G4AW: Lessons for Digital soil health advisory in Africa

G4AW
GEODATA FOR AGRICULTURE AND WATER

Netherlands Space Office

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Summary

The Geodata for Agriculture and Water (G4AW) program is funded by the Netherlands Ministry of Foreign Affairs and implemented by the Netherlands Space Office (NSO). It has run 25 projects supporting satellite-based services which should positively impact the lives of smallholder food producers in Africa and Southeast Asia. As the program comes to a close, it was found that the services particularly aimed at improving soil health did yield relevant products (promising in innovation), but few buying customers (limiting in business model).

The current study was commissioned to analyse what keeps advise on this component of sustainable agriculture from becoming commercially attractive, knowing it is of paramount importance to feed a growing population. The study focused on Sub-Saharan Africa, and aims to analyse the G4AW program to leave a useful legacy for long-term soil health programmes currently running in West Africa (incl. World Bank FSRP, NL-MFA Soil Values).

Soils in Africa (apart from the Rift Valley area) have a generally low natural fertility due to old age. Continuous cultivation and low input use leads to declining soil fertility and crop production increases that mainly have to come from new land opened up for agriculture. In the more fertile volcanic and in irrigated areas, farms have meanwhile become very small due to inheritance-related partitioning. It is obvious that soil health needs to be improved in order to feed a growing African population.

The road ahead is in Integrated Soil Fertility Management (ISFM), of which fertilizer use is a major, but costly, component. Major capital investments are needed to improve soil health and increase agricultural production in Africa, and advisory services can play a key role now that digital solutions in agriculture (D4Ag) flourish at a global level. At the same time, early-warning services related to weather and crop protection find an easier audience than soil health, as drought and pests can wipe out entire crops in a season. National insurance programs therefore also seem to be more geared to dealing with 'damage and disaster' risks. Soil fertility decline manifests itself rather as a 'stress' of gradual deterioration, therefore perhaps being less in the picture as a process needing immediate action.

Advisory services on soil health management have traditionally been based on soil testing in laboratories. A threshold level of a nutrient was used to coin it 'deficient' and then the advise was to apply it in fertilizer. In Sub-Saharan Africa, soil organic carbon (SOC) shows the best correlation with crop production. Currently we know a lot more on the relationship between soil test values, nutrient uptake and crop yield, which has led to several well-known crop production models. Also, traditional soil testing found a 'competitor' in spectrometry, allowing the determination of soil properties by hand-held, non-destructive sensing devices.

The digital era also allows large-scale mapping of soils, helped by remote sensing and imagery. SOC has been mapped at continental scale, and the use of AI techniques such as machine learning allows us to explain different soil types by physiographic covariates. Although covariate datasets are still below desirable levels, this opens up massive opportunities for better soil management at the landscape level and above.

Meanwhile, risk-averse African farmers cherish heterogeneity, showing the distance between remote sensing and machine learning on the one hand and a useful pixel- or field-based soil health advisory service on the other. At the farm level, the customers for paid advisory services seem mainly to be owners of plantations and irrigated lands with a clear commercial perspective. Precision farming here is helped by digital solutions and the financing model is business-to-business. Resource-poor farmers with limited digital skills and poor internet and smartphone access though seem not to pay for soil health advisory services, unless in a community-setting and at landscape-level. There are many reasons to prefer this spatial scale for advisory services for reasons of cost and experience sharing, working with average soil fertility and expected yield ranges rather than trying to be too precise, making input from remote sensing more useful and rapid opportunities for scaling.

Services need to be bundled to offer more choices than just soil fertility management, also including credit and insurance options, and the financing needs to be brokered, i.e. in a business-to-customer setting but with cost-sharing mechanisms. It is argued that technology and customer seem not to find each other easily when it comes to paid services for soil health improvement, unless an enabling institutional environment in between them is created. Also, there should be a better balance between 'sending' and 'receiving', bringing in more citizen science, customized interaction and communication strategies (including call centres, mobile phone-apps, tablets), and community-led soil and landscape classifications.

To make better use of advisory services for soil health improvement, a *road map* is suggested allowing to tick off a list of prerequisites to check whether the environment enables successful digital innovation, particularly for soil health improvement. The prerequisites (step 1) focus on *supporting policies and institutions*, *finance/business case*, *production systems*, *agricultural communities* and *appropriateness and quality of the technology*. As a *road map* step 2, an ex-ante analysis in a given context can reveal whether the prerequisites that rank poorly can be addressed adequately in a given time-frame. This can lead to a *go / no go* decision, In case of go, step 3 will be the rolling out of new, or strengthening and rerouting ongoing initiatives for advisory services for soil health, preferably for a period that also allows scaling. This *road map* should of course not discourage local innovation and initiatives from within communities.

Digital solutions for agriculture, including soil health, is like a 'moving train'. It is not a matter of whether it works, but rather when we will see the most effective and affordable support services for smallholder farmers in Africa appear on the market.

▼ *Margret Kigozi, farmer in Uganda, SUM-Africa ©NSO/G4AW*

1. Rationale

In the year 2050, an estimated 2,5 billion people will live in Africa, from around 1,4 billion in 2024. To feed the people and not rely increasingly on food imports, soils need to be productive and healthy and crop and animal production needs to go up. The Geodata for Agriculture and Water (G4AW) program of the Netherlands Space Office (NSO) believes part of the solution lies in rapid development and adoption of digital technology. The program has supported 25 partnerships in 15 countries across Africa and South-East Asia in developing digital solutions, utilizing geodata, to sustainably improve food and income security for smallholders and pastoralists. Also, at Dutch policy level, interest in digital solutions for different societal fields is reflected by a set of showcases (including G4AW projects) that highlight the role of digitalisation for development.

Figure 1 gives a broad overview of the plethora of tools and instruments potentially available in digital agriculture. In the middle is the 'client' who should benefit from targeted and customized application of such tools to increase agricultural production and improve livelihoods. A major challenge is to bring the technology to the client, but also to bring the client to the technology. In a low external input and low investment context in developing countries, the latter may be even more challenging and relevant than the former.

G4AW Goal 3 reads '*Help achieve a 10% more effective use of inputs for food production (water, seeds, fertiliser, pesticides, etc.*' Within the G4AW program, numerous digital services have been developed. However, services addressing soil health seem to lag behind in development and adoption compared to those related to water, seeds and pesticides.

Although fertilizer advice has been identified as a priority by end-users (small-scale farmers in Africa) in most G4AW projects, there is still no clear path how to develop and scale advisory services on soil fertility management for which clients are ready to pay.

This report addresses the following research questions:

- Which are the current challenges for small-scale farmers in Africa when it comes to soil health and sustainable soil management?
- How can satellite data and digital tools (SDDT) be used to assess and monitor important indicators of soil health for small-scale farmers, such as soil moisture, chemical soil fertility, and soil erosion?
- Which existing (G4AW) projects and practices have successfully integrated SDDT to improve soil health? How can these be effectively upscaled, and what are their possible impacts as to agricultural productivity and farm income for small-scale farmers in Africa?
- Which challenges and limitations as to adoption and upscaling of SDDT for soil health can be identified, and how can they be tackled? What Road Map would be needed to get there?

The geographic focus will be on Sub-Saharan Africa, eyeing in particular West Africa, where two major soil health-related programs are underway, i.e., the Food Systems Resilience Program (FSRP, World Bank) and Soil Values (Netherlands Ministry of Foreign Affairs).

Figure 1. *GEO-ICT Framework. Source: FAO-ITU. Adapted from E-Agriculture Strategy Guide: Piloted in Asia-Pacific Countries*

2. State and dynamics of soil health in Sub-Saharan Africa

Carbon and nutrient stocks

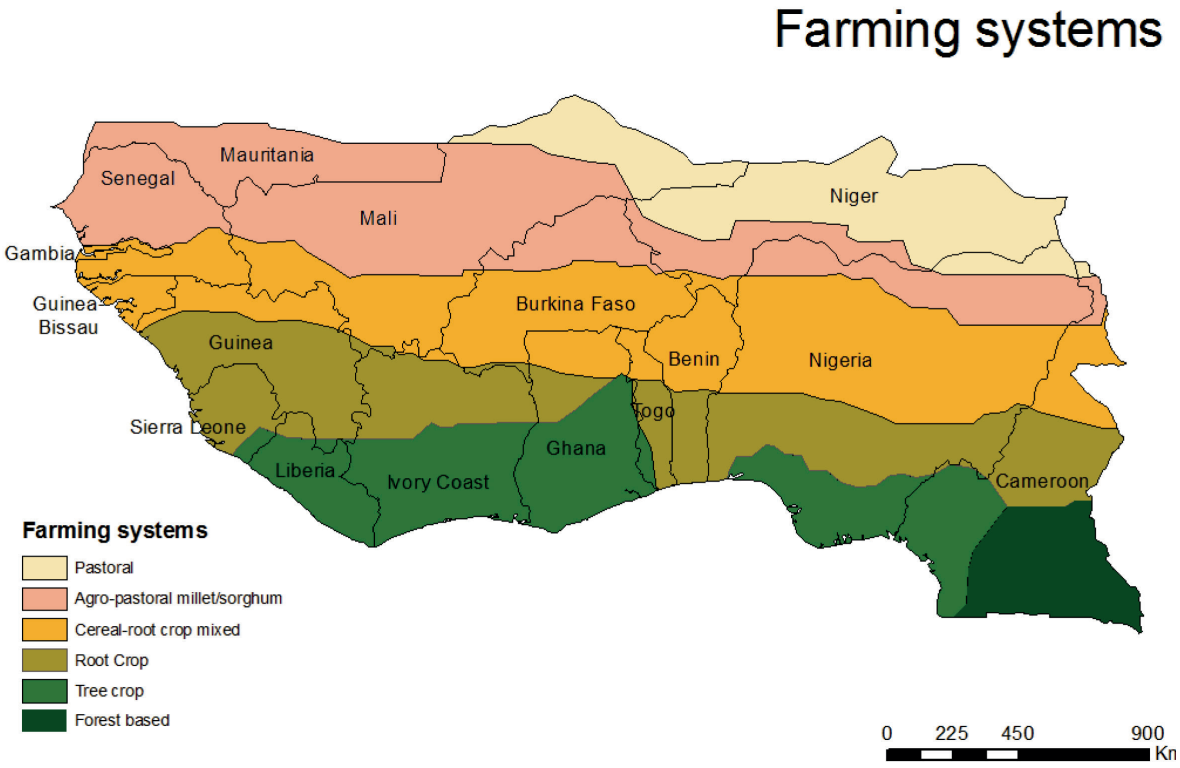
Africa is an 'old' continent with (in most places) soils that have lost a lot of their natural fertility due to long cycles of weathering and erosion. Many soils are therefore low in nutrients and acid. The exception is the area covered by Rift Valley volcanics and other isolated volcanic areas, where younger and more fertile soils prevail, mainly in Ethiopia, Kenya, Tanzania, Uganda, DRC and Rwanda. The current state of soil health in Africa in terms of nutrient stocks is strongly related to soil organic carbon (SOC) which, together with pH, is a good proxy indicator of soil health and agricultural production.

SOC stock is strongly related to climatic zones and temperature. For West Africa, for example, pH, organic carbon and total nitrogen and phosphorus levels differ much for the three major zones running parallel and East-West (Table 1). These zones also represent major farming systems (Figure 2). Together with oxalate-extractable metals (Al and Fe) and exchangeable Ca, climatic factors explain approximately two-thirds of SOC variation across sub-Saharan Africa (Von Fromm et al., 2021).

Table 1. *Average values of pH, organic carbon, total nitrogen and phosphorus stocks (0-20 cm) in Upland soils on acid rock types in the three major agro-ecological zones of West Africa (Windmeijer and Andriesse, 1993)*

Agro-ecological zone	pH-H2O	Organic carbon	Total N	Total P
		percentage	percentage	percentage
Sudan Savanna Zone	6.8	0.3	0.05	0.03
Guinea Savanna Zone	5.7	1.2	0.14	0.04
Equatorial Forest Zone	5.3	2.5	0.16	0.06

Figure 2. *Agro-climatic zones / farming systems in West Africa (after Dixon et al., 2001)*



Stocks of organic carbon seem to be the most appropriate entry point for judging soil health in Sub-Saharan Africa. There is a plethora of reasons for this choice:

- Many studies in Africa show a reasonable to good correlation between SOC content and agricultural production (e.g. Eyasu et al., 2019 for the Ethiopian Highlands);
- SOC is, through C/N ratio, also a proxy of soil nitrogen stocks;
- As it hosts biodiversity and contributes strongly to soil structure and water holding capacity, it is an indicator of soil health rather than just chemical soil fertility;
- SOC is detectable by satellite sensors at different soil depth and digital SOC maps these days abound in Africa;
- African farmers often use ‘topsoil colour’ as a local soil health index, which relates well to SOC content; and
- SOC can team up with the larger carbon debate in the climate change and sequestration domain and become more part of international efforts and finance mechanisms surrounding carbon credits (e.g. Carbon Bank - Rabobank).

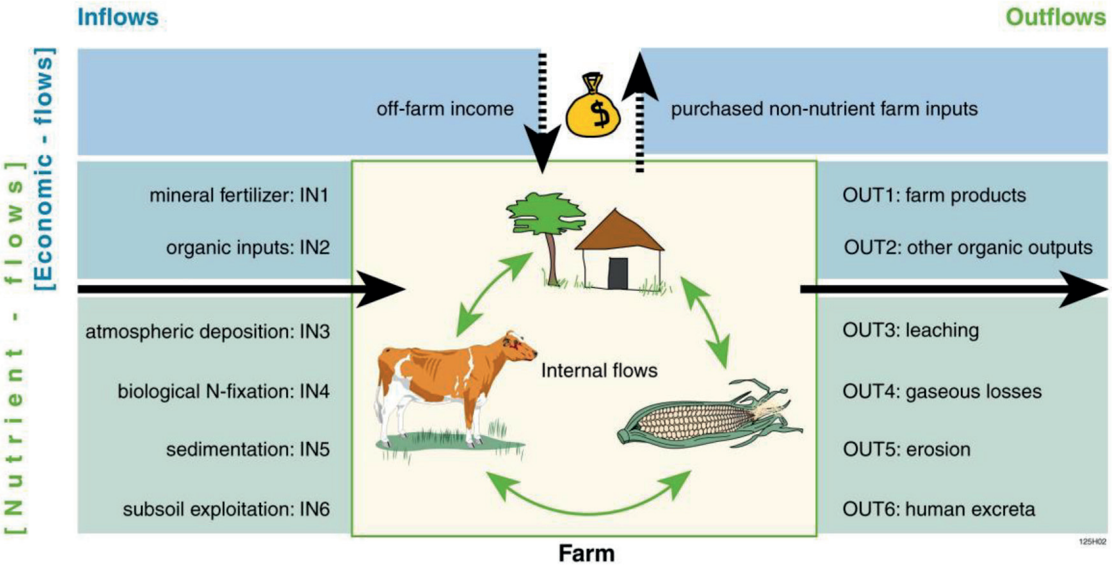
Carbon and nutrient flows

Stocks of carbon, nitrogen and phosphorus are not static. Overall in Africa, they tend to shrink (Stoorvogel et al., 1993). The remedy against this has been coined ‘Integrated Soil Fertility Management’ (ISFM), boiling down largely to the careful management of these stocks in such a way that they do not decline, and that agricultural production taken from it is satisfactory and sustainable for the small-scale farmer (Vanlauwe et al., 2010). Figure 3 shows how this can be viewed at the farm scale (Van den Bosch et al., 1998). The essence is that nutrients can be added to fields and farms (IN), removed (OUT) and recycled. Sustainable management of (chemical) soil health implies that IN and OUT are more or less balanced at a satisfactory level of carbon and nutrient stocks.

For nutrient flows, several known farm management strategies are in place. Agroforestry for example increases IN 6 and reduces OUT 3, adding leguminous species to the cropping system increases IN 4, ridges and terraces reduce OUT 5, irrigated and valley bottom agriculture benefits from IN 5, which can be made up of sediments eroded elsewhere.

Recycling is important in crop-livestock systems as animals scavenge on waste, whereas manure and urine can be reutilized on preferred plots. In general, it can

Figure 3. *Nutrient input and output flows and balance at farm level (after Van den Bosch et al., 1998)*



be stated that livestock (also including aquaculture) can play a positive role in regenerating soil health and landscapes as it offers many ISFM pathways that are not available in cropping systems alone (Paul et al., 2023).

The key financial flows are IN 1 and OUT 1. Applying fertilizer (more IN 1) is not done to improve soil health, but mainly to increase production (more OUT 1). A combination of IN 1, IN 2, and the recycling of organic materials does improve soil health and increases production (e.g., Workineh Ejigu et al., 2022). IN 2 can be obtained from slaughter houses and other off-farm sources, but is often in relatively short supply. The financial picture when comparing production (OUT 1 translated into crop yields) with fertilizer (IN 1) is key in a soil health advisory service context. As crops may also benefit from the residual effect of a previous fertilizer application (particularly the less mobile nutrient phosphorus), the picture is often a bit more favourable than commonly communicated in literature.

The other IN and OUT indicators do not have a monetary value, although attempts in the context of 'payment for environmental services' have been undertaken. In Asia, fertilizer use is high and advisory services for soil health are also geared towards reducing IN 1, while trying to maintain the same level of OUT 1, meanwhile reducing OUT 3 and associated reduction of pollution of the environment.

Opening up new land for agriculture often causes a major decline in carbon and nutrients, due to exposure to higher temperatures and erosive rainfall. Organic carbon that is 'easily decomposable' in natural conditions may disappear rapidly after slash and burn of savanna and forest due to changed circumstances. Also natural C-cycles are cut off when above-ground carbon is removed from the ecosystem. Although Africa still has ample land that is suitable but not yet used for agriculture, the consequences of continued opening up of such lands is huge loss of above-ground but also below-ground carbon and the risk of rapidly declining soil health once the land has been cultivated for some time.

Cherishing and managing soil health heterogeneity

As a strategy to spread risk and be more food secure, farmers tend to cherish heterogeneity. This can be reflected in a wide choice of crops (field crops and tree crops) and farm animals, with different feed needs and resistance against drought, soil fertility needs and susceptibility to pests and diseases. Also farmers tend to use local names for farm plots, some of which receive more fertilizer than others, or they receive compost or manure collected in enclosures (Eyasu et al., 1998).

▲ *Ring management systems in West African Sahel/Sudan zone – cattle stay overnight in a ring around the village, adding fertility, leading to higher sorghum and millet yields in the rainy season (IN 2-based system)*

▲ *Nomadic herdsmen in West Africa – from symbiosis to competing claims on land – two G4AW projects paved the way to call centre-based improved land and water use planning*

In parts of West Africa, villagers employ ring management systems, where pastoralists are allowed to have their animals stay overnight in a ring around the village, and feed further away during the day. In this way, the inner ring becomes more fertile and constitutes the basis for sorghum and millet production during the growing season (Table 2). Fallowing also helps to rebuild soil health, but that time is often not available at growing land pressure.

Table 2. *Spatial and temporal variation in soil organic carbon stocks (0-15 cm) in ring management crop-livestock systems in the Sudan Savanna Zone of Mali (Samaké et al., 2005)*

Distance from village	10 m	100 m	1000 m
Organic carbon %	0.54	0.36	0.15
Fallow period	0 year	3 years	6 years
Organic carbon %	0.15	0.26	0.31

Inland valleys in West Africa are bread baskets and are also preferred agricultural lands because of the presence of water and eroded sediments, and the option to grow two crops a year (Windmeijer and Andriesse, 1993).

▲ *Cotton in West Africa with sorghum benefitting from fertilizer applied to cotton the previous year*

3. Soil health-related challenges for small-scale farmers in Sub-Saharan Africa

Broader picture

The agricultural economy in 2023 employed 42.5 percent of Africa's labour force and accounts for 17 percent of GDP, but with a large spread among countries, Ethiopia being at almost 40% (World Bank) (USAID). Hence the agricultural sector is of paramount importance for many people to earn a living. Although varietal improvements and general productivity increases occur, overall development in smallholder agriculture in Sub-Saharan Africa does not look particularly promising.

Farm and field sizes in the most populated and fertile areas have reached low levels upon several rounds of inheritance (from the Rift Valley highlands in Kenya and Ethiopia to the Nile Delta in Egypt), and production increases mainly come from opening up new land. Meanwhile, growing unemployment among young people in Sub-Saharan Africa is a serious challenge as other sectors than agriculture do not grow sufficiently to absorb this new labour force. Rural reconstruction programs implemented in other parts of the world allowing small farms and plots to be managed at larger scales in cooperatives also stand the risk of knocking farmers out of business by lack of alternative income sources.

Production factors

Small-scale farmers in Africa face many challenges when it comes to soil health and sustainable soil management. When looking at production factors, there is a blatant lack of capital (investment) in smallholder agriculture keeping the use of mineral fertilizers at very low levels compared to other continents (6,5 million tons in Africa versus 57 million tons in East Asia – www.statista.com). Farmers that are short of cash are risk-averse and may buy seeds, but then depend largely on what nature has to offer. After all, the rains may not come (if irrigation is not available), and pests and diseases may undermine the fertilizer investment.

Labour seems abundantly available in small-scale agriculture in Africa, but in many cases there are shortages at least in peak periods, and particularly educated young people prefer not to work in agriculture. Land is often not owned and even not demarcated in cadastral maps, and size of holdings has decreased seriously over the last decades, making it increasingly difficult for small-scale farmers to remain food-secure (Giller et al., 2021).

Capital, labour and land are the drivers of successful soil health restoration and ISFM. Going by figure 3, the 'ideal' ISFM-driven farm architecture could be made up of erosion control measures (reducing OUT 5), a compost pit (recycling organic waste), chickens, ducks, fish and other animals recycling organic waste, a tree/crop mix including leguminous species (increasing IN 4 and IN 6, reducing OUT 3), keeping crop residues on the field (reducing OUT 2), and including horticulture and high-value crops receiving an efficient mix of mineral and organic fertilizers (adding IN 1 and IN 2 against a high money value of OUT 1).

Risk, markets, investment

Risk aversion manifests itself in farm heterogeneity management. But also investment in mineral fertilizers (IN 1) is met with several challenges. The price may vary across the continent depending on national pricing mechanisms, but the product has several caveats that are not easy to square. The connection between nutrient stocks, the nutrient needs and uptake of the crop to be grown, the yield the farmer would like to see, and the amount and nutrient content of the fertilizer to reach those yields is poor, and facing variability within fields, farms and landscapes. Moreover, the product is often offered in large bags without certainty about the quality, and has to be obtained from agro-dealer distribution points where the fertilizer is not always available at the right time.

The 'last mile' therefore is also an issue of concern. And finally, the farmer needs return on investment when producing for the market, relying much on the price offered after harvest and the functioning of value chains in general.

Risk aversion can be countered by insurance and credit programs, which were also prominent parts of the G4AW projects. Rwanda and Uganda for example have agriculture insurance schemes, but they mainly cover damage and destruction due to droughts, flooding and uncontrollable pests and diseases, but not low and declining soil fertility which is seen as a 'stress' rather than a 'shock' in ecosystem theory (- MINAGRI: GOVERNMENT LAUNCHES A SUBSIDIZED AGRICULTURE INSURANCE SCHEME Uganda Agriculture Insurance Scheme – The Continuing Agricultural Education Centre (CAEC) – Makerere University). A Farming First publication however shows that African countries are not sitting back in the field of digital solutions for soil health improvement.

Opportunities

In spite of the above challenges, there are ways to restore soil health and obtain higher yields through ISFM approaches. The expected further growth of the African population means there is a growing food market and hence, opportunities for farmers to service a larger market, even at low purchasing power of the urban population. Getting to that point will not work at the current state of soil health in most of Africa. A combination of investment, job creation, land consolidation, and effective ISFM technologies will be needed to get ready for the next decades. This is also where geospatial and digital solutions come in.

Also, there is nothing like the small-scale farmer. In a large farm survey in the Ethiopian highlands, Okoth et al. (2022) showed that 20% of the survey sample has generally better access to one or more production factors, which often translates in more land, higher crop diversity, more tropical livestock units, and higher education levels. This group also tends to apply fertilizer more often, has higher production and value chain connection, and higher net farm income. Such lead farmers can be instrumental in getting the next groups of farmers adopt better ISFM practices.

▼ *G4AW project CommonSense*

4. Satellite data and digital tools (SDDT) for soil health assessment and monitoring

SDDT in general

Among developments currently making headway is the use of SDDT in agriculture. The past decades have seen rapid improvement in assessing soil health (helped by digital soil mapping and analysis) and crop performance (helped by NDVI interpretation) through remote sensing (RS). Meanwhile, a plethora of mainly weather and crop protection-related platforms, apps and advisory services have seen the light of day. The adoption of these technologies is also driven by the growing mobile phone and Internet penetration of rural areas and the falling costs of data worldwide[1].

Satellites permit repetitive coverage of the earth's surface on a continuing basis. The high temporal resolution of datasets due to a) increasingly frequent satellite overpasses; and b) the possibility to combine different sensors (sensor fusion), enables the use of accurate change-detection algorithms to check for relevant changes in the field (deforestation, irrigation, harvesting, etc.). Precision farming platforms such as EOSDA Crop Monitoring: Farm Software For Agricultural Sector are already available and in use at the high-end user community (e.g., Zhenong Jin et al., 2017).

Apart from weather satellites, the G4AW program mostly used open source data from US and European satellites such as Sentinel 1, 2 and 3, MODIS and LANDSAT. There has been limited use of commercial satellites, as both the availability was still relatively limited in the period in which most projects commenced (2014 – 2018), and the costs can still be considered to be restrictive in the early stages of business model development (especially for services that are tailored to smallholder farmers).

SDDT for soil health

Remote sensing has significantly advanced in measuring soil properties via satellite, airborne, and ground-based methods. These advancements have greatly enhanced our ability to understand and manage soils for various applications such as agriculture, environmental monitoring, and land resource planning. The multispectral and hyperspectral capabilities can extract valuable information about soil composition.

Satellite-based tools offer global coverage and continuous monitoring capabilities (equipped with sensors that capture data in different wavelengths of the electromagnetic spectrum, including visible, infrared, and microwave) but have limitations regarding spatial resolution and cloud cover interference. In contrast, aerial-based tools provide higher spatial resolution for detailed mapping and monitoring of smaller areas but are limited by flight restrictions and higher costs.

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[1] United Nations Development Programme, Precision agriculture for smallholder farmers (UNDP Global Centre for Technology, Innovation and Sustainable Development: Singapore, 2021).

Box 1. *Remote sensing and imaging techniques for soil health monitoring*

Satellite Imagery: Satellite-based remote sensing employs satellite sensors to capture multispectral and hyperspectral images of Earth, offering insights into vegetation health, soil moisture, and composition. These images aid in pinpointing soil health concerns, guiding effective soil management decisions for farmers and researchers (Babaeian et al., 2019).

Aerial Imagery: Aerial imagery, acquired through unmanned aerial vehicles (UAVs) with cameras or sensors, provides high-resolution data for soil erosion assessment, soil variability detection, and crop health monitoring. This aids farmers in precise soil management and sampling strategies (Adak et al., 2022).

Hyperspectral Imaging: Hyperspectral imaging captures Earth's surface in narrow spectral bands, offering precise insights into soil composition, nutrient levels, and organic matter. This cutting-edge technology facilitates seamless soil analysis and precise mapping of soil properties (Chabrillat et al., 2019).

Thermal Imaging: Thermal imaging, as demonstrated by Das et al. (2023), reveals temperature disparities, enabling assessment of soil moisture and water stress. These images pinpoint moisture variations, aiding farmers in irrigation optimization and detecting drainage issues or soil compaction.

Electromagnetic Induction (EMI): EMI is a geophysical technique used to measure soil electrical conductivity. EMI sensors generate electromagnetic fields and measure the response from the soil. This information can be used to map soil texture, salinity, and moisture content. EMI is particularly useful for characterizing soil variability and identifying areas with different soil properties.

Ground Penetrating Radar (GPR): GPR, a non-destructive geophysical technique, employs radar pulses to visualize subsurface soil layers. It offers insights into soil depth, compaction, and the detection of subterranean elements affecting soil quality, making it a valuable tool for soil profiling and compaction assessments.

Ground-based devices offer high-resolution data at close range and can provide detailed information about specific areas or objects of interest. Each type of RS tool has its advantages and limitations, making them suitable for different applications and research needs (Abdulraheem et al., 2023). A listing of relevant RS techniques includes thermal, radar, hyperspectral, and optical sensors (Yahia et al., 2021; Box 1). Using sensors in an Internet of Things environment allows determination of a set of key soil properties (Box 2).

Box 2. *Soil sensors and IoT devices*

Soil Moisture Sensors: These sensors gauge soil moisture content at varying depths. The real-time data they provide aids farmers in optimizing irrigation schedules, preventing both overwatering and underwatering. This precision is critical for efficient water management and maintaining soil conditions (Soulis et al., 2015).

Soil pH Sensors: Soil pH levels influence nutrient availability to plants. IoT-based pH sensors measure soil acidity or alkalinity, allowing farmers to adjust pH levels for optimal nutrient uptake by crops. Monitoring soil pH is essential for maintaining the correct nutrient balance and preventing deficiencies or toxicities (Yin et al., 2021).

Soil Temperature Sensors: Monitoring soil temperature is vital, as it affects seed germination, root growth, and microbial activity. This data helps farmers make informed decisions about planting schedules, crop selection, frost-prone area management, and soil moisture (Wang et al., 2021).

Soil Nutrient Sensors: Equipped with nutrient sensors, IoT devices can measure essential nutrient levels in the soil, such as nitrogen, phosphorus, and potassium. This information assists farmers in recognizing imbalances in nutrients, enabling precise and targeted administration of fertilizers. Optimized nutrient management improves crop health and reduces nutrient runoff (Rossel and Bouma, 2016).

Soil Erosion Sensors: IoT-based erosion sensors detect and monitor soil erosion rates by measuring factors like soil moisture, slope, and rainfall intensity. Identifying erosion-prone areas empowers farmers to implement erosion control measures and conservation practices to safeguard soil health (Liu et al., 2023).

Soil Organic Matter Sensors: IoT devices can measure soil organic matter content, a crucial indicator of soil health and fertility. Monitoring organic matter levels aids in understanding soil structure, water-holding capacity, nutrient cycling, and microbial activity. This information guides decisions regarding organic matter management and soil health enhancement (Wu et al., 2017).

IoT-enabled Soil Monitoring Systems: IoT platforms combine multiple soil sensors and devices, enabling comprehensive soil health monitoring. These systems gather data from diverse sensors, perform analysis, and supply farmers with valuable insights. User friendly interfaces aid in data visualization and interpretation, empowering farmers to make informed decisions regarding irrigation, fertilization, and overall soil management (Sudharson et al., 2023)

From wet chemistry to soil reflectance spectroscopy

Soil analysis is still an important part of nutrient management, and it is going through a transformation with the shift from wet chemistry-based methods towards proximal soil sensing and field soil scanners. These methods will help to significantly reduce the time between soil sampling and application of input materials. Soil reflectance spectroscopy, employed not only in laboratories but also via satellite, aircraft, and unmanned aerial systems, plays a pivotal role.

Within the visible near infrared (vis-NIR) spectrum (400 to 2500 nm), soil characteristics like mineralogy, organic matter, texture, and colour become noticeable. In contrast, mid-infrared (MIR) spectroscopy, spanning wavelengths from 2500 to 25,000 nm, utilizes molecular bond vibrations to generate MIR absorption curves when interacting with soil samples (Stenberg et al., 2010). MIR spectra have proven highly effective in predicting various soil physical, chemical, and biological attributes (Soriano-Disla et al., 2014).

Notably, MIR spectra exhibit more and stronger absorption features than vis-NIR, resulting in superior accuracy for soil property predictions (Hutengs et al., 2019). The assessment of soil health in a manner that is rapid, precise, cost-effective, and environmentally sound has emerged as a critical priority to ensure its sustainable management.

Soil moisture determination

Satellite-based RS can provide valuable information about soil moisture content over large areas (e.g., Ensuring soil moisture data quality with reference measurements - Earth Online (esa.int)). Sensors aboard satellites measure microwave radiation emitted from the Earth's surface, which correlates with soil moisture levels. Digital tools can process this satellite data to generate soil moisture maps, indicating areas with low or high moisture content. These maps can help farmers make informed decisions about irrigation scheduling, ensuring optimal soil moisture levels for crop growth while minimizing water waste. G4AW projects also developed many soil moisture databases. It is used in irrigation advice and more general crop management, but also in index based insurance.

Digital Soil Mapping

After many years of traditional soil mapping and using the famous Walkley and Black (1934) analysis method, the Global Soil Partnership in 2017 launched the first global digital Global Soil Organic Carbon (GSOC) Map | Global Soil Partnership | Food and Agriculture Organization of the United Nations (fao.org), at 1 km2 resolution and 0-30 cm depth. Following this, many country-level digital soil mapping efforts at different resolution took place (e.g. Zander et al., 2021 for South Africa, Hounkpatin et al. (2022) for Benin).

Objective sampling plans can be implemented to statistically capture variability of the landscape, represented by digital environmental covariates (environmental data representing soil forming factors; Leenaars et al., 2020).

Qualitative detection and quantitative estimation of SOC using RS and proximal sensing methods has been significant, with multispectral and hyperspectral RS images used to estimate and map spatial patterns across different regions and soil types (Angelopoulou et al., 2019). However, reliance on UAV/satellite data alone may not always provide accurate estimates of SOC content if covariate data are insufficiently available. Cambule et al. (2013) showed that the approach allows proper SOC assessment in poorly accessible areas when landscape features resemble those of accessible areas where SOC and covariate data are available.

An ongoing review by IFDC in the context of the Soil Values and Ferrari projects will provide a detailed account of the position of SOC as a key indicator of soil health (IFDC, 2024 – draft). Another recent overview on satellite-driven mapping of topsoil SOC in cultivated land is by Vaudour et al. (2022). Next, an evaluation of the current state of digital soil mapping in Africa was published recently, particularly on data density, availability of covariates and the rescue of legacy data (Nenkam Mento et al., 2024).

Translating soil health into agricultural production and advisory services

The sampling and mapping can result in lookup tables showing when a nutrient is deficient or not, and as a consequence, whether it should be supplied in a fertilizer. This still works if circumstances do not require advanced methods. But in the modern era, digital sampling and mapping is combined with modelling techniques in order to provide a useful, marketable product for farmers and aggregators from government, NGOs or private sector. There is in fact a whole toolbox available for the integration and interpretation of various data sources (Box 3, after Adak et al., 2023).

Chemical soil fertility as an indicator of soil health has long relied on laboratory analysis of soil samples, and classification of measured soil properties. Thresholds were often used to coin a soil 'deficient' or not. Through correlation analysis and empirical field models, theoretical and mechanistic crop production models took over and came closer to describing real processes, including inclusion of timing of fertilizer application. (e.g. QUEFTS, Oryza).

The combination of mapping (traditional or digital) and sampling and analysis (wet chemistry or spectrometry-based) feeds crop models that can simulate the effect of ISFM measures on crop performance. The big question is whether the model structure but also the spatial and temporal accuracy it provides lives up to the desire of buyers of advisory services. In a high-tech mechanised precision agriculture environment with irrigation (hence, no water-limited crop production), this may be the case. In smallholder rainfed Africa, with many different crops on small tracts of land, this is a challenge. As purchase of IN 1 in ISFM (fertilizer application) has a cost, the buyer needs to be sure his product (OUT 1) justifies the investment in the advisory service.

Box 3. *Data analytics and modelling techniques for soil health assessment*

Statistical Analysis: Statistical methods are essential for examining soil data, revealing patterns, trends, and connections among various soil health indicators. Descriptive statistics, correlation, regression, and multivariate analysis facilitate comprehensive soil parameter understanding and soil properties estimations using predictive models.

Data Integration and Fusion: Assessing soil health typically combines diverse data sources like soil sensors, satellite images, climate data, and historical records. Data integration techniques merge these datasets for a holistic soil condition analysis.

Machine Learning: Machine learning methods are valuable for assessing soil health by analyzing extensive datasets and constructing predictive models. These algorithms discern intricate data patterns, enabling the anticipation of soil characteristics and conditions through supervised techniques like decision trees, random forests, support vector machines, and neural networks (Mandal et al., 2023; Adak et al., 2018).

Geo-statistics: Geostatistical methods like kriging enables spatial interpolation of soil properties by leveraging spatial correlations among sample points and thereby enabling precise mapping of soil properties for comprehensive landscape soil health assessment. Soil Health Indices: Soil health indices integrate multiple indicators like organic matter, pH, nutrients, and compaction, into a single numerical value, offering a comprehensive evaluation of soil health. These indices can be generated using statistical methods, or expert knowledge (Rinot et al., 2019).

Modelling of Soil Processes: Process-based models simulate soil dynamics, including water flow, nutrient cycling, carbon storage, and microbial activity. They aid in analyzing soil health trends, assessing management effects, and conducting scenario assessments (Santra et al., 2009).

Decision Support Systems: Decision support systems combine data analytics, models, and expert insights to aid farmers in making informed choices about soil health management, encompassing irrigation, fertilization, crop rotation, and conservation practices (Adak et al., 2023).

Mobile Applications and Software: Mobile apps and software platforms are developed to facilitate data collection, management, and analysis. These tools often provide user-friendly interfaces for inputting and accessing soil-related information, generating reports, and sharing data with stakeholders.

5. Project-level application of satellite data and digital tools for soil health

Larger SDDT initiatives for African agriculture

At the more general level of 'digital agriculture', many developments have taken place globally and will continue to do so. In policy and outlook documents, digitisation is often regarded as synonymous to 'transformation'. CTA, a joint international institution of the African, Caribbean and Pacific (ACP) Group of States and the European Union (EU), in 2018-2019 held an enthusiastic plea for the development of Digital Agriculture in Africa (The Digitalisation of African Agriculture Report 2018-2019 (cgiar.org)). The findings included:

- Investments remain too small, primarily fuelled by donors, while private investment is lagging
- Digital Agriculture's reach figures are impressive given the relative nascence of the space, but use remains low
- Average yield improvements across all data points are roughly 20% for advisory services, 70% for market linkages, and 40% for digital financial services, bundled services standing out.
- There is a high share of youth engagement.

The expectations of CTA are that we enter a platform-led era. Platforms that bring together several use cases, diverse value chains, and the best capabilities of multiple players are the most likely to succeed. Such D4Ag 'super platforms' are already emerging, with a range of private, donor-led, government-led, and public-private partnership models. Several of today's barriers – notably, limited access to technology and connectivity – will begin to be overcome. Big Tech and Big Agri players coming in.

A spin-off of the work of CTA is the Digital Agri Hub, which allows a global search on digital solutions in agriculture by a fine-textured filter system. The site, now hosted by Wageningen Environmental Research (part of WUR) is interactive and offers events and online meetings.

Although more on the general issue of automation and digitization, FAO 'State of Food and Agriculture' in 2022 (In Brief to The State of Food and Agriculture 2022 (fao.org)) has many elements that are relevant for digital applications in agriculture and soil health management. A support study by Ceccarelli et al. (2022) looked at the degree to which automation and digitalization has supported precision agriculture on a global scale. It was found that those considered profitable and financially sustainable mostly serve large-scale producers in high-income countries. Most solutions are still scaling or getting close to the market. National data policies – including data protection and privacy regulations – are key enablers of adoption, as are investing in national data infrastructures, connectivity (e.g. accurate weather forecasts, land demarcation, crop calendars and broadband internet connectivity) and electricity in rural areas.

Digital solutions, including RS and simple mobile devices, are rapidly scaling, including in low-and middle-income countries. More advanced solutions, such as big data analytics, AI and machine learning, are also expected to be further developed and applied. Costs are prohibitive for individual small-scale producers in lower-middle-income countries, although research in Rwanda (Niyitanga, Kazungu and Mamy, 2020), Burkina Faso (Pouya et al., 2020) and Ghana (Annor-Frempong and Akaba, 2020) points to the willingness of farmers growing the same crop on adjacent areas to share unmanned areal systems (UAS)-based advisory services.

FAO also recently published an overview of progress and adoption of digital agriculture in its own projects in Sub-Saharan Africa (FAO, 2024). Forty-two percent out of 72 projects were largely or predominantly digital, East Africa being in the lead. The most represented digital technologies are the relatively simpler ones such as mobile applications or SMS or interactive voice response (IVR) services. Mostly used solutions in many countries include the Fall Armyworm Monitoring and Early Warning System (FAMEWS), the Event Mobile Application (EMA-I) for livestock management, eLocust3m App to fight desert locus, the Digital Service Portfolio, the Identification, Delivery and Empowerment Application (IDEA). National successful digital platforms built by FAO include Integrated Agriculture Management Information Systems in Zambia and Kenya (ZIAMIS; KIAMIS).

The African Union has a digital transformation strategy 2020-2030, with a chapter on digital agriculture with rather general recommendations (38507-doc-dts-english.pdf (au.int)). African Development Bank (AfDB) has done reviews on the State of Digital Agriculture in several countries. The example for Côte d'Ivoire speaks of input, production, distribution hubs, which provide a picture of where the country stands on digital transformation (Digital Agriculture Profile - Côte d'Ivoire | African Development Bank Group (afdb.org)). Another initiative aimed at promoting the use of Digital Agriculture technologies in Africa is the African Agricultural Technology Foundation's Digital Agriculture Services project (HOME - AATF (aatf-africa.org)). Next, there is also the Soil Initiative for Africa at the level of the Pan-African Forum for Agricultural Research aiming at coherence, coordination and borrowing leaves from successful members - Soil Initiative for Africa - FARA Africa.

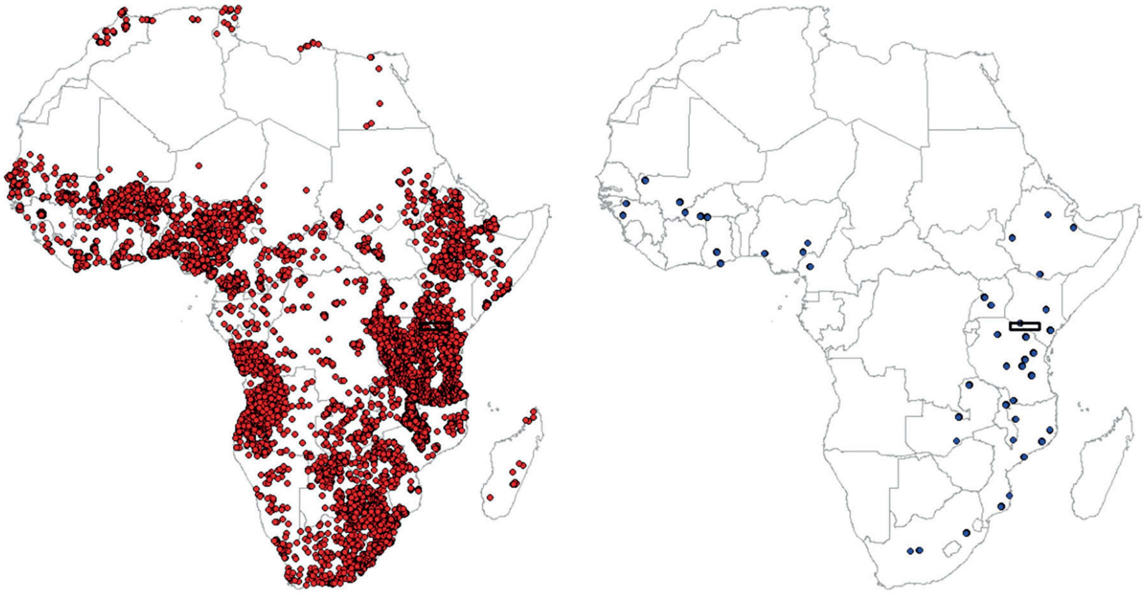
The WaPOR database (FAO) offers a comprehensive collection of data related to water productivity across various regions. This database provides users with access to extensive information derived from RS. Users can utilize the WAPOR database to access spatial data layers related to land and water use for agricultural purposes. The aim of the WaPOR portal is to assist countries in monitoring water productivity, identifying water productivity gaps, proposing solutions to reduce these gaps and contributing to a sustainable increase of agricultural production.

Other initiatives, projects and facilities related to data & technology for digital advisory services include the Google Earth engine, FAO's Hand-in-Hand initiative, the SEPAL platform, the CGIAR Platform for Big Data, and Digital Earth Africa.

Projects with SDDT applications for soil health advisory services in Africa

A key initiative in Africa towards digital soil mapping and creating building blocks for soil health advisory services has been the African Soil Information Service AfSIS, technically and scientifically described by Vagen et al. (2010) and Hengl et al. (2015) respectively, and run as a consortium with large inputs by ISRIC — World Soil Information. AfSIS is visualized at Soil property maps of Africa at 250 m resolution (isric.org). Over the period 2008–2014, the AfSIS project has compiled the Africa Soil Profiles database holding legacy soil profile data and a Sentinel Sites database holding newly collected data. They jointly consist of 28 thousand sampling locations (Figure 4).

Figure 4. *Legacy soil profile data (left) and Sentinel-trained new soil data clusters (right)*



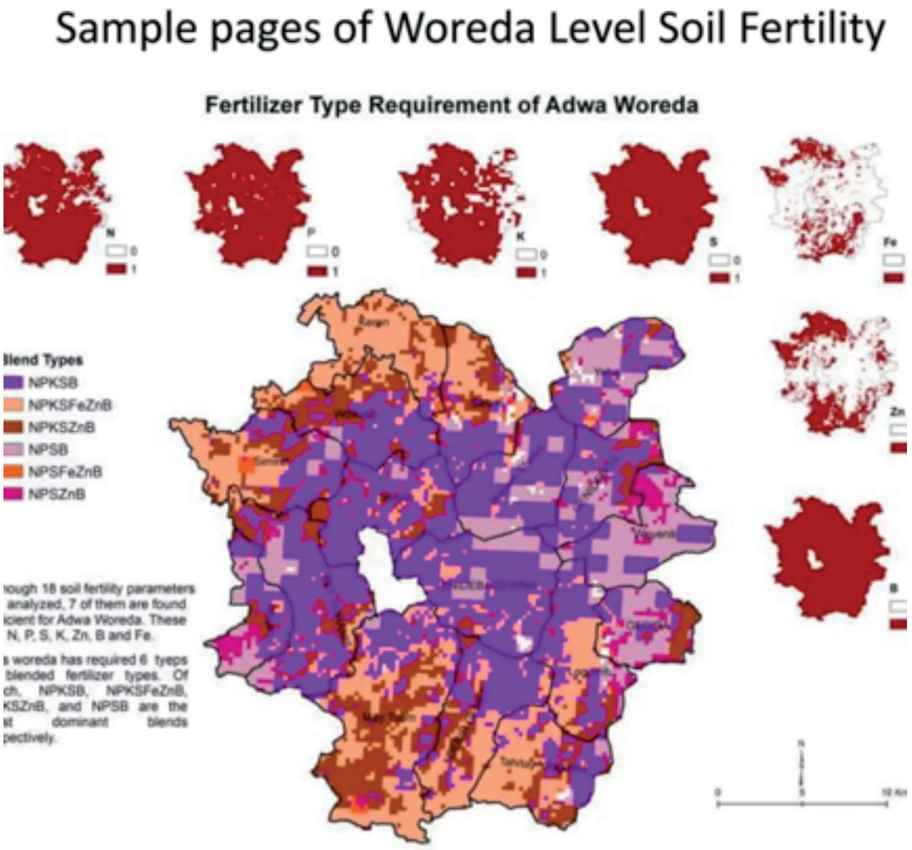
Using these soil point observations and measurements and an extensive collection of global ([SoilGrids — global gridded soil information | ISRIC]) and continental (African) environmental covariates, predictions were made of soil property values for the whole African continent at 250 m spatial resolution at either two or six standard soil depths. The predictions are obtained using an automated machine learning-supported mapping framework (3D regression-kriging based on random forests). ISRIC in 2017 then ventured into open access of a new generation of African Soil Property Maps at 1 km^2 resolution: https://www.isric.org/projects/africa-soil-profiles-database-afsp/newgeneration.

AfSIS can be used for soil environmental modelling, land use planning and land degradation studies, but it is also a basis for the assessment of total carbon stock for the African continent and further planning of soil surveys and applications.

As soil data sets kept increasing, Hengl et al. (2021) then published the production of a 30 m resolution Soil Information System of the African continent using the most comprehensive compilation of soil samples (N ≈ 150, 000) and Earth Observation data in *Nature*. It allowed predictions of many soil properties at several soil depths, helped by a 2-scale 3D Ensemble Machine Learning framework implemented in the Machine Learning in R (mlr) package. It should be noted though that machine learning can also yield results that are meaningless when covariates are not suitable to explain relevant differences. Hengl et al. (2017) for example reported a major Africa-level machine learning-supported exercise that showed that Mn, Zn, Al, B and Na appeared as the most important nutrients for predicting crop yield. This is not supported at all by field trials, and makes no sense from a plant nutrition viewpoint either.

An example of a country-specific application of AfSIS in Ethiopia, and a translation of the digital soil maps into district-level soil fertility and fertilizer recommendation maps is Ethiosis (EthioSIS | ATA). The approach largely follows AfSIS, but went as far as studying and mapping deficiencies of soil nutrients such as S, B, and Zn. Consequently, fertilizer blends (supported by new blending factories) were tailored to the observed deficiencies indicated on the district maps (Figure 5).

Figure 5. *Fertilizer recommendation maps at district level in Ethiopia, based on digital soil mapping*



ough 18 soil fertility parameters analyzed, 7 of them are found icient for Adwa Woreda. These N, P, S, K, Zn, B and Fe.

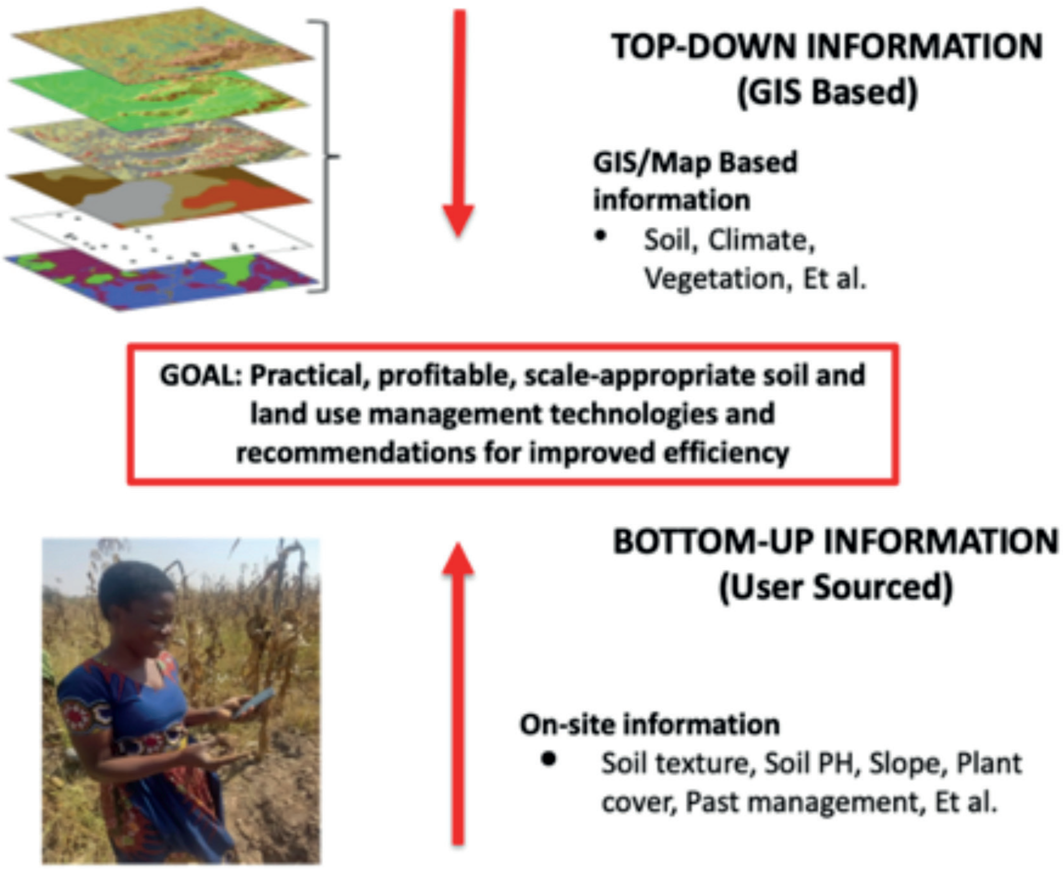
s woreda has required 6 tyeps blended fertilizer types. Of ch, NPKSB, NPKSFeZnB, KSZnB, and NPSB are the st dominant blends pectively.

These NPSZnB blends even pushed common fertilizers such as DAP from the market. On the one hand, this is a very practical way to make soil health advisories concrete at the district and agro-dealer level, and through the large extension service in Ethiopia, also to farmers. On the other hand, the fertilizer recommendations are insufficiently based on crop responses to the nutrients in the blend, which is mainly due to the choice to call a nutrient 'deficient' below a rather arbitrary threshold and then decide that it should be part of the blend fertilizer.

Crop models such as QUEFTS as described in Chapter 4 are needed here as an in-between validation, showing the relationship between soil properties, actual nutrient supply and uptake and crop yield. The Ethiosis approach does not take the supply-uptake-yield suite into consideration. In principle though, the SDDT supported approach in Ethiosis is a big step ahead in making soil heath-advisories area-specific and attractive to customers. The remaining step is to involve farmers through experimentation and demonstration, in what is now commonly known as Citizen Science (Rossiter et al., 2015).

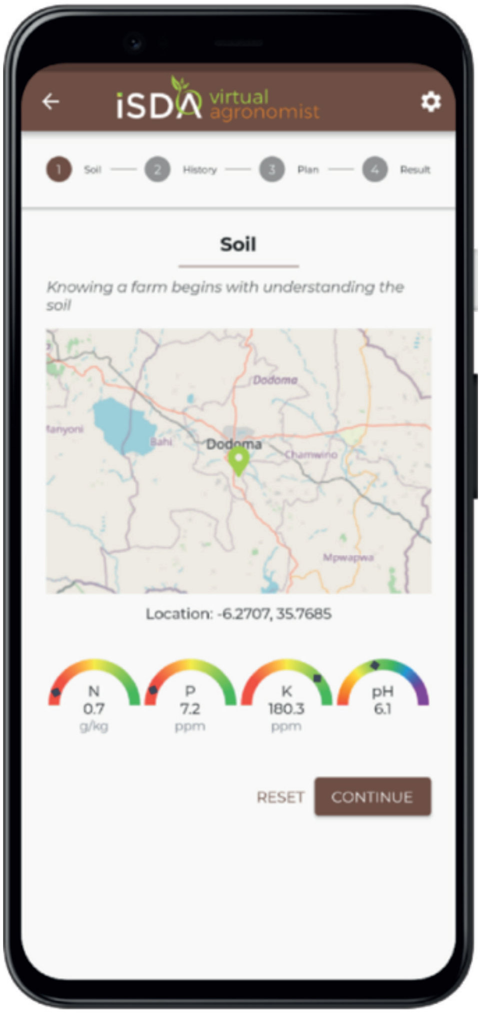
The USAID funded SOILS-Space to Place - IFDC (2023-2025) attempts to make site-specific fertilizer recommendations in eight African countries. The top-down GIS-based geospatial data sets are matched with user-sourced local land use information (Figure 6). The focus is on increasing the efficiency of fertilizer use, i.e., to increase production per unit applied fertilizer nutrient. This will increase the return on investment in fertilizer. The approach is also hyper-localized, aiming at giving rather precise advisory services at farm level, by using a decision support tool currently under development. It has government, private sector, and NGO involvement and targets the entire value chain.

Figure 6. *Space to Place project philosophy*



The ICRAF spin-off iSDA (isda-africa.com) built the first field-level soil map for Africa, with 20+ soil properties estimated at 30m resolution for the entire continent. This open resource is used globally by researchers, startups, agribusiness and governments to produce advisory and analysis. iSDA developed the 'Virtual Agronomist' (Figure 7) allowing extension services and farmers to communicate and receive tailored advice (call center function). It is based on soil nutrient status, local knowledge of yields, farm history, forecasts, economics and the best scientific knowledge of the crop and region.

Figure 7. *Virtual Agronomist app of iSDA*



Soil

Knowing a farm begins with understanding the soil

Location: -6.2707, 35.7685

Kenya Agricultural and Livestock Research Organization (KARLO) (https://www.kalro.org/) has developed a digital agriculture platform that integrates satellite data, weather information, and agronomic models to provide tailored recommendations to farmers in Kenya. The platform offers insights into soil health indicators, such as moisture levels, nutrient availability, and erosion risk, enabling farmers to make data-driven decisions about soil management practices. By leveraging digital tools and satellite data, KALRO's platform aims to improve soil health, enhance agricultural productivity, and promote sustainable farming practices among small-scale farmers in Kenya.

There are more projects in Africa entirely devoted to ISFM, also using RS and crop modelling, e.g., cocoa in West Africa (Overview – CocoaSoils). CABI also invested in a Fertilizer Optimization Tool and hosts the Africa Soil Health Consortium (Home | Cabi ASHC), focusing on ISFM campaigns in rural areas. CABI also published an important overview per country on Fertilizer Use Optimization and ISFM in Sub-Saharan Africa, giving entry points for advisory services (Wortmann and Sones, 2017).

Many more tools and apps have been developed, such as the Soil Quality Analysis Tool - SQAT – Laboratory In The Field), and the open-source multistakeholder landscape technology platform (Terraso | Supporting locally-led landscape collaborations), but it is hard to link them to potential success in a smallholder context in Africa, in terms of sustainable soil health improvements, sustainable yield increases, scaling successes, and improved livelihoods.

Two recent developments related to ISFM and soil health are worth mentioning. Next to the FSRP and Soil Values programs, the ECOWAS-led Regional Soil Fertility Hub was launched during the 2024 Africa Fertilizer Summit (Box 4). This Hub is an excellent virtual venue to foster use of SDDT in soil health advisory services. Also, a new EU- Horizon research and development program on the Assessment of Soil Health in Africa has been launched, singling out improved advisory services for farmers in Africa (Box 5).

Box 4. *Regional Hub for Fertilizer and Soil Health in West Africa*

Regional Hub for Fertilizer and Soil Health in West Africa

Agriculture in Africa is at a critical point, where the condition of the soil is essential for its succes. The key to sustainable agriculture and food security lies in the good health of the soil. Unfortunately, the region has been struggling with a vicious cycle of soil health decline, land degradation, poor yields, and loss of ecosystem services, wich has led to poverty and region, a Regional Hub for Fertilizer and Soil Health is proposed. It includes the Economic Community of West African States (ECOWAS), the International Institute of Tropical Agriculture (IITA), OCP Africa, The African Plant Nutrition Institute (APNI), the University Mohammed VI Polutechnic (UM6P), the International Fertillizer Development Centre (IFDC), and the World Bank. The proposal's specific objectives are aligned with the Priority Actions and Sub-actions outlined to be a catalyst for transformative change, based on a multi-faceted strategy that focuses on soil health improvement, sustainable fertilizer use, and climate change adaption practices. It aims to comprehensively address critical challenges by disseminating information, managing knowledge, providing agronomic recommendations, developing capacity, supperting policies, advocating for awareness, and mobilizing collective recources.

Launced during World Fertilizer Summit May 2024 - https://www.cgiar.org/news-events/news/eia-to-launch-fertilizer-and-soil-health-hub-for-west-africa-and-the-sahel-at-africa-fertilizer-summit/

Box 5. *Soil Health in Africa - Horizon research program of European Union*

HORIZON-MISS-2024-SOIL-01-09 assessment of soil health in africa (7MEuro) wp-12-missionshorizon 2023-2024 en pdf (europe.eu) page 294 +

Project results are expected to contribute to all of the following outcomes:

- Enhanced and accessible data for policy makers and intergovernmental organisations to inform a continental 'convergence of evidence' map that indicates areas in Africa that are likely to be affected by soil degradation processes (as has been implemented for Europe with the EUSO Soil Health Dashboard).
- Enhanced access to knowledge that can be used by a wide range of stakeholders to inform soil and land management policies and practices, prioritize areas for intervention and research and development, and support improved advisory services for farmers in Africa.
- Improved datasets are available on soil threats/properties which will contribute to the development of an interactive Soil Health Dashboard for Africa.

Including links to:
Home | Soils 4 Afrika - Horizon 2020 programme of the European Union (https://www.soils4africa-h2020.eu/)

Soil health advisory services in G4AW projects and by G4AW partners

Within G4AW, development of STTD for soil health advisory services received ample attention. The level of prominence of this component, however, differed among projects according to the specific foci the projects had. Out of the 25 projects (14 in Africa and 11 in Asia), around 50% had a medium or high relevance for soil health.

For a number of projects, soil fertility advise was hardly or just indirectly relevant as they were mainly addressing pastoralism, weather forecasting, crop protection, or issues related to insurance and credit (SUM-Africa; CommonSense; STAMP, MODHEM; GEOPOTATO – the latter having a good by-catch on fertilizer use efficiency).

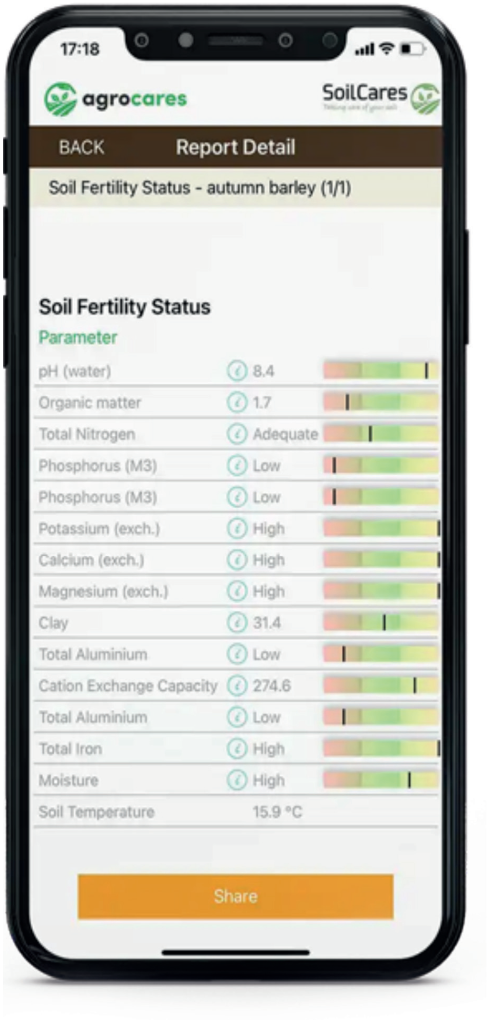
Some projects used FAO data or ISRIC SoilGrids which are too coarse for advise to small-scale farmers (G4INDO, GEOBIS). In others, NDVI and SOC were employed as proxy indicators of soil fertility, which worked well (GIACIS, GEODATICS, SAM Myanmar, MYVAS4AGRI). In many projects, information, optimization and advisory tools for soil fertilizer management were built: FOT in MUIIS; CaddyFish in SAT4Business, SAT4Farming Field Development Plans through aggregators; SpiceUp pepper advise; GEODATICS advanced fertilizer recommendation tool; CROPMON and MYVAS4AGRI SoilCares scanners and recommendation tool; GAP4A Burundi AgriCoach; AngkorSalad available vs required nutrients tool. MavoDiami worked with Voicebots.

As opposed to the African projects, the Asian projects had a more standardized bundled approach, addressing several yield-determining factors at the same time, and were met with higher smartphone density, more irrigated/rice-based or other high value crop-based production systems, targeted to more efficient and often also lower fertilizer use. Soil fertility management tools and look-up tables were largely based on traditional approaches though. The Asian projects also had a stronger early warning/real time component in the fertilizer advisory approach than the African projects (Sat4Rice; IDSS; R4A; SAM Myanmar; SpiceUp; Angkor Salad).

In conclusion, many projects reached a certain stage in the development of simple analogous or more advanced SDDT tools to assess soil health and how to improve it, but from the end-of-project reports, little evidence is obtained as yet that products and services were developed that found a determined (convinced) buyer group, rendering the advisory service fit for the commercial market. Those getting closest represent a Business-to-Business (B2B) rather than a Business-to-Customer (B2C) model, with hybrid finance structures.

Meanwhile, there is a plethora of smaller and larger companies and NGOs providing relevant geospatial and other data collection, management and infrastructure support, allowing rapid scaling up of proven approaches towards profitable agricultural advisories. Below are some that were involved in one or more G4AW projects.

Figure 8. *Agrocares / SoilCares soil fertility status app*



Soil Fertility Status - autumn barley (1/1)

Soil Fertility Status

Parameter	
pH (water)	8.4
Organic matter	1.7
Total Nitrogen	Adequate
Phosphorus (M3)	Low
Phosphorus (M3)	Low
Potassium (exch.)	High
Calcium (exch.)	High
Magnesium (exch.)	High
Clay	31.4
Total Aluminium	Low
Cation Exchange Capacity	274.6
Total Aluminium	Low
Total Iron	High
Moisture	High
Soil Temperature	15.9 °C

The company Home | AgroCares advertises with the slogan 'Precision farming based on real-time nutrient intelligence', also showing its desire to deliver advisory services at farm level. It has developed several Nutrient Scanners and delivers on-the-spot insight into soil fertility by translating spectral features into soil health assessments (Figure 8). They are smartphone-based and rely on a big data environment.

A local company using and spreading SDDT is Ghana-based Esoko (About Us – Esoko). SDDT and services were developed for farmers, agribusinesses and development organizations. It provides services like weather forecasts, agronomic advice, market linkages and insurance coverage over a range of channels including SMS and a call centre. Being rooted locally, Esoko is aware of challenges faced by data collectors in the field – ranging from agent non-performance, to bad data to logistics problems.

Esoko was also involved in the early geodata-supported value chain research on tomatoes travelling from Burkina Faso to markets in Ghana (Venus et al., 2008). This work, with the University of Twente and Ramani by Ujuizi Laboratories, The Netherlands has now developed into the crowdsourcing app Cheetah (ujuizi.com).

Other G4AW partners in The Netherlands are less soil health-driven but have expertise that is most useful. Weather Impact Weather Impact | Experts on Weather, Serious about Impact is successful in rolling out Chatbots in Tanzanian agricultural communities, and combines this with citizen science, expressed in farmers taking rainfall data and measuring soil moisture. eLEAF is specialized in linking water management with insurance, which is of high importance in irrigated and wetland agriculture.

Upscaling

Scaling can be defined in many ways but is basically the process of expanding beneficial practices over geographies and across organizations to impact larger numbers of people. Scaling has many dimensions. GIZ developed an interesting Toolkit for scaling - GIZ-Toolkit-for-Scaling-Digital-Innovation-19032024.pdf (bmz-digital.global). Four levels of scaling are recognized here:

- Scaling vertically / scaling up: changing the institutional environment to achieve greater impact
- Scaling horizontally / scaling out: expanding impact through replication and adoption in large geographies and populations
- Scaling functionally: expanding/adopting the functional scope of an innovation for greater impact
- Scaling deep: increasing impact of solutions by changing relationships, cultural values and beliefs, hearts and minds.

For commercial advisory services to be scaled, buyers have to be pulled towards the product. If investors see a market-product fit, they may be convinced of an increasing turnover, improving profit-margin, or strengthen loyalty. The impact a product can make on sustainable development (linked to SDGs) is also increasingly also taken into account when investing in products and services (impact investors).

In a broader sense on digital advisory services, scaling requires cross-industry collaboration, training algorithms with sufficient ground-truth data, and a clearly defined value proposition for end users with trusted, actionable insights. This relates to more outcome-oriented scaling as a third wave of understanding and guiding scaling, beyond technology adoption (first wave) and the scaling of innovation (second wave) (Schut et al., 2020). It involves rural radio to spread the message conventionally, but also eBay type of advertising and marketing of products, and (particularly for young entrepreneurs) clever use of social media, artificial intelligence and mobilizing influencers. Of particular importance is the consideration of designing a good sales funnel while identifying tools that fit each of the elements of a marketing and sales process in the continuum of awareness creation-interest isolation-decision-consideration and eventually action taking (AIDA).

Geoinformation derived from satellites is particularly (horizontally) scalable, both in a spatial and temporal way (historic datasets, regular overpass). The AfSIS approach, for example, allows Sentinel-1 to do an ever better job on recognizing SOC levels (Figure 3).

Scaling is also helped by working at the landscape/community level from the start, the G50 approach by AUXFIN in GAP4A Burundi being a case in point. Not only is ‘landscape’ already a dimension above ‘farm’, but it also levels out spatial heterogeneity because of using averages, and it makes application of remotely sensed information and digital soil maps more more feasible and attainable.

In a machine learning and big data environment, large datasets are needed to train sensors. A ‘landscape’ then is therefore from a feasibility stand-point a better start than at the farm of field-plot level managed by a risk-averse farmer growing many crops and observing deliberate soil heterogeneity. It also means that an R&D approach of spending five years in two villages is not the way to go as there will be no scaling effect. Technology development must therefore consider more robust algorithms derived from the available huge datasets in the continent to predict what happens on the next meter of soil using artificial intelligence, machine learning and prediction modelling. We may not be there as yet.

Apart from that, spoiling the two villages may cause envy in surrounding villages, causing more harm than good. Project durations (commonly < 4 years) are not very helpful when it comes to scaling, as there needs to be a high-quality proof of concept before an advisory service can and should be properly scaled. In G4AW this was the case for GEODATICS.

At a more general and African/national level, upscaling projects and practices that integrate SDDT for soil health improvement in Africa require the following strategies to be translated into concrete digital transformation programs:

- **Capacity Building**: Provide training and support to (male and female, young and old) farmers, extension workers, and other stakeholders on the use of SDDT for soil health monitoring and management.
- **Infrastructure Development**: Invest in the development of data infrastructure, including satellite data processing facilities, digital platforms, and communication networks, to facilitate widespread access to SDDT.
- **Policy Support**: Implement policies that promote the adoption of SDDT in agriculture, such as incentives for technology adoption, funding for research and development, and integration of SDDT into agricultural extension services.
- **Partnership and Collaboration**: Foster collaboration between governments, research institutions, private sector entities, and civil society organizations to leverage expertise, resources, and networks for scaling up SDDT-based soil health initiatives.

By employing these strategies and building upon successful projects and practices, it is possible to upscale the integration of SDDT for soil health improvement in Africa, ultimately leading to more sustainable and productive agricultural systems.

▼ *G4AW project Geodatics*

6. Challenges and limitations to adoption and upscaling

The technology is developing rapidly and holds promise, also for smallholder farmers in Sub-Saharan Africa. But at this point in time, both the G4AW projects and other programmes and activities reviewed and mentioned mention similar challenges to adoption of advisory services (in general and for soil health). Some challenges and opportunities, as singled out in the CTA report (The Digitalisation of African Agriculture Report 2018-2019 (cgiar.org)) include:

1. **Pace of Technology vs. User Readiness:**
    - Technology in digital agriculture is advancing rapidly, often outpacing the readiness of entrepreneurs, users, and government actors to fully embrace and leverage these solutions.
    - This gap is evident as many companies are still in the process of developing viable business models to sustain and scale their digital innovations.
2. **Enabling Environment:**
    - The enabling environment for digital agriculture is not yet fully developed. This includes the lack of essential digital infrastructure, such as farmer registries, digital agronomy data, soil mapping, pest and disease surveillance, and weather data infrastructure.
    - These deficiencies significantly reduce the effectiveness and potential impact of digital solutions in agriculture.
3. **Country-Level Leadership and Variation:**
    - There is significant country-level and regional variation in the investment and adoption of digital agriculture solutions.
    - Some countries are leading the way with market-driven growth in D4Ag solutions, serving as strong examples and sources of inspiration for others.
    - Notable leaders in this space include Kenya, Ghana, Nigeria, Senegal, Rwanda, and Côte d'Ivoire, which have shown considerable progress and innovation in digital agriculture.

Suppliers of technology

A major constraint relating to RS and its interpretation is cloud coverage. Clouds severely reduce the usage of optical data. This problem however does not affect SAR data (Sentinel-1) because the signal used by their sensor can penetrate through clouds. A solution is to develop a multisource approach by integrating RS data from different sensors to maximize the change of cloud free pixels at a given date. Another related challenge is the quantity and quality of in situ measurements. For the development of a precise and robust model, sufficient and consistent information across the region of interest is required, which is often not (yet) the case in Africa, something also hampering full use of AfSIS.

Other technical challenges include insufficient capacity and infrastructure to store and process huge RS datasets (e.g., at petabyte-scale), poor internet connectivity and bandwidth to access remotely sensed data platforms (i.e., USGS Landsat data), and a limited number of highly trained qualified individuals in RS. Another constraint for most of the African countries is the lack of computing power, infrastructure, and cloud computing that facilitate access to the powerful processing facilities of the Google Earth Engine platform (Khechba et al., 2021).

Digital soil health monitoring has the potential to revolutionize agriculture and improve sustainable land management practices. However, it also comes with its own set of challenges. Some of the key challenges are listed in a review paper on unveiling the potential of soil health monitoring by Adak et al., (2023), and include :

(i) Data quality and standardization - Standardizing data collection methods, equipment, and lab analyses is vital for accurate and consistent soil health monitoring, minimizing errors and ensuring reliable information;

(ii) Data volume and management - Monitoring soil health digitally yields extensive data on physical, chemical, and biological soil properties. Handling and analyzing this data demand robust tools, infrastructure, and expertise (Liakos and Panagos, 2022);

(iii) Cost and accessibility - Affordable and accessible digital soil health monitoring systems are essential for widespread adoption, as their initial costs and ongoing maintenance can hinder small-scale farmers and resource-constrained regions;

(iv) Sensor accuracy and calibration - Accurate soil health sensors require proper calibration and validation due to factors like sensor drift, environmental variations, and soil differences, ensuring reliable data (Fan et al., 2022);

(v) Analyzing digital soil health data with physical, chemical, and biological aspects demands advanced analytics to uncover valuable insights and inform decision-making due to its complexity;

(vi) Training farmers, agronomists, and land managers in soil health monitoring is crucial - It requires skilled individuals to operate systems, gather data, and communicate results effectively.

Receivers of technology

Digital solutions for soil health improvement also need to be brought closer to the user. CABI recognizes the rapid development and spreading of Soil Information Systems in Africa, but expressed worries on data utility (Soil Information Systems Review: a process toward strengthening national soil information systems - CABI.org). Currently, it works with partners to see how the information systems can be made more responsive to local demand. This addresses data quality, data standards, data security and privacy, data sharing and access, governance, data literacy, trust and benefits, policy and technical infrastructure.

It is obvious that the socio-economic context determines adoption and success of digital agriculture. Marketing should be done through channels that are used by the target audience. This can be tv, radio, mouth-to-mouth, social media or others. It is key that the marketing and service delivery approach takes into account the differences in access by gender and age, to ensure digital inclusiveness. Quantity vs. quality is an important trade-off in service delivery. Mass-media such as websites, tv and radio can easily reach large numbers, but are channels for awareness raising rather than facilitating interactions and decision making. Mobile phones are the most used technology in service delivery: depending on the type of service, a lot can be through mobile-apps, SMS messages, voice messages or by calling call centres. Chatbots are also increasingly becoming handier and more meaningful for specific purposes. Social media platforms can combine the benefits of reaching large numbers with the location-specific information provided through apps.

Charging for a service is relatively easy when using mobile phones. The downside is that farmers might be hesitant to pay for individual services. This is the reason why many of the created services have been integrated into existing products: existing marketing and service delivery approaches can be used that are familiar to the farmers. Bundling of services can provide the target group with more flexibility to select the services they require and are willing to pay for. In order to bundle services, the service delivery method should facilitate this additional complexity. Apps and dashboards on smartphones/tables provide a better technological framework for bundling than mobile phones. An app like WhatsApp that is easily installed and used in information, data and pictures sharing that is dedicated to soil health and other exchanges maybe the solution.

Packing and promoting soils information should be built around the farmers most immediate needs and made understood for meaning and application. AI and machine learning could be used for this purpose. Bundling theory also needs to be taken from the marketing literature to the smallholder context and the consumer specific needs and wants. In a study in Ethiopia, product bundling enhanced preferences of smallholders and intentions to adopt technologies (Tamira Amanu Abetu et al., 2024).

Bringing supplier and receiver closer

It appears that challenges and limitations in the spreading of soil health advisory services can be attributed to the technology side alone (as it is in a state of development, not yet fully operational, not precise enough, not fitting national infrastructure), to the customer side alone (lack of knowledge, no internet connection, risk-averse attitude, reluctance to pay), but also to the lack of interconnectedness between supplier and receiver, between seller and buyer. Table 3 shows which features need to be taken into account to be a successful seller (column 1) or an interested buyer (column 3), but it is argued that the institutional infrastructure (column 2) is of paramount importance to bring seller and buyer closer together.

Specific challenges for soil health advisories

Prolonged dry spells or excessive rainfall and major diseases or pest infestations can wipe out entire crops. In ecosystems theory this is a 'shock' as opposed to low and declining soil fertility, which is regarded as a 'stress'. Therefore, soil health advisories or as components of broader bundled advisories have different characteristics than the others. They are listed below:

What are production goals and how much fertilizer goes with that?
Since fertilizers come at a cost, farmers have a production level in mind. Based on that, they decide on their ISFM strategies, which can range between almost absent to making many soil health-improving efforts, including procurement of fertilizer. For irrigated systems and high-value crops and in commercial plantation or clustered agriculture, the latter is more likely to happen. Decisions on fertilizer use are generally taken prior to planting and not affected much by real-time considerations during the growing season.

The drivers for the decision making are influenced by proven fertilizer types, rates and their applications regimes that correspond as much as possible to the expected crop produce.

Is the fertilizer available in the market at the right time, at the last mile?
Not every fertilizer is available in the quantities desired, at the time needed, and at the most nearby agro-dealer shop. This makes real-time fertilizer-based interventions unlikely. Farmers also fear poor fertilizer quality from local blending plants, or from untrustworthy importers. Many of the fertilizer blends available to the farmers do not match their labelled performance and therefore many times end up demoralizing the farmer.

Apart from topdressing, no need for alerts during the growing season.
Topdressing by N-containing fertilizers after plants have reached knee-height is a well-known way of increasing the efficiency due to the establishment of a plant root system. The timing of topdressing can be alert-based and coincide with light rains. Advices on, for example, placement are more common in drip irrigation systems where water supply is based on human decision-making. One common additional top-dressing omission occurs just before the crop starts fruiting or grain filling five or seven weeks after planting this missing top-dressing results to depressed yields during harvest.

Repeat advisories serve different purposes.
Occurrence of unpredictable weather and pests and diseases may differ from year to year and season to season hence requiring early warning alerts every time. Soil fertility only changes gradually, so an advisory service that worked well in year 1 does not add a lot of added value in year 2. Soil fertility decline or build-up and changes in pH occur through several years and depending on the intensity and regularity of the harvests. The soil conditions persist for a good period of time and therefore soils tests may not be required every year. This also holds for second years/seasons where unfertilized crops could benefit from the fertilizers applied to the crop in the previous year (residual effect). This is particularly relevant for phosphorus.

Attribution issues
Field inspection helps to 'groundtruth' advisory services supported by satellite data. When this is based on NDVI, it is however not immediately clear if differences observed are due to shortage of rain, pest infestation or lack of nitrogen in leaves. This implies that a good analysis and interpretation of the satellite data is required and matched with the groundtruth situation before it is recommended for adoption as fit for purpose.

Soil test values in models supporting advisory services
Unlike weather and crop protection, soil health-based advisory services often rely on models that build on soil property values. These are obtained after field sampling and values are derived from wet chemistry or from spectrometry. (Composite) soil sampling for wet analysis gives a wide range of results due to sampling and analytical errors. Uncertainty within and between laboratories is such that site-specific recommendations may promise more accuracy than can realistically be expected (Schut and Giller, 2020). Also, it has been found that efficiency gains from tailored advice will prove to be minor compared to those obtained from general agronomic improvements in fertilizer placement or timing (Van Heerwaarden, 2022).

Models such as QUEFTS (Janssen et al., 1990) are deployed to translate soil property values into yield ranges. Without experimentation though, such (partly) empirical models need calibration for each location under study). QUEFTS also uses a 0-20cm standard soil depth from which to sample, but differences in rooting depth have a large bearing on production potential too (Leenaars et al. 2018). Plant analysis aiming at optimal yield/uptake ratios could help, but is surprisingly uncommon. Meanwhile, machine learning plays an increasing role in a big data environment, as it 'chooses' its own relevant covariates that explain production differences. Machine-learning based approaches and algorithms on digital soil maps at 30m resolution have come into the picture, but have still met large uncertainties (Hengl et al., 2017, 2021).

7. Road map to effective soil health advisory services in Sub-Saharan Africa

A clearcut *road map* to tackling the challenges to adoption discussed in Chapter 6 may be a bridge too far, as each situation where SDDT could be applied is unique. However, a step-wise approach could be used, including an ex-ante assessment of likely success before venturing into further investment. This could be leading the way for initiatives under the umbrella of the three major programs currently underway in West Africa. As Step 1, spelled out below, it is suggested to develop a generic prerequisite listing that provides a picture of the likelihood of success of SDDT initiatives supporting soil health. Step 2 could be a further detailed, customized assessment and ranking of the prerequisite list, including ways to positively influence prerequisites that are not met in the pre-investment situation. That could lead to a go-no or go moment. Step 3 would then be the testing of STTD for soil health in the field along the suggested criteria of the prerequisites, up to the level of advisory services that are packaged with an inbuilt business model.

The above prescriptive approach does not mean local innovation should be neglected. Many well-adapted local tools can do a great job too. At the same time though, many start-ups are active in this field and many apps and other tools are continuously being developed. However, many are short-lived or do not provide the promised results. This can be a blow to communities targeted for SDDT-supported advisory services, and getting them on board again after a disappointment may be a challenge, particularly if they are asked again to be available for long interviews and participatory activities without a clear benefit looming. Therefore, the below prerequisite listing can be a useful guideline for preparing and developing any investment adequately, while at the same time addressing the three columns of Table 3 in a balanced way.

Prerequisite list

Institutional prerequisites

There should be a *license to operate*, made up of:

- Digitization of agriculture and improvement of soil health is reflected in written national policies and is implemented in concrete and financed programs
- National data infrastructure, including the definition of technical and legal interoperability and other standards is present and functional: Call centre / Mobile Platform / Information system / Effective extension system
- Countries are ranked according to the degree of facilitation of SDDT

Financial / business case prerequisites

There should be a clear *business case* for advisory services, modified by:

- Market potential for agricultural produce is known based on up-to-date input-output market and price information, value chain functioning, and includes indirect revenue models and where possible forward contracts are in place before placing the seeds into the soil.
- Inclusive finance is known and applied, i.e., farm risk models and management tools are in place and tested, crop insurance (spearheaded by input providers) combined with access to credit being a leading mechanism. Insurance instruments should be more robust and also take into account the soil health risks of farming. Otherwise, early mitigation interventions should be integrated such as fertigation as well as soil productivity improvement resources such as additional and sufficient quantities of organic matter. The supply and distribution networks also need to be mapped with market certainty for ease of production estimations and supply.
- Buyer groups of advisory services are preferably broad and hybrid involving different customer groups, made up of commercial and public parties and farmers / cooperative structures and targeting different financiers, hence B2B, rather than B2C (brokering); the exception is higher-end commercial farms requiring customized precision agriculture support. The B2B models should ensure that they manage and tamper the consume prices and hence ensuring affordability of the specific farm produce.
- Initial investment financiers are key in overcoming the ‘valley of death’ when local farmers lack the cash flow to get investments going by their own means, on the premise that the post-investment situation is deemed sufficiently sustainable as to the use of advisory services. Agencies should bridge this interface where they aggregate, supply to the market and give to the farmer what is theirs while taking in their commissions that are based on robust pricing model and hence ensuring sustainability of the value chain.
- To provide more return on investment, the advisory services go beyond just soil health improvement and fertilizer recommendations, and also include weather/crop protection and market information/ insurance (bundling)
- Taking SOC as a key soil property for soil health advisory services may allow linking up with ongoing financed initiatives on (above and below-ground) carbon sequestration in the climate change mitigation context (borrowing leaves).

Production system prerequisites

The area under consideration for development and adoption of advisory services needs *physical and social mapping and database development.*

- A detailed relevant dataset is available for the area under scrutiny and consideration: land, farm and field sizes, types and ownership (preferably on cadastral or clearly defined though on an informal basis), digital elevation models, soil (organic carbon) maps and spatial variation of soil properties, farming/cropping/livestock systems, yield gaps, net farm income, etc.
- The above should (at least initially) cover the spatial levels 'landscape/district' and 'community' rather than individual field-plots, farm or farmer; the G50 community approach in GAP4A Burundi may serve as an example (AUXFIN › News); soil properties show large spatial heterogeneity, which is levelled off though at the landscape level when mixed samples from larger areas are used as the 'average' and basis for advisory services. Downscaling to farm level can then follow to trace deliberate farm heterogeneity management patterns (integrated approach).

Community prerequisites

Approaches for development of advisory services should be entirely be *user-centred* and include *citizen science.*

- Coalitions of stakeholders (government, private sector, lead farmers and cooperatives, service providers, start-up innovators, local influencers, R&D) with a sound level of mutual trust exist or are identified, and ready to work in a mindset of innovation, co-creation, demonstration, and digital transformation, under the banner of citizen science.
- Digital literacy, smartphone penetration in rural areas, and both gender- and a generation-specific approach in communication (e.g., rural radio vs. social media / startups) are in place; specific agenda for promoting agricultural digitalization and automation among young people should be prioritized in government policies and investments; data ecosystem should be community-driven up to the level of Chatbots (as done by Better data, bigger impact | Akvo Foundation in G4AW).

Technology prerequisites

Any advisory service product advocated should be *technically and scientifically sound and transparent and easy-to-use,* but this does not mean it has to be highly sophisticated.

- The sensor, crop and soil data, models and machine learning approaches underlying the advisory services should be transparent and provide recommendations on management of soil health and fertilizer use that are accurate and profitable to the buyer. SOC seems a plausible point of departure to build soil health features in advisory services. There is a market developing for precision and real-time soil health advisory services at the commercial level, but for smallholder farming, trying to be too precise at the level of a farm or a pixel may backfire when gaps between advice and reality are too large. Advises are better targeted to landscape level, using 'recommendation windows' where a range of N P fertilizer use or other ISFM options are linked with a range of to-be-expected crop yield increases (Eyasu et al., 2023). Substandard and technically unsustainable services cause aggregators to lose business as customers back off, and it may not be easy to get their buy-in again.

8. Conclusions and Recommendations

Outlook of soil fertility management in Africa

Most of Africa has old soils whose fertility is declining. Most increases in agricultural production have been realized from opening up new land, rather than by increasing productivity through better soil fertility management. Low investment levels, challenges on labor and agricultural education, insecure land ownership and decreasing sizes of farm holdings all contribute to the current worrisome situation. Meanwhile though, Africa expects to double its population in the coming decades, with many more mouths to fill. Improving soil health is mandatory to allow the continent to feed its own people. At the same time due to this, agriculture is facing improving market perspectives which should be an incentive to producers but also to the private sector who are selling inputs and buying outputs. Key to the solution is the wider adoption of integrated soil fertility management (ISFM), where profitable digital advisory services have a clear role to play. SOC is a reasonably sound proxy for soil fertility in Africa and could be linked more strongly to carbon sequestration initiatives that already have monetized values (e.g. Rabo Carbon Bank).

Using satellite data and digital tools for soil fertility management

Satellite sensors (radar, optical, thermal) are able to capture relevant data for soil fertility advisory, at increasingly fine-textured resolution (SOC, soil moisture, and indirectly by NDVI). This development goes fast and will continue to do so. Drones, lidar and hand-held spectrometry further allow assessments at point, field and pixel level (texture, color, nutrients). Historical datasets also show changes in such properties, allowing for example the assessment of the ongoing soil erosion or land rehabilitation efforts. Frequent overpass satellites help in change detection and monitoring change. In addition, soil-water-crop

▼ *G4AW project Cropmon*

models such as QUEFTS have been used to translate properties and processes into yield predictions, including the effects of mineral fertilizers.

Traditional soil sampling and analysis by wet chemistry and empirical and mechanistic modelling now have a competitor in spectral soil analysis and machine learning-based soil fertility and crop production assessments. On a big data basis, covariates will come out of this AI process explaining soil-crop relationships and differences. Meanwhile, a plethora of advanced and simple tools and apps with or without geospatial support have been developed that can help producers in taking informed decisions in soil fertility management. This ranges from simple look-up tables to smartphone-driven apps and information platforms using Chatbots.

Unlike services for weather and pest/disease control, soil fertility advisory services face more challenges and uncertainties, such as choice of fertilizer, availability at right time and place, farmer's production goals, field fertilization history and spatial variability of soil properties. Soil fertility advisory is also less of an early warning undertaking and alert-sensitive (apart perhaps from the timing of topdressings), and there is no straightforward relationship between soil properties, fertilizer use and crop yields unless measured and modelled. Fields in smallholder farms are generally small and may have more than one crop, as part of risk strategy, and cadastral systems (or even informal land rights) are lacking which can complicate pixel-based advice.

Using average sampling data at watershed/landscape level reduces field level uncertainties. Furthermore, this scale is more suitable for soil fertility advisory that is supported by RS to a conglomeration of communities while at the same time scaling up and consolidating properties of their individual field-plots. Farm scale advisories could also work, but success seems more common in homogeneous environments, under irrigated conditions and happens best where high-value crops with profitable market outlets are grown in a customized, precision agriculture layout (as shown in some Asian G4AW projects).

Projects that successfully integrated satellite data and digital tools

Digital soil and water mapping projects have resulted in a large availability of publicly accessible data at different resolutions on which other initiatives can build (e.g., AfSIS, WAPOR). An also important repository of digital agriculture was originally built by CTA in the Dashboard - Digital Agri Hub. The dashboard and hub enable meetings among stakeholders with a worldwide network distribution.

Many projects try to come up with geodata-supported tailored fertilizer recommendations at field and farm scale levels (Space to Place, iSDA), SOCe based on sampling, measuring and modelling, others on machine learning. Many G4AW projects also followed these approaches: Fertilizer Optimization Tool in MUIIS; CaddyFish in SAT4Business, SpiceUp; GEODATICS nutrient management tool, CROPMON and MYVAS4AGRI SoilCares spectrometry tool; SAT4Farming Field Development for cocoa; GAP4A AgriCoach for G50 community groups; Angkor Salad lookup tables for available vs required nutrients; Mavo Diami local innovation tools.

The development of such tools was met with challenges on the way and it is not always clear from end-of-project reports how successful they were. This is due to (i) relative short project duration not allowing sufficient time to put aggregators in the driver's seat to roll out advisories once the approach is rooted in smaller communities, (ii) hindrances in digital data infrastructure, including hinderances in free data sharing opportunities, unoptimized platform support and lack of privacy, (iii) replacing advanced SDDT-based approaches with already known simple procedures in soil fertility assessment, (iv) digital literacy, connectivity and smartphone penetration challenges, (v) other constraints than soil fertility (markets, insurance, credit).

A major conclusion however is that no matter how good and convincing the product maybe, the 'client' seems to be taken too much for granted. Whereas business to business approaches seem to have worked relatively successfully, smallholder farmer groups were often not sufficiently part of the development process. As a result, they rejected the technology, be it through sheer poverty (SAT4Farming) or lack of understanding the technical language, lack of trust, and other priorities when investment opportunities are small.

Bringing the technology to the farmer or the farmer to the technology?

As said, although technology to support advisory on soil fertility in Africa is increasingly available, it still seems to poorly fit the needs of the buyer community

▲ *G4AW project Modhem*

at a larger scale. This is due to a disconnect between the technology provider and the buyer group, where ‘sending’ tends to outpace ‘receiving’. Rather than pixel-based, farmers use vernacular names to classify land and soil fertility, and have deliberate risk-related soil fertility management strategies. Approaches should work more on ‘citizen science’ basis with true participation, co-creation and demonstration, allowing gradual internalization of technologies. A three-column checklist is proposed, where ‘technology/seller’ and ‘customer/buyer’ come closer by means of in-between ‘institutional environment’ checklist, that are needed to bridge the gap between the two.

Road map to be based on a Prerequisite List

For future initiatives and projects to make SDDT for soil health advisory services in Sub-Saharan Africa more successful and ready to scale, an ex-ante assessment can be done on the basis of a to-be-ranked list of prerequisites. These have five dimensions: Institutional, Financial, Production Systems, Community, Technology. Upon ranking the prerequisites, a study can be undertaken where those ranking poorly can be adjusted to become better and fit for purpose. Following the results of that study, a go / no-go can be given for the project / investment. Although this may sound like a prescriptive approach, small-scale start-up level innovation should of course be fully encouraged. However, care should be taken that not too many local, poorly underpinned attempts eventually spoil the market for more robust, scalable products and services.

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