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Old problem, the Millennial solution: using mobile technology to inform decision making for sustainable fertilizer management

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According to the World Bank, as of mid-2000s, more people have access to mobile technologies than clean water. Mobile technologies were quickly recognized as excellent high performing work tools and became adapted early on for use in the agricultural sector. They offer exciting opportunities for improving farming practices, including operating sustainable fertilizer management strategies and related extension support. From assessing potential Nitrogen losses in California to fine-tuning fertilizer recommendations in Thailand — harnessing the potential of mobile technologies was recognized as an essential piece in the worldwide move towards information-driven, efficient, and sustainable agriculture. In this review, mobile technologies designed to augment existing methods of fertilizer management were reviewed and challenges to their adoption together with missing links in their development process were emphasised.

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Introduction

Mineral fertilizers (MFs) play an irreplaceable role in ensuring that the growing demand for food is met without jeopardising long-term soil fertility [1,2]. However, greenhouse gas emissions associated with fertilizer production and continuous use [3,4], soil and water pollution resulting from over application and mismanagement [5], and soil degradation caused by lack of organic inputs [6] have all been recognized as posing serious threats to global food security.

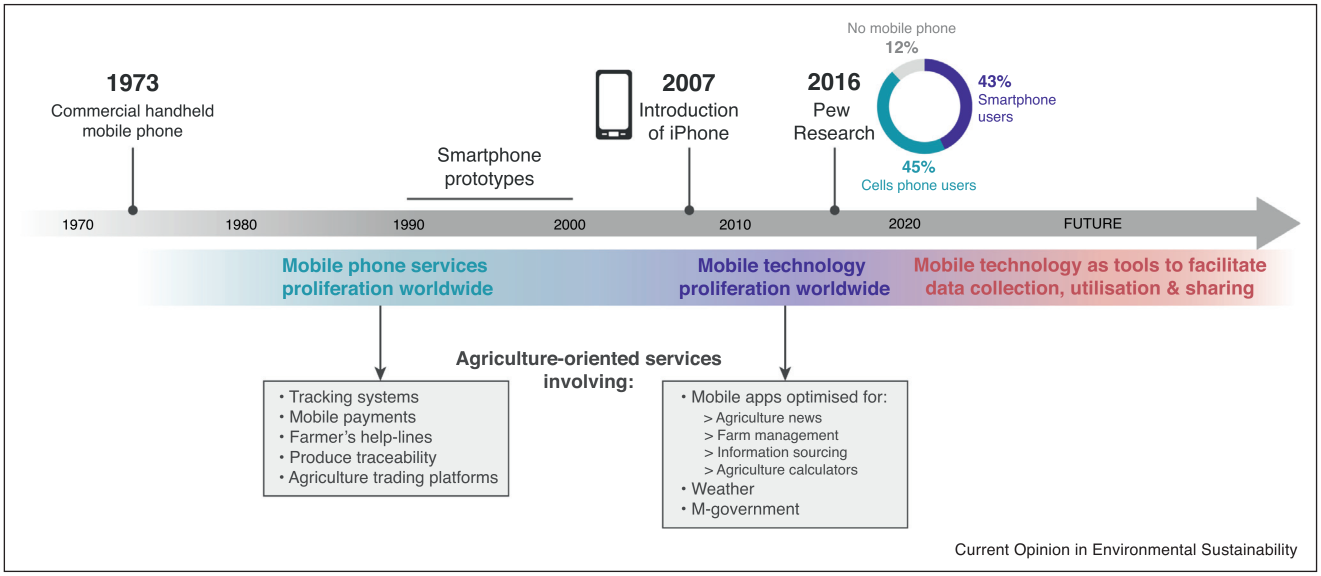
Regardless of this, both the developed and developing countries are set to increase their MF demand, predicted annually to reach 201 thousand tonnes by the end of 2022 [7]. Despite the fact that MFs have been available for over sixty years, their application is often suboptimal for crop growth due to limited access to critical soil and plant information and the resulting low nutrient use efficiency [8]. Lack of information, in combination with decreasing farmer participation in soil testing and farm planning (<30% of American and Australian farmers take part in such programmes at recommended frequencies) [9] give rise to concerns regarding the long-term sustainability of conventional agriculture. Thus, it is essential to enhance the availability and access to tools that allow for better MF management. These include, for example, fertilizer advisory service [10,11••], models of plant-soil processes [12], in-field [13,14] and off-field [15,16] soil and plant matter testing, and improved communication between farmers, farming communities and agricultural consultants or governmental extension workers [17].

Mobile technologies offer a wide range of opportunities for potential ways to contribute to creation of such tools. Smartphones have been repurposed for use in farm management the moment they became affordable, and thus, available to the general public [18] and continue to play a compelling role as decision support tools (DSTs) [19,20••]. This paper aims to review the increasing impact of mobile devices on agricultural decision making relating to sustainable use of MFs via phone based soil-plant testing, farm-level agronomic extension advisory, and assessment of economic viability of fertilizer application, whilst highlighting opportunities and challenges associated with these technologies.

The evolution of mobile technology and its role in farming

Starting with a 412 MHz CPU and 128 MB eDRAM in 2007 and transitioning today into powerful microcomputers with 64-bit multi-core processors supporting 4 GB of RAM; and over 250 GB of internal memory by 2019, smartphones demand little IT literacy and provide an easy and cost-effective means to access information at will via the Internet. In the early years of mobile technology adoption, the devices available gave rise to productivity-oriented software with weather monitoring, agricultural

Figure 1



Simplified timeline of smartphone development and its application in agricultural services.

news, and record keeping, acting as a backbone of 'mobile Agriculture', or m-Agriculture [21] (Figure 1).

However, as technology advanced, smartphone apps began to display a higher degree of sophistication and task-specificity to accommodate the growing needs of modern and information-intensive agriculture. From assessing potential Nitrogen losses in the west of the United States [22] to connecting farmers in Ghana [23••], and fine-tuning fertilizer recommendations in Thailand [24], they showed potential for contributing to the development of a new generation of agriculture-oriented information technology architecture, where data is instantly received, recorded and either shared between interested parties or stored in the cloud for ease of recall or use.

Because of their capacity to collect and manage data both quickly and easily, mobile devices enable the idea of smart farming, which builds on the concept of precision agriculture but is not confined solely to accounting for in-field variability. In smart farming, decision making that forms part of agricultural management is based on data, and thus, becomes enhanced by context awareness and situational awareness whilst remaining responsive to events taking place in real-time [25]. This approach can bring substantial benefits to sustainable and integrated MF management as field-specific and geo-located information and agronomic knowledge become democratized through access to Information and Communication Technology (ICT) brought about by mobile devices.

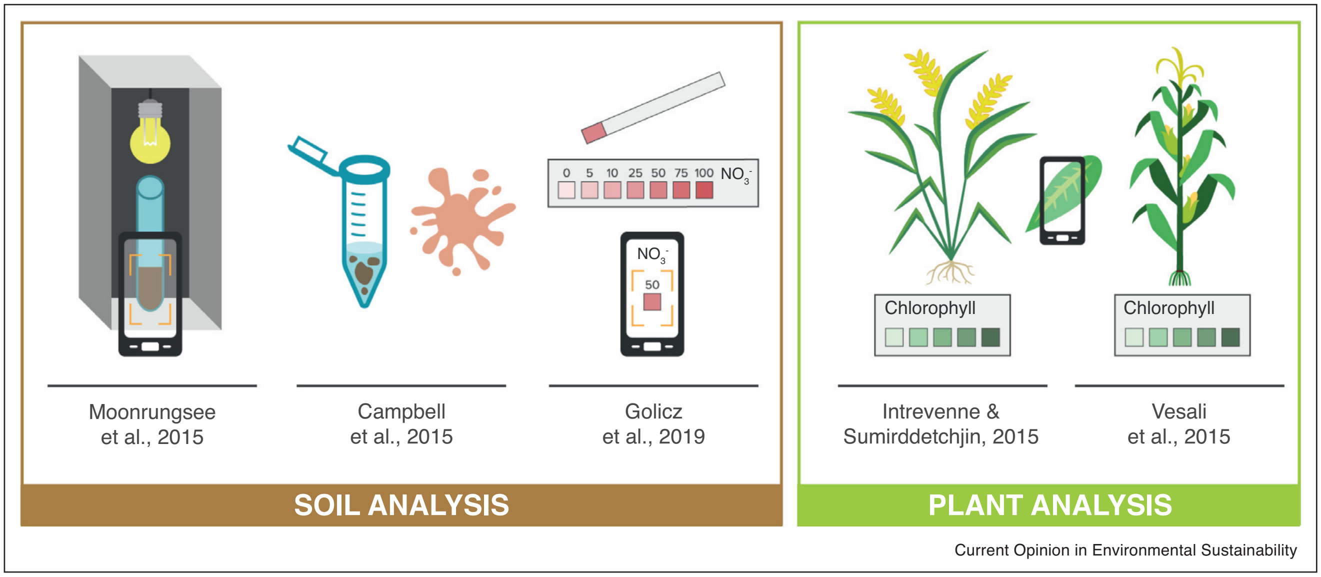
Opportunities and challenges for mobile technology innovation, adoption and use

Tools for sustainable mineral fertilizer management: portable soil and plant analyzers

Responsible nutrient management requires frequent (3–5 years) soil and plant matter testing [26,27]. However, traditional methods of soil-plant analysis are often expensive, time-consuming and labour-intensive [28]. Smartphones have been recognized as having the potential to act as portable testing devices [19,29] but there are still only a limited number of complementary apps that would inform farm workers about soil-plant nutrient content in real time.

There was an early attempt to develop a portable colorimetric analyzer to determine plant available phosphate [30], whereby a smartphone was affixed onto a device used to capture a set of images of soil extract, which were analyzed for RGB values via a custom-made Phosphorus Analysis App (Figure 2). Images obtained from the smartphone camera were subsequently analyzed by the app and were found to be highly correlated (R^2 = 0.996) with the standard spectrophotometric methods. Concurrently, Campbell *et al.* [31] used a smartphone-mediated green chemistry enzymatic method for assessing soil P assessment in field conditions with similarly promising results (1.5–4.0% error between the methods). More recently, Golicz *et al.* re-purposed a water quality testing app, Akvo Caddisfly, to measure soil mineral nitrogen (N) content via colorimetric test strip method on smallholder suburban farms in South-East China [32••].

Figure 2



Application of smartphones in soil and plant analysis. In recent years, mobile devices have been repurposed to act as low-cost alternatives to expensive laboratory tests. This offers a great potential for improving fertilizer management, especially on smallholder farms. However, accuracy and precision, as well as accessibility need to improve if smartphones are to become a viable alternative to standard testing.

Other apps such as BaiKhao — a widely popular app used to assess the level of N and potassium (K) deficiency in rice plants [24], and Smart SPAD, which was demonstrated to accurately measure chlorophyll content of maize [33], have been employed, offering an indirect measurement tool to inform farmers about nutrient content of their soils. BaiKhao reduces errors associated with subjective comparisons of leaves against the standard leaf colour chart (correct leaf colour assignment rate = 93%) providing accurate estimates of N K inputs required during the crop growing season. SmartSPAD estimates the chlorophyll content by contact imaging and was shown to correlate well (R^2 = 0.88) with an expensive Minolta SPAD 502 mmeter.

These apps offer a low-cost alternative for conducting soil and plant analyses, potentially enhancing farmers' capacity to improve MF application across their fields. Provided they are used alongside other sources of agronomic advice, they can contribute to minimising the economic and environmental risks associated with overfertilisation and underfertilization. However, few were made fully accessible to the public, they require some form of hardware and/or reagents that are not immediately or widely available and lack context (with exception of BaiKhao) as they are not integrated with wider fertilizer recommendations adjusted for singular crops that can be quickly understood and applied in practice by the farmer.

Tools for sustainable mineral fertilizer management: digital agronomic advisory services

In emerging economies, and especially on the African continent, MFs have been demonstrated to increase crop yields under smallholder farming conditions, provided they were applied at the right quantity and spatial-temporal scale and accompanied by appropriate agronomic practices [34]. Unless these conditions are met, investment in on-farm inputs has been shown to bring negligible benefits and to cause disfranchisement resulting from financial difficulties brought about by purchase of expensive MFs [35]. Thus, both governments and international NGOs have recognized the importance of providing dynamic and location-specific nutrient information to agricultural practitioners [36].

Complex agricultural decision support tools such as the International Rice Research Institute's Nutrient Manager for Rice (NMR) have been optimized for use with a smartphone and/or tablet [37]. The application of NMR in the Senegal River Valley was widely successful and shown to increase yields (up to 2.3 t ha^{-1}) and incomes (by US$ 216–640 ha^{-1}) whilst decreasing inputs including water and mineral fertilizers, bringing precision agriculture to smallholder farms in West Africa. However, such apps are directed largely at extension workers and are less likely to be taken up by individual farmers without targeted training. Top-down transfer of knowledge limits the potential of mobile devices to involve multiple end users in responsible nutrient management. By contrast, Lomotey *et al.* surveyed Cocoa farmers in Ghana, finding that 78% of the respondents owned a smartphone and that all (100%) interviewees would be interested in using Cocoa farming-oriented apps if they were made available. Information regarding pest control and fertilizer application alongside discussion forums topped the list of desired features [23••]. The digital agronomic advisory service developed subsequently was considered 'very helpful' by 72% of end-users, paving the way for informed application of on-farm inputs on Cocoa plantations.

This farmer-inclusive digital extension service is also widely popular in India, where the IFFCO KISAN app has complemented a farmer-to-advisor helpline first implemented by the Indian Farmers Fertilizer Cooperative Limited (IFFCO) in collaboration with Airtel, India's largest mobile network provider [38]. Both the helpline and the app allow farmers to access location-specific advice regarding best practices for crop cultivation, including MF recommendations. The programme is now being used by over one million farmers across the country and has been deemed successful at disseminating information to agricultural practitioners [39••].

Developed countries have historically had more access to multiple sources of fertilizer advice, for example, paper or computer-based [9]. However, regulatory pressures have given rise to interest in applications designed to support sustainable nutrient management planning. The Nitrogen Index is a USDA-approved software package that can assess the risk of nitrogen loss resulting from farm-specific nutrient management practices [22]. The software was adapted to the smartphone ecosystem, allowing for data input to be conducted away from the desktop computer and thus, providing a portable and effective tool for N management to farmers across the US.

Considering the high level of interest in utilising mobile technologies for optimal and thus, sustainable MF use — there is little doubt that more applications will continue to be developed. In the future however, consultation with practitioners should constitute an essential part of the development process to ensure that these tools respond to the needs of agricultural workers and can be quickly and easily made available to the interested parties. Concerns regarding the 'black box' approach to soil management, which ignores farmers' experience, have been voiced with regards to a variety of decision support tools [40–42] and should be avoided in the ICT-mediated smart farming approach at all cost.

Tools for sustainable mineral fertilizer management: cost calculators and fertilizer purchase facilitators

MFs represent a substantial draw on farmers' financial resources [43]. Thus, precise calculation of fertilizer needs (adjusted for expected yield and soil-plant test results) relative to their market price and the price fluctuations at the point of purchase constitute essential information for successful farming operations regardless of their scale. Hence, relying on mobile technology for fertilizer calculations is likely to be considered risky comparative to getting advice from agronomists or extension workers, especially since there is no clear governmental architecture that determines who, that is, the farmer, the software developer or the software distributor, is responsible and accountable for erroneous information provided by mobile apps [44].

Governments and NGOs have recognized this concern and are taking an active part in tool development for augmentation of fertilizer calculations. In Canada, the Saskatchewan Soil Conservation Association lists a number of state approved apps, with Fertilizer Blend app being designed to assist in calculating a liquid and/or dry MF blend that meets crop demand whilst optimising its cost [45]. The Government of South Australia publishes updated inventories of farming-oriented apps that work in both iOS and Android environment, including the NPK app [46]. Bueno-Delgado *et al.* conducted a non-exhaustive review of similar smartphone applications alongside the introduction of the Ecofert app, designed to calculate the best combination of fertilizers whilst taking into account self-updating price of fertilizers made available via a cloud-based service [47].

Furthermore, the Centre for Agriculture and Bioscience International (e.g. Fertilizer Optimizer) [48] and Food and Agriculture Organization e-Agriculture (e.g. MITRA) [49] offer apps that can not only be used in fertilizer calculations but also offer an opportunity to facilitate the process of procuring MFs, which is associated with additional costs in emerging economies [50].

These types of apps require meticulous cross-examination to reduce the potential for calculation error, well thought-out architectural designs that account for the challenges likely to be encountered in the agricultural sector, for example, intermittent Internet access, bandwidth fluctuations, and energy conservation necessary for prolonged in-field use [51,52] as well as regular post-release updates, to remain relevant to the end-user. This level of engagement in app development requires a robust and dynamic collaboration between farmers, governmental organizations (potentially requiring a separate regulatory body that could provide certification for verifiable apps), and related MF industry, which is not yet fully capitalized upon.

Integration of knowledge for sustainable fertilizer management

In the coming years, mobile technologies will be firmly established as a factor helping to address one of the biggest weaknesses of rural markets in developing nations — asymmetric access to useful and relevant information [53,54]. As well as, offering opportunities to small-scale agriculture in the developed countries, where large-scale competitors have greater access to technological innovations [44].

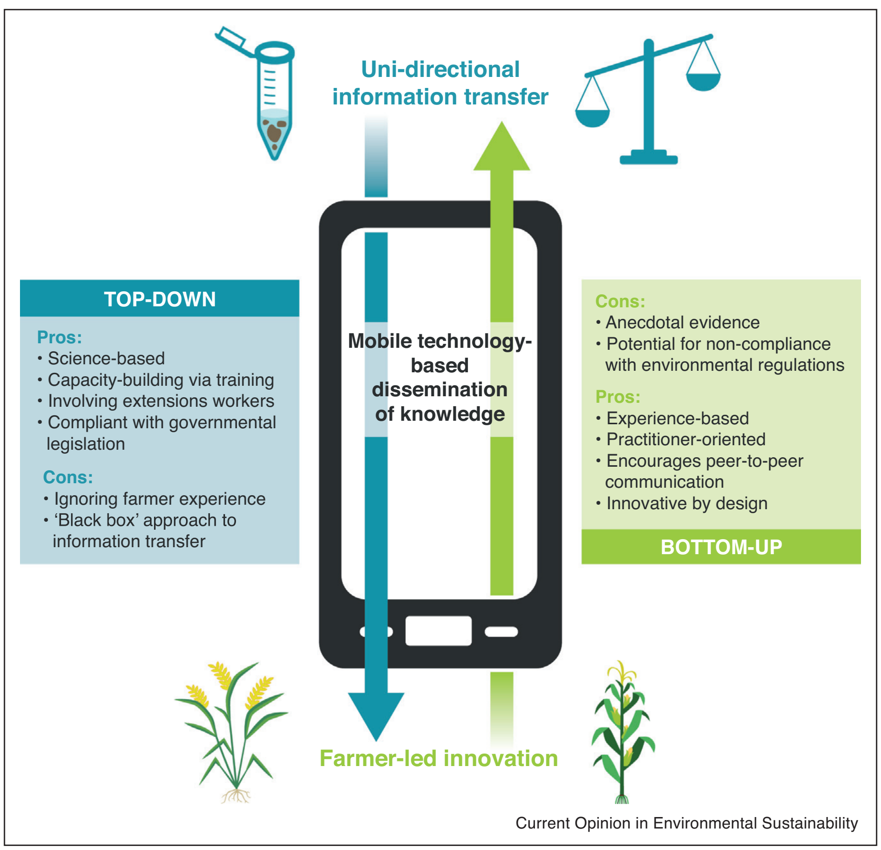
However, schemes aimed at improving agricultural productivity whilst enhancing sustainability have failed frequently over the years. In such cases, the lack of technological solutions was rarely identified as the chief barrier to their adoption [55]. Instead, socio-economic problems arising from linear transfer-of-technology and top-down approaches that did not account for innovative systems and informal peer-to-peer information systems were highlighted [56,57,58••,59] (Figure 3).

Providing agricultural practitioners with decision-support tools to better manage MFs through mobile technologies constitutes a promising tactic but it is insufficient to bring about a significant behavioural change on its own. DSTs, in the form of paper-guidance, email/text alerts, computer-based tools and finally, smartphone apps, have been available for a number of years but their uptake was limited despite of their apparent value [41].

Provision of information does not equate to its full utilization and considering the costs involved in the DST development, more research effort must be directed towards identifying what socio-economic factors might impact farmers' uptake of mobile technologies in agriculture. The on-the-ground implementation strategies should constitute a part of the DST development process and not be assumed or an afterthought.

Smartphones and smartphone apps repurposed to act as soil-plant analysers, digital agronomic advisories and fertilizer calculators must become better integrated into the farming systems. They should be considered trustworthy, quality controlled and certified to address liability concerns, and emphasize connectivity by facilitating transfer of knowledge and agricultural innovation on a person-to-person basis (facilitated by extension workers), rather than focusing solely on passive information transfer. If those conditions are met, mobile technologies will play an irreplaceable role in closing the gap between theoretical

Figure 3



Modern technology allows for easy communication between farmers and between farmers and extension workers linking top-down and bottom-up approaches to MF management.

knowledge and on-farm MF application across the developed and the developing world.

Data access statement

No new data was collected in the course of this research.

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Declaration of Competing Interest

The authors report no declarations of interest.

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