution camera, and multiple processors, all in one easy-to-use package. This allows for the development of apps for individuals and communities to locate and map out their parcels, link to a cloud-based server, and receive an approved certificate of land tenure. Another example is the use of imaging services such as drones or high-resolution satellite images, in conjunction with GNSS and machine learning, for the automated identification of parcel boundaries. Software solutions can also be used to integrate multiple data sources, allowing for improved analytics. By taking an integrated approach, with cognisance of contextual needs, frontier technologies can provide fit-for-purpose land tenure solutions. For example, the its4land 'toolbox' approach of independent, innovative tools for specific land administration activities and integrated outputs via the 'Publish and Share' cloud-based platform (Koeva *et al.*, 2019, 2021). Cadasta also takes an integrated approach to designing tailor-made solutions for specific contexts and needs (Coughenour and Molina, pers. comnm., 2022). The SOLA approach integrates data collection, community validation, and certification under one platform (Rizzo, pers. comm., 2022).

Engagement with communities is an important aspect of integration. Most interviewees and publications reviewed adopted participatory approaches to land rights mapping. Interventions aimed at improving tenure security must involve partnerships with the land rights-holders themselves. This may mean taking a low-tech, low accuracy, fit-for-purpose approach. For example, in Mozambique, project developers moved away from using remote sensing images on mobile devices and resorted to printed maps on A3 paper, because people found those easier to use and understand (Norfolk, pers. comm., 2022). It may require concentrated input for training and sensitization, such as in Tanzania prior to implementing MAST; and it may mean adjusting expectations to fit local customs and conditions. But it will yield a more sustainable and relevant solution in the end.

> **We believe that partnerships with local organizations are crucial because they know the local context, they usually know local languages, they know local customs, and they can ensure that everyone is engaged in the process. We as foreigners coming into the country, we will never be able to have the trust of the community. It's so important to collaborate with local mapping organizations.**
>
> (Stöcker, pers. comm., 2022)

4.2 FOCUS ON SUSTAINABILITY

There must be a focus on sustainability. The two main challenges discussed in the previous section relate to capacity for sustainability, and an enabling political and legal environment.

Consider the Rwandan and Mozambican experiences mentioned previously, with millions of land titles registered but a lack of trained personnel and institutional capacity to manage them. Or the Ugandan experience with SOLA, where land rights were recorded but there was no political will or long-term plan for incorporating them into the national land information system. Investments in technology and personnel risk being wasted if sound maintenance and capacity concerns are not built into project planning from the beginning. The intended users need to have the technical competency to, for example, repair and maintain a UAV to continue drone-based mapping (Stöcker, pers. comm., 2022) or maintain and update land records in a cadastral database (TerraFirma, 2017). "The successful implementation of a land registration process is not of long-term value unless future transactions are protected" (Sullivan *et al.*, 2019). There are many factors to consider when choosing technological solutions for projects, but sustainability considerations should be the deciding factor (UN-HABITAT, IFAD and GLTN, 2016).

Technology is also changing all the time, and people need to update their skills and knowledge to keep pace. Today's frontier technology may become obsolete tomorrow, and investments in technologies for land tenure security need to keep this in mind (Sagashaya, pers. comm., 2022).

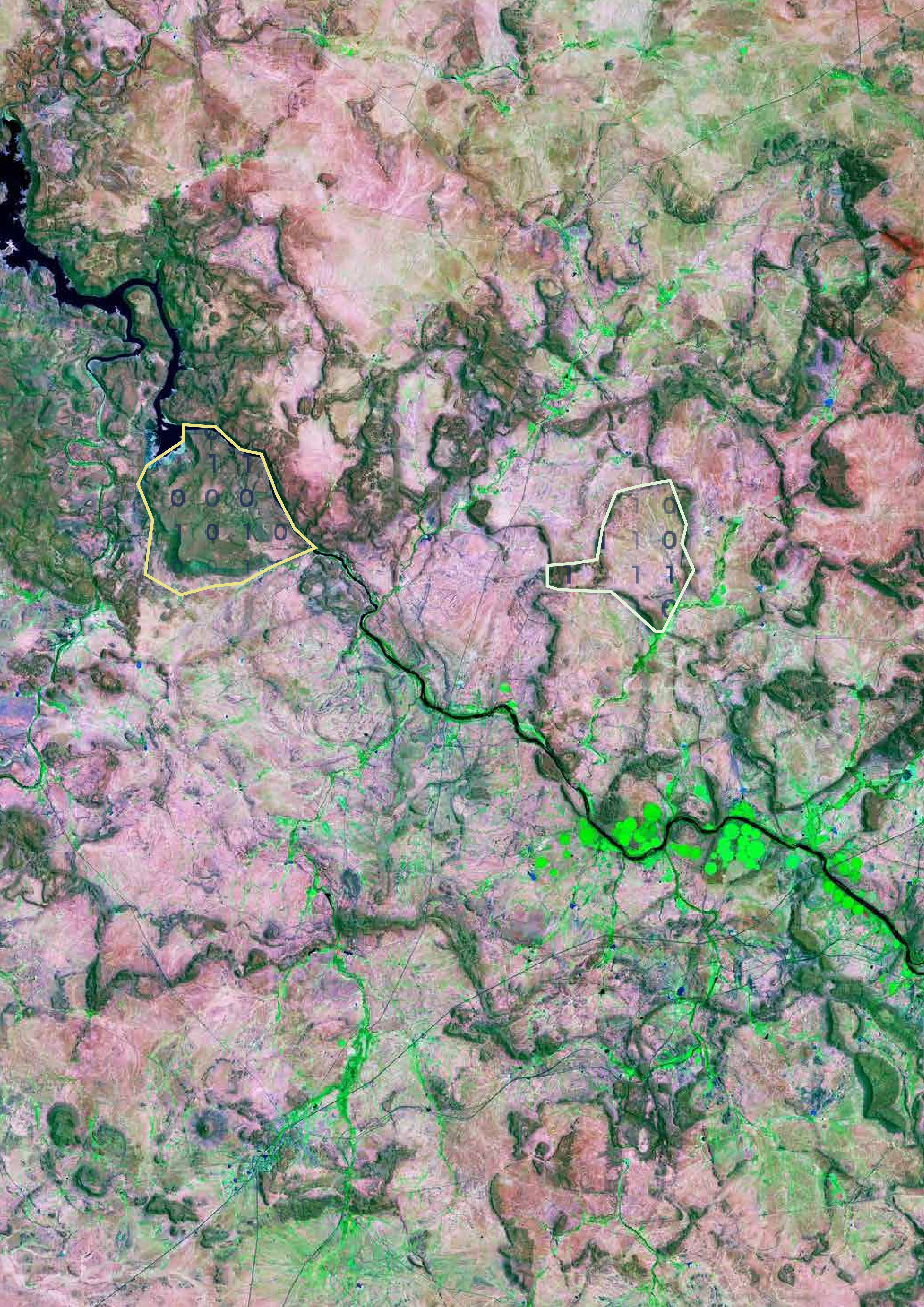
> **When a land tenure project starts, you need a sustainability plan in motion. Once we finish to do the titling or tenure certification, what is going to happen to the data? Who will manage it and how? When you don't have that in mind, it becomes a problem… Before you start, before you choose any tech, see if there is a law or policy in place supporting what you want to do, then political will, then start with the end in mind regarding how you are going to use these technologies.**
>
> (Sagashaya, pers. comm., 2022)

4.3 IT'S NOT ABOUT THE TECH!

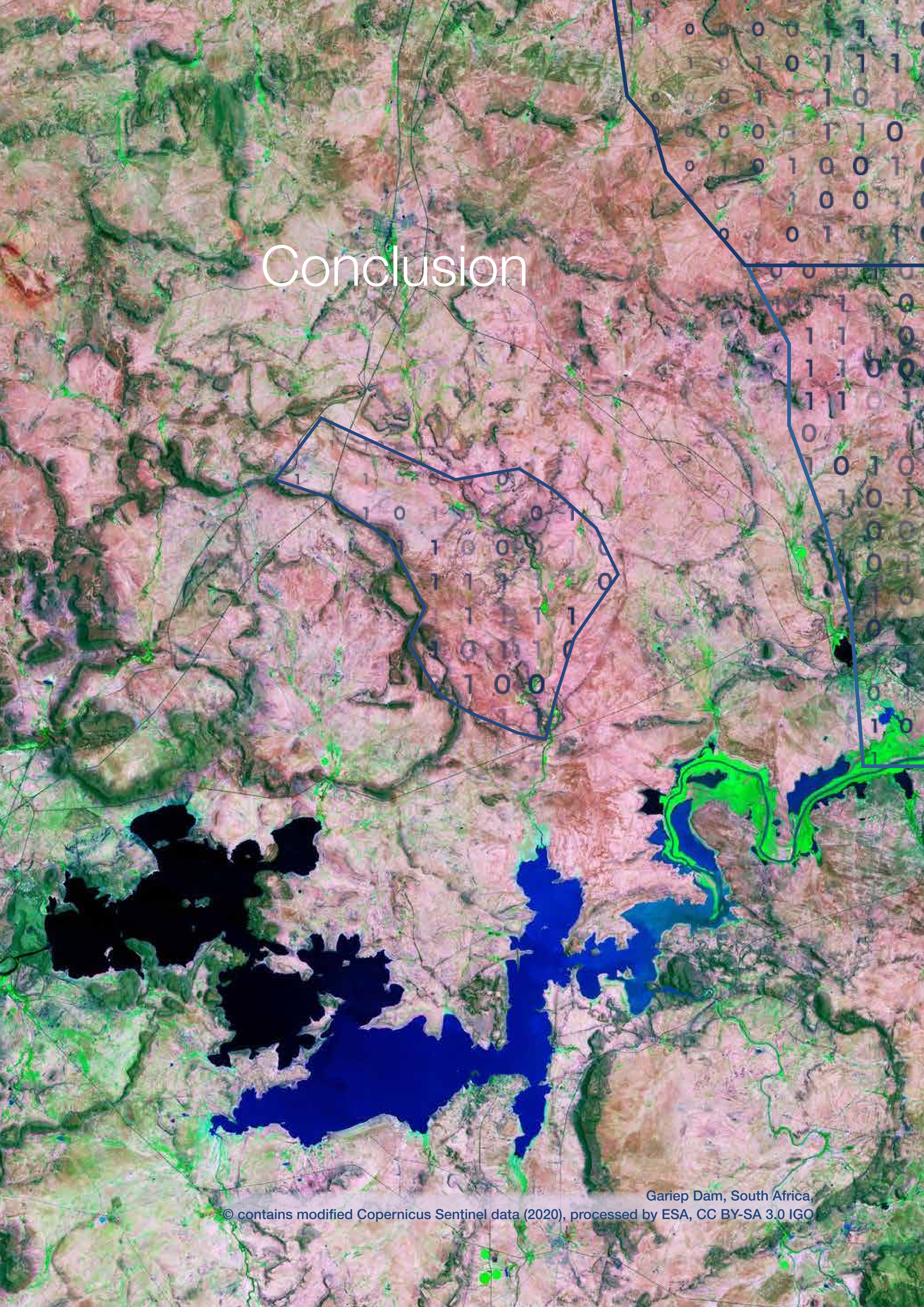
Developing technological solutions is important, but more important is making sure that the solution is fit-for-purpose and has the necessary political and social support. "As long as sensible policy and practice approaches are applied, then technology should not be a problem" (Beck, pers. comm., 2022).

Several interviewees referred to overinvestment in technologies that far exceeded the specifications required or the capabilities of people to use and maintain them. The adoption of technical solutions should be needs-driven, rather than driven by the desire to use the latest technology. There should be balance between the possibilities of the technology and the social need. It is easy to lose sight of the social requirement behind land rights mapping if the focus is on the technology (Beck, pers. comm., 2022). Frontier technologies are not the issue, it is the non-technical aspects that create the challenges (Bennett and Galić, pers. comm., 2022).

> **The big problems now aren't spatial or technical… It's the social issues that need to be managed… While technology is a key enabler, and it's a key disruptor, it's not always technology which is required to get you to the place that you need to go.**
>
> (Beck, pers. comm., 2022)



Conclusion



Gariep Dam, South Africa,

5 Conclusion

Land tenure insecurity is a reality for a large proportion of the world, especially those in lower income, developing contexts. Frontier technologies, which are new and emerging technologies that have the potential to disrupt and supplant existing processes, create new opportunities for addressing this challenge.

This publication show cases the range of current frontier technologies that are being used in land tenure projects, as well as the associated benefits and challenges. The study reviewed twenty publications published over the last ten years and conducted thirteen interviews with knowledgeable experts. Publications included peer-reviewed journal articles, conference proceedings, and associated 'soft' literature, while the interviewees were drawn from academia, international organizations, and solutions providers. These were analysed using elements of a grounded theory approach, focusing on coding and categorising the datasets to reveal themes.

The **dominant technologies** are the following:

- various software solutions (including GIS),
- machine learning and artificial intelligence for automated feature extraction and big data analytics,
- distributed ledger technology (including blockchain and other distributed database management solutions),
- image-based solutions (including high-resolution satellite imagery and drone-based imagery), and
- mobile devices (including smartphones and tablets with built-in GNSS).

Integrated solutions predominate and a combination of technologies and approaches provides the best outcomes.

The **benefits** that frontier technologies bring include:

- improved efficiency,
- reduced cost,
- improved access to geospatial information for better decision- and policy-making,
- ability to manage disputes and other land-related conflicts, and
- creating opportunities for new approaches.

The **biggest challenges** relate to:

- capacity for governments and users to adopt and maintain new technologies and approaches,
- the lack of supportive legal and policy frameworks,
- the costs of adopting and maintaining new technologies,
- a mismatch between expectations and reality,
- the need to overcome resistance to new approaches and technologies, and
- the complexity inherent in mapping customary land rights.

Although the challenges appear to outweigh the benefits, they should not be seen as impediments but as opportunities. Policy-makers and project planners who are aware of these challenges and design appropriate solutions will see positive results.

Hence, common-sense recommendations are proposed:

1. **Taking an integrated approach regarding technologies, data and methods is strongly advocated**. The technologies reviewed were not used as standalone solutions but were always paired with other technologies. Frontier technologies allow for integration of data sources, creating opportunities for enhanced data analytics. And technologies should be used in partnership with the communities and beneficiaries they are intended to support. The use of participatory approaches is strongly recommended, especially in contexts involving customary land rights mapping.
2. **There must be a focus on sustainability.** Technical, financial and institutional capacity need to be addressed before implementation. Training programmes should be built into maintenance plans. Without a supportive legal, political, and institutional environment, land tenure projects will face many challenges that cannot be addressed using technology.
3. **The focus should be less on the technologies and more on ensuring an enabling environment.** The focus should also be on choosing the most appropriate technology for the task and context, bearing in mind that this might not be the latest, most advanced solution.

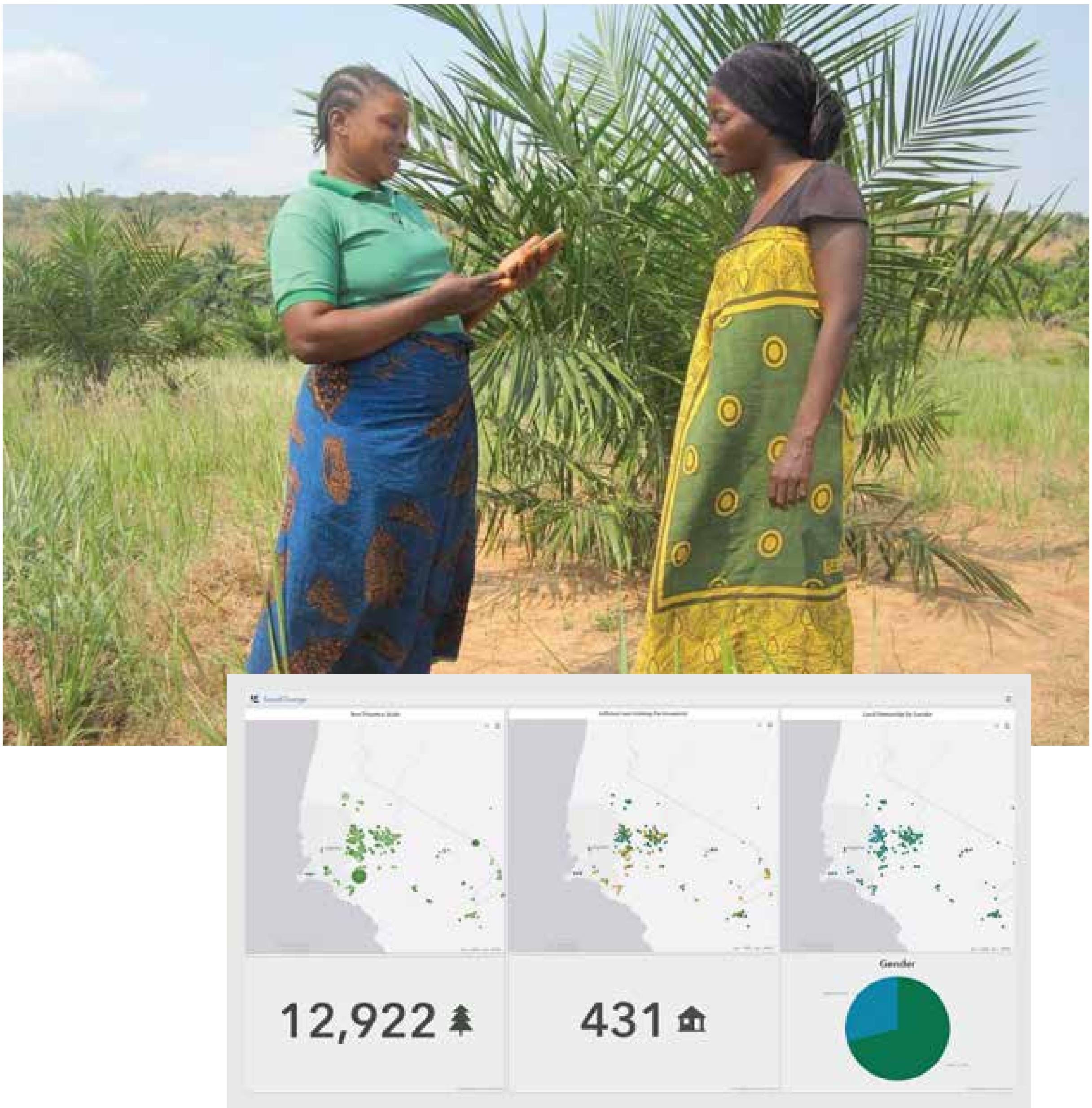


Figure 19 Creating a transparent supply chain for sustainable palm oil in Kigoma, Tanzania (image courtesy: Casdasta)

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Appendix

SOME FRONTIER TECHNOLOGIES DESCRIBED

Table 3 **A selection of frontier technologies and their uses.**

Technology	Description	Uses
Artificial Intelligence (AI) / Machine Learning	**AI** refers to "the capability of a machine to engage in cognitive activities typically performed by the human brain" (UNCTAD/TIR, 2021). **Machine learning** is an application of AI whereby digital systems learn and improve from past experiences. Computers analyse patterns based on sample datasets and hence make predictions about much larger datasets (Panfil *et al.*, 2019).	Automated Feature Extraction (AFE) for identifying land parcel boundaries in aerial images.
Big data and the Internet of things (IoT)	The **IoT** is "a global network infrastructure that connects the virtual and the real through data capture and transmission" (Chen, 2021). It refers to "the growing trend for data communications technologies to be built into physical objects" (Ramalingam *et al.*, 2016) creating "a giant network of connected 'things' (which also includes people)" (Morgan, 2014). Relationships in this network are between people-people, people-things, and things-things. All these interconnected sensors create a lot of data (**big data**) that is "beyond the capabilities of traditional database structures to capture, manage and process" (UNCTAD/TIR, 2021).	Data collection, management, and analysis.
Distributed Ledger Technology (DLT) & Blockchain	**DLT** refers to technological infrastructure and protocols that allow "simultaneous access, validation, and record updating in an immutable manner across a network that's spread across multiple entities or locations" (Frankenfield, 2021). **Blockchain** is a type of distributed ledger, though not all DLTs employ blockchain technology (Graglia and Mellon, 2018). "Members of a blockchain network collectively validate new data through consensus algorithms and add the information to 'blocks', which are linked cryptographically into a 'chain' (hence the term blockchain)" (Panfil *et al.*, 2019). Because the network is decentralised and there is a record of the time and origin of every data input which is stored on multiple independent computers, it is reported to be virtually immune to cybercrime.	Recording transactions of land parcels and rights without the need for a national registry.
Geographic Information Systems (GIS)	**GIS** are systems of hardware, software and procedures designed to support the capture, management, manipulation, analysis, modelling and display of spatially referenced data for solving complex planning and management problems.	Spatial data mapping, modelling, management and analysis.
Global Navigation Satellite System (GNSS)	**GNSS** refers to the full suite of satellite constellations providing location data for earth-bound users (both on the ground and in the air). Colloquially, this is often referred to as GPS because the United States Department of Defense's system was the first of its kind. Since then, five other constellations have been added: QZSS (Japan), BEIDOU (China), Galileo (EU), NAVIC (India), and GLONASS (Russia). Of these, QZSS and NAVIC have regional coverage (Japan and India respectively), while the others have global coverage. On the sensor-side of the system, most handheld devices (such as mobile phones and tablets) use single-frequency receivers that provide location precision to within about 5 metres. Recently, some mobile phone manufacturers have included dual-frequency receivers which greatly improve the obtainable precision for such devices (to sub-metre) (Panfil *et al.*, 2019). Survey-grade receivers provide position to centimetre-level precision.	Positioning.

Technology	Description	Uses
Mobile devices	**Mobile devices** are multi-functional, handheld devices (smartphones and tablets) that incorporate several integrated sensors that can contribute data towards the IoT. These days, most mobile devices include good quality cameras, GNSS and inertial sensors as standard. **Apps** are programmes that run on mobile devices and can make use of the onboard sensors. There has been a rapid rise in ownership rates of mobile devices in emerging and developing nations over the past decade or more (Ramalingam *et al.*, 2016), improving inclusivity and empowering the participation of vulnerable groups in securing their land tenure and natural resource use rights, yet their adoption still relies on good mobile data access.	Data collection (geospatial and qualitative).
Remote sensing	**Remote sensing** may be defined as "the process of scanning or monitoring the physical characteristics of the surface of the earth" (Bennett *et al.*, 2020) and is considered to be an art, science, and technology (ITC, 2013). A key feature of remote sensing is that the sensors employed are not in physical contact with the object being sensed, thus three out of five human senses are remote (sight, smell, hearing). Although aerial photography and underwater acoustics are remote senses, the term usually refers to satellite-based sensors observing the earth in the electromagnetic spectrum. It is this, 'usual' understanding that is employed in this report.	Creating images of large portions of the Earth's surface.
Unmanned Aerial Vehicles (UAVs)	**'Drones'** is the colloquially accepted term for unmanned aerial vehicles (UAVs). They come in a variety of different guises, whether fixed-wing or rotary, and can be remotely controlled or fly autonomously through software-controlled flight paths, often using GNSS and inertial systems for navigation. "The key innovation of drones is the suite of sensors, software, and communications equipment that allows these comparably small and light-weight vehicles to be operated remotely" (Panfil *et al.*, 2019).	Creating images of localised regions of the Earth's surface.

INTERVIEW QUESTIONS

For the purposes of this project, typical examples of frontier technologies include (but are not limited to): artificial intelligence, machine learning, distributed ledger technology (such as blockchain), drones, satellite-based imaging sensors, the Internet of Things, big data, Global Navigation Satellite Systems (such as GPS), and mobile (smart)phone applications.

1. What has been your involvement in land tenure / land-rights related projects?
2. Where does your interest in this line of work / research come from and how long have you been doing it?
3. What is your understanding of 'Frontier Technologies'?
4. Please describe your experience of using any of these, or similar, technologies for mapping land rights?
5. What have been the biggest challenges you have encountered in this regard?
6. What have been the biggest successes you have experienced in this regard?
7. What are the challenges and risks associated with land tenure security projects?
8. Based on your experiences, what advice would you give to an organization embarking on a land rights mapping / land tenure security project?
9. Who do you think are the leaders / innovators in this field?
10. In your opinion, where do you see the future for land rights mapping?

Thank you for your time and assistance! If there is anything else you would like to add concerning any of the topics we have discussed, please feel free to do so. If you would like to elaborate on any of the topics we've discussed, you may also send supporting documents to simon.hull@uct.ac.za.

We look forward to collaborating further with you in future.

ETHICS DECLARATION

- The use of all information is in terms of the ethics policies of the University of Cape Town, FAO and IFAD.
- No information will be published which will lead to your detriment.
- All information is used for research purposes only.
- You may refuse to answer any question and may also withdraw any information provided at any stage.
- You may refuse to let a recording be made of the interview. If you agree to a recording, this will only be used for the purposes of accurate data collection and will be reviewed to add detail to written notes and to make corrections.
- A copy of the interview summary will be provided to you so that you can verify or refute any information and add to the information recorded.
- You may withdraw from the research at any stage.

Do you agree to being recorded? Y/N

Do you agree to being identified by name or would you prefer to remain anonymous? Y/N

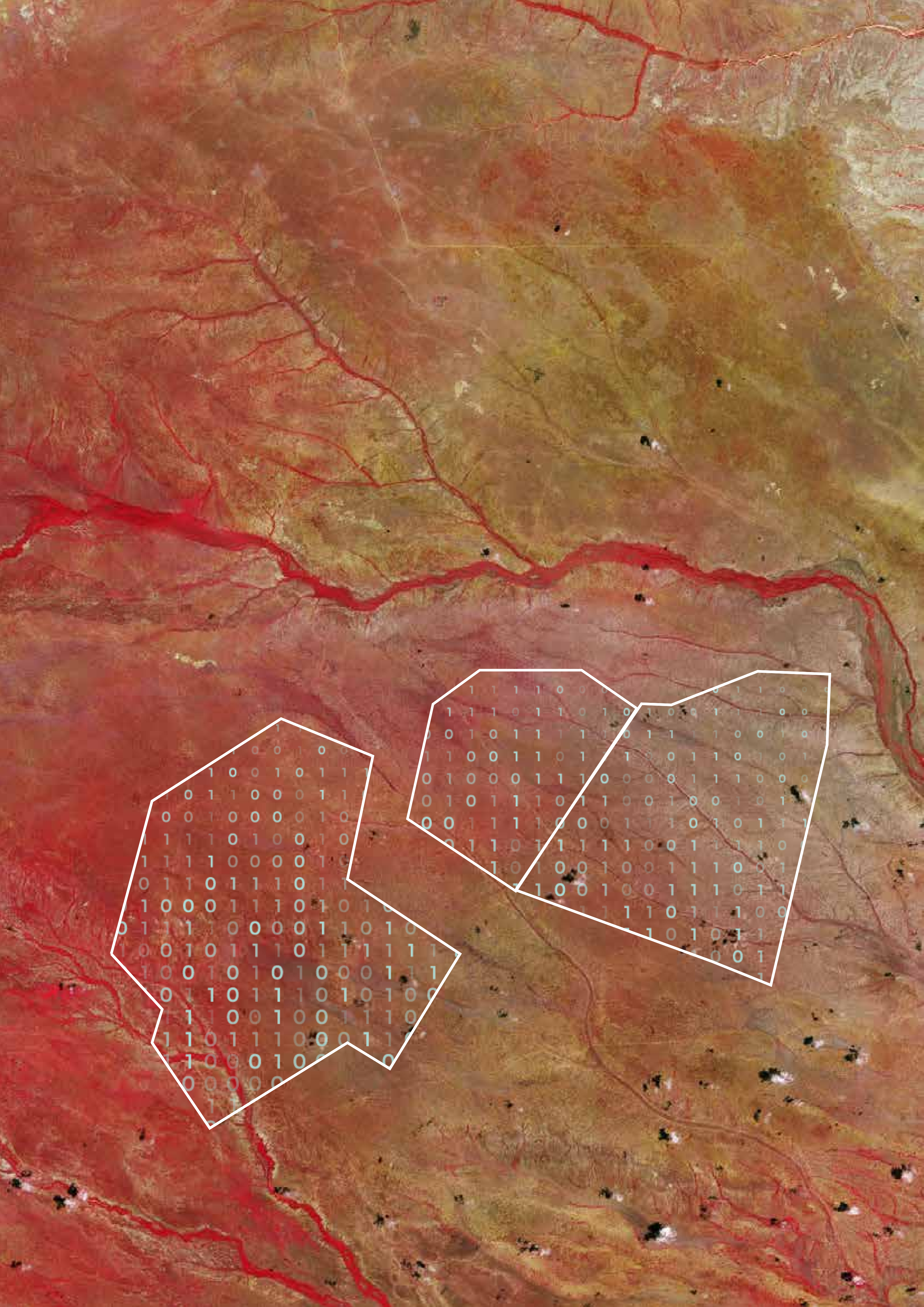
DATA SOURCES

Table 4 **List of interviewees**

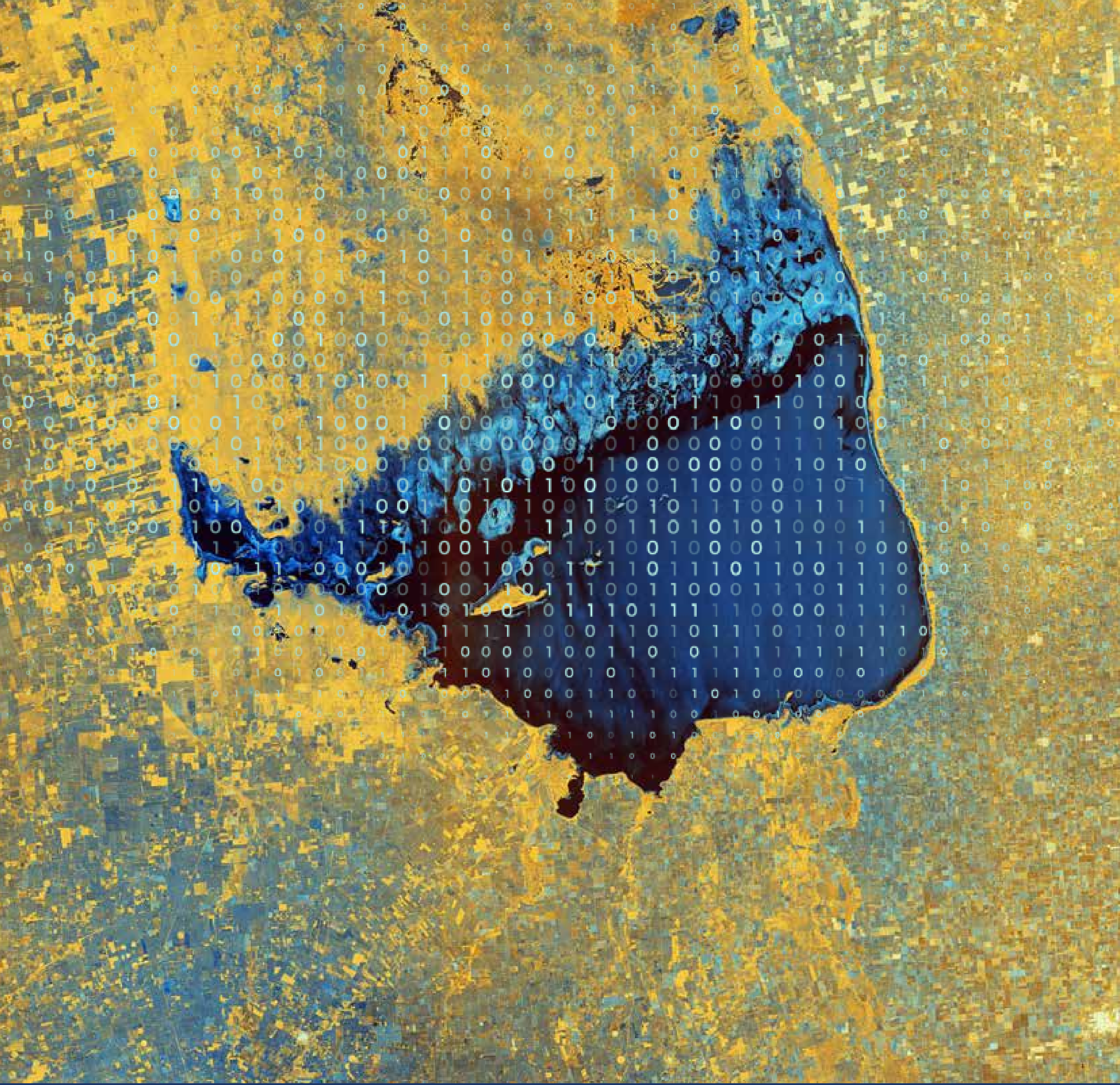
Name	Organisation
Anthony Beck	Ordnance Survey
Keith Bell	Independent consultant
Rohan Bennett	FIG / Swinburne University of Technology
Mykhailo Cheremshynskyi	Independent consultant
Amy Coughenour-Betancourt	Cadasta
Vladimir Evtimov	FAO
Zdravko Galić	University of Zagreb
Mila Koeva	ITC (University of Twente)
Juan Pablo Soliz Molina	Cadasta
Simon Norfolk	TerraFirma
Yuliya Panfil	New American
Maria Paola Rizzo	FAO
Didier Sagashaya	Medici Land Governance
Claudia Stöcker	SmartLandMaps / University of Münster
Olivier Vernin	Meridia

Table 5 **Publications reviewed**

Author	Title	Date	Type
IFAD & GLTN	Mapping Land and Natural Resource Rights, Use and Management	2012	Factsheet
Hay	Cloud, Mobile and Big Data Technologies in Responsible Land Administration	2016	Conference paper
UN-Habitat, IFAD & GLTN	Learning Note: Using approaches and technologies for mapping land and natural resource use and rights	2016	Report
Terra Firma	The application of the Community Land Value Chain (CaVaTeCo) to land tenure formalisation processes in Mozambique	2017	Report
Bennett et al.	Innovations in land data governance: unstructured data, NoSQL, Blockchain, and big data analytics unpacked	2018	Conference paper
Koeva et al.	Its4land - Innovative Geospatial Tools for Fit-for-Purpose Land Rights Mapping	2019	Conference paper
Sullivan et al.	An innovative, affordable, and decentralized model for land registration and administration at a national scale in Tanzania	2019	Conference paper
Galić & Vuzem	A Generic and Extensible Core and Prototype of Consistent, Distributed, and Resilient LIS	2020	Journal article
Koeva et al.	Geospatial Tool and Geocloud Platform Innovations: A Fit-for-Purpose Land Administration Assessment	2021	Journal article
Eilola et al.	Lessons learned from participatory land use planning with high-resolution remote sensing images in Tanzania: Practitioners' and participants' perspectives	2021	Journal article
Chipofya et al.	SmartSkeMa: Scalable Documentation for Community and Customary Land Tenure	2021	Journal article
Technology and Innovation Lab	Use Case Viability Report: AI for Parcel Mapping	2021	Report
Galić	LIS in the era of BDMS, distributed and cloud computing: Is it time for a complete redesign?	2021	Article
Tembo and Sagashaya	Zambia: Private sector investment in security of land tenure – From piloting using technology to National rollout	2021	Journal article
Stöcker et al.	Scaling up UAVs for land administration: Towards the plateau of productivity	2022	Journal article
Hughes et al.	Harnessing Technology to Advance Citizen-Centric Land Administration in Rwanda	2022	Journal article
Stow et al.	Evolving registration - how do established Registrars embrace change?	2022	Conference paper
Wilson et al.	Re-imagining the role of a national mapping agency to support spatially enabled governance	2022	Conference paper
Beck	The use of LADM primitives and structured indexing to support automated registration using submitted applications	2022	Conference paper
Stöcker et al.	Accelerating participatory land rights mapping with SmartLandMaps tools: Lessons learned in Benin	2022	Conference paper



Tana River, Kenya,



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