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REVIEW ARTICLE

State of apps targeting management for sustainability of agricultural landscapes. A review

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Abstract

The triple-bottom-line approach to sustainability in agriculture requires multi- and inter-disciplinary expertise and remains a major design and implementation challenge. Tools are needed to link extension agents, development workers, farmers, and other agriculture decision-makers to information related to practices that improve sustainability across agricultural landscapes. The digital age has brought many new cloud-based and mobile device–accessible software applications (apps) targeted at farmers and others in the agriculture sector; however, the effectiveness of these tools for advancing sustainability goals is unknown. Here, we review apps for agriculture in order to identify gaps in information provisioning and sharing for tools that connect decision-makers to knowledge in support of sustainable agricultural landscapes. The major findings are (1) Agricultural apps can be categorized as supporting regulatory compliance, equipment optimization, farming simulator games, information management, agronomic reference information, product tracking, pest identification, emissions accounting, or benchmarks for marketing claims. (2) Many apps are developed to link specific products for single solutions, such as GPS-guided crop implementation or sensors within Internet-of-things connectivity. (3) While pilots, prototypes, and case studies are available in both Apple and Android digital markets, public mobile apps to improve multidirectional agriculture knowledge exchange are limited and poorly documented. (4) There remains a need for apps emphasizing knowledge exchange and resource discovery, rather than simply information delivery, to help farmers identify evidence-based practices that improve indicators of sustainability. (5) Development of a digital decision support tool requires early and ongoing interactions with targeted end users to clarify app performance objectives and social networking preferences, ensure reliability of scientific input and business management plans, and optimize the user experience.

Keywords Sustainable resource management · Apps for agriculture · Digital decision support tools · Knowledge sharing · Software design

Contents

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1 Introduction

Agricultural sustainability is an aspiration that challenges practitioners and researchers to consider farming effects on ecosystems and communities while also advancing food and energy security, clean abundant water, healthy productive soils, and other benefits to socio-economic and environmental systems (Brundtland 1987; Pretty 2008; Wu 2013; Pretty et al. 2014). Sustainable agricultural landscapes can be defined as those areas that provide ecosystem services supporting productive and economically viable agriculture (including forestry and fisheries) and resilient, healthy, and secure societies (Dale et al. 2013; Kumaraswamy et al. 2013). Goals for achieving greater sustainability should be identified by stakeholders through an iterative and engaged process that addresses needs in key categories such as water, soil, and air quality; biodiversity, climate change, social well-being, equity, education, energy security, trade, employment, profit, and land tenure (Eichler

Inwood et al. 2018). Contextual goals therefore differ depending on stakeholders' values and resources. Applying a landscape perspective when assessing agricultural systems can highlight co-benefits and tradeoffs between management choices within social, economic, and environmental goals for agro-ecosystems at spatial and temporal scales that are relevant to farms and regions (López Ridaura et al. 2002; Gerdessen et al. 2013; Schader et al. 2016; Eichler Inwood et al. 2018). This so called "triple-bottom-line" approach gives equal importance to people, profit, and planet (Elkington 1997) and requires multi- and inter-disciplinary expertise. Thus, it remains a major challenge in sustainability science.

Despite the increase in research on agriculture sustainability assessment in the last 15 years (from 20 citations in 2003 to 165 citations for 2017 in Web of Science), sustainability goals have not often been described for agricultural landscapes. Assessment tools such as those reviewed in Eichler Inwood et al. (2018) reach dozens to several hundred farmers, out of 570 million worldwide (Lowder et al. 2016). Thus, we surmise that relatively few farms and even fewer agricultural landscapes have systematically addressed sustainability goals. Farmers and communities interested in beginning a formal assessment process can choose from at least 170 frameworks utilizing hundreds of different indicators (inventoried in (Wustenberghs et al. 2015). These procedures range from qualitative ratings of indicators completed by a farmer in a few hours to reports prepared by third parties over the course of months. They tend to have more bio-physical indicators than social indicators.

Trends in indicators, such as increases in soil organic matter for example, can be viewed as evidence for progress toward goals only when the end users perceive that the indicator is relevant to their own system, thus contextual indicators should be selected. Selecting appropriate indicators is not simple and requires a process to address conflicting value positions in cases where there are multiple stakeholders, even among members of the same project team (Eichler Inwood 2018). Development of adequate decision support tools that target specific landscapes or farm types therefore seems unfeasible if the goal is to accommodate the enormous variety of systems requiring sustainability improvements. In contrast, a broadly applicable knowledge sharing tool could provide a structure or platform for matching farmer peers to each other and to trusted and scientifically robust information. Such a network would be useful for developing customized indicator-based farm system and landscape assessments and ultimately identifying which farm management choices are available to individual farmers to help them achieve their desired outcomes. Digital tools could facilitate an agricultural knowledge sharing platform.

Tools are needed to link extension agents, development workers, farmers, and other agriculture decision-makers to information related to practices that improve sustainability across landscapes. The digital age has brought many cloud-based and mobile device–accessible software applications (apps) targeted at farmers and others in the agriculture sector. These apps span from equipment use guidelines, to satellite navigation support for machinery, and pest or nutrient management to business recordkeeping tools, and are available in diverse locations (Fig. 1). Specific examples are discussed below.

Farmers with internet access face an information overload from digital decision support systems or tools (henceforth referred to as decision support tool) that could support on-farm management decisions (Rose et al. 2016; Schröer-Merker et al. 2016). Limited reviews of agriculture mobile tools are available (Karetsos et al. 2014; Costopoulou et al. 2016; Patel et al. 2016; Schröer-Merker et al. 2016; Xin et al. 2016) but generally focus on a specific geographic region, farm system, and/or agronomic issue. Any list of apps is everchanging as new products are released or updated, while others become obsolete. Thus, any analysis of such apps must be considered in the context of the rapidly changing digital milieu, and we encourage the reader to explore the current availability of agricultural apps. Many apps are tools for reference and record

Fig. 1 Milpa—the ancient system of intercropping maize, bean, and other vegetables—grows beneath modern cellular towers on steep slopes in the remote Guatemala highland town of Todos Santos. Digital decision support tools could help development workers and farmers address environmental, social, and economic concerns in the landscape through knowledge sharing on locally effective practices that, for example, increase soil organic matter and prevent erosion, improve educational equity by reducing labor burdens on women and youth, diversify marketable products to local, national, and international consumers, and reduce post-harvest storage losses

keeping and are not explicitly decision support tools. Data that are relevant to agriculture may be available for large geographic areas and must be filtered for local relevance, for example precipitation forecasts by state or region. Other tools may supply information related to individual crops, such as commodity prices and pest reports for grain corn. Many apps focus on Internet-of-things connectivity, which refers to the network of physical objects—devices, vehicles, buildings, and other items—embedded with electronics, software, sensors, and network connectivity that enables these objects to collect and exchange data.

Agricultural apps generally focus on individual users. Much of the mobile-accessible agricultural information is directed toward field- or farm-level diagnostics and decisions, while very little information is provided that explicitly links farms to broader landscape and community knowledge bases (Fig. 2). It is difficult to address the spatial variability of agricultural landscapes, in part, because applications designed for field-level management by individual app users are not easily expanded to broader spatial scales. Key crop management decisions are often made just a few times per cropping cycle, so farmers need tools that can help them collect and process up-to-date, contextually appropriate information on both biophysical conditions (such as what to plant, when to fertilize) and local socio-economic concerns (e.g., determining if an activity is profitable, facilitating employee management, and marketing). There is demand for and value in apps that address individual farm management issues such as bookkeeping or fertilizer planning for achieving sustainability goals, as evidenced by the number of free and paid apps available in those categories. There may be an opportunity to multiply that value by expanding the scope of agricultural apps to encompass concerns across the landscape and acknowledge broader agro-ecological networks through knowledge sharing. Broadening the scope may help communities address potential synergies and tradeoffs from farm-level decisions.

There is an opportunity for community learning through low-cost apps that incorporate geophysical databases with crowd-sourced agricultural information and social networking (Bruce 2016). New technology alone is insufficient for successful adaptation in agriculture (Hellin et al. 2016), but an app could facilitate connecting people to knowledge that leads to greater capacity for decision making. A decision support tool that shows regionally appropriate methods for soil improvement and relative costs, for example, could link farmers to local extension personnel as a means to enhance training and material resources. Such a "bottom-up" approach could encourage farmers' ownership of technology decisions and increase successful adoption of practices that improve sustainability.

The purpose of this paper is to examine the state of smartphone or mobile device–accessible apps for agriculture in order to identify gaps in information provisioning or sharing in decision support tools that connect policy-makers, extension agents, farmers, and other decision-makers to local, regional, and global knowledge in support of sustainable agricultural landscapes. We present categories of functionality for agriculture-targeted apps and review a sampling of decision support tools that provide information for farm management related to sustainability knowledge sharing. Quantification of the impact of using agricultural apps to achieve sustainability goals is a research endeavor beyond the scope of this review. We discuss opportunities for apps that supply integrated data that are relevant to decisions affecting landscape sustainability considering environmental, social, and economic dimensions of agriculture.

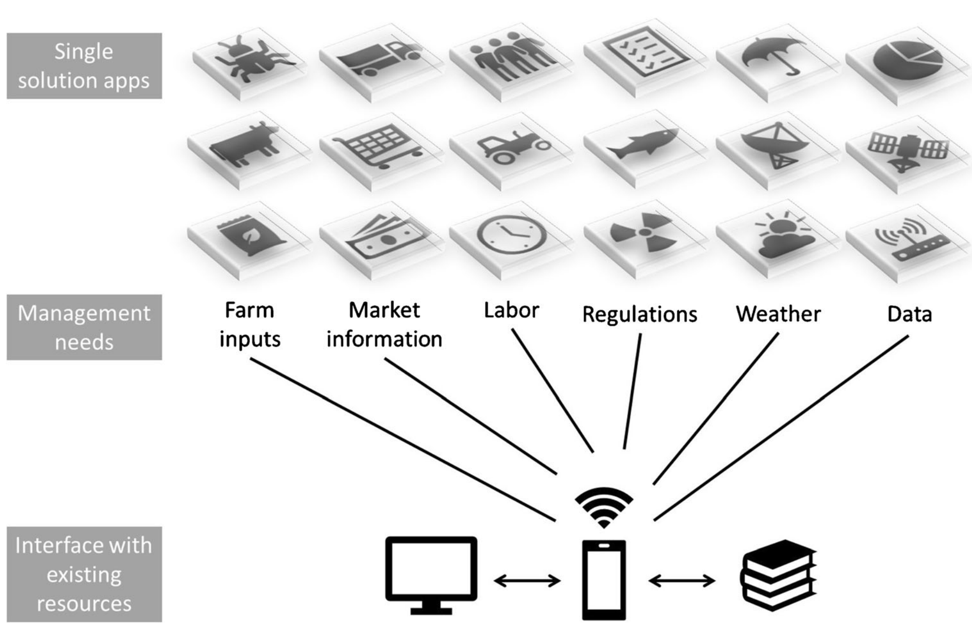

Fig. 2 Hundreds of digital tools are available for a variety of farm management needs. Generally, these apps do not take an integrated approach to addressing environmental, social, and economic issues surrounding agricultural sustainability goals, and instead support individual commercial equipment or specific farm management objectives

2 Approach

This analysis is based on a review of published literature pertaining to apps for enhancing sustainability of agricultural landscapes. We searched the Web of Science for peer-reviewed publications related to apps for improving sustainability in agriculture using the following terms: smartphone or mobile application and agriculture or sustainability or ecosystem; smartphone and sustainable agriculture or ecology; smart farming and sustainability; agriculture information and landscape ecology (Table 1). Based on published titles and abstracts, relevant articles were selected for more detailed review. Titles and abstracts that refer to proposed/conceptual software, Internet-of-things (often termed "IoT") connectivity, equipment management, recordkeeping, market status services, consumer behavior, or field-level agronomy decisions (fertilization, irrigation, pest, weather) in isolation from off-farm conditions or human networks were not included in further review.

Additional English language apps were identified by searching the iOS Apps Store (available at itunes.apple.com) and the Android Apps store on Google Play (available at play.google.com/store) for products related to sustainable agriculture, agriculture sustainability, landscape sustainability, or sustainable food. These searches were repeated within a third-party website for Apple app searches (theappstore.org). A detailed search within Android products was not reproducible on the same device, and the store search function automatically prioritizes search results based on the device one uses to initiate the search. Consequently, a thorough understanding of all Android products would require searching from a wide variety of devices; therefore, we provide only a snapshot of Android agriculture apps. When multiple apps by the same name were found in Android, a cross-reference to iOS apps was sought. If no further information for the app was available through a web or developer link, we dismissed the app from further analysis. We surveyed the app's title, tags, and public-facing English description of functionality to broadly categorize the apps and select specific apps that potentially relate to agricultural landscape sustainability improvement efforts. The following types of apps were excluded from detailed review: games or farming simulators, record keeping or business management tools, equipment management/optimization, Global Positioning System (GPS) guidance, sensor connectivity for Internet-of-things, retail product information, agriculture product tracking, digital reference tools including pest identification and spray calculators, home landscape design, and consumer food sourcing. Relevant publications and publicly available apps were reviewed to examine the current state of apps for agriculture that can provide information supporting management for sustainable landscapes. Apps identified in this paper and their reference or web address are noted in Table 2.

3 State of the art: apps for sustainability in agriculture

Over 6100 citations were returned for a Web of Science search for "smartphone application." We modified and refined searches (Table 1), retaining 157 abstracts for additional review, and examining 16 relevant peer-reviewed publications in detail. Additional references were found through citations in the returned Web of Science results and through searches using similar terms in Google Scholar.

Agricultural software can be categorized generally as programs that support regulatory compliance, equipment optimization, farming simulator games, information management, agronomy references, product tracking, pest identification, emissions accounting, or benchmarks for marketing compliance claims (Table 3). Each app store has its own set of classifications for the apps it hosts. For example, the Apple store classified apps tagged with "agriculture" as one of the following: business, education, finance, food and drink, games, lifestyle, navigation, news, productivity, reference, shopping, social networking, travel, utilities, or weather. To illustrate the types of mobile apps available, we re-categorized the first 100 search returns for iOS iPhone or Android apps tagged with

Table 1 Search terms and results of Web of Science search for citations dating Jan 2008 – Nov 2017

Topic	*joiner*	Topic	Total citations	Abstracts retained	Publications examined
smartphone application			6165		
smartphone application	*search within*	agriculture	25	25	2
smartphone application	*search within*	sustainability	26	26	1
smartphone application	*search within*	ecosystem	48	8	2
mobile application	*and*	agriculture	333	67	3
mobile application	*and*	sustainability	195	12	1
smartphone	*and*	sustainable agriculture	2	2	2
smartphone	*and*	ecology	29	1	1
agriculture information	*and*	landscape ecology	93	7	1
smart farming	*search within*	sustainability	28	9	3

Table 2 Website or developer links for apps noted in text

App, (reference or sponsor if known)	Internet or developer web address
AgPhD (Ag PhD TV/IFA Productions; several corporate sponsors)	http://www.agphd.com/resources/ag-phd-mobile-apps/
Agri Marketplace	https://agrimp.com/
Agriculture Survey App (Fulcrum)	http://www.fulcrumapp.com/apps/agricultural-survey/
AgriMarket	https://www.cdac.in/
Agroportal Greece	meli.aua.gr/agroportal/
AgSense	http://www.agsense.net/agsense-farm/agsense-app/
Agworld for iPhone	https://agworld.co/product/agworld-apps
Climate FieldView (The Climate Corporation, Monsanto)	https://www.climate.com/
Crop Nutrient Calculator	https://www.extension.umn.edu/agriculture/nutrient-management/crop-calculators/crop-nutrient-calculator-app/
Crop Specific Mobile Apps (India)	http://www.jayalaxmiagrotech.com/
CROPROTECT (Rothamsted Research)	https://croprotect.com/
CropTracker	https://www.croptracker.com/
CropX	https://www.cropx.com/
Digital Inputs Financing Toolkit by AGRA	https://agra.org/news/digital-toolkit-to-give-tanzania-smallholder-farmers-access-to-finance-farm-supplies-and-training/
DoneGood: Ethical Shopping App	https://donegood.co/
Environmental Sustainability Dashboard for Tanzania (Fegraus et al. 2012)	teamnetwork.org/agriculture-nature-livelihoods
Envirowalk	https://www.dairynz.co.nz/environment/envirowalk
US Cooperative Extension group	eXtension.org
Farm Carbon Calculator (Farm Carbon Cutting Toolkit)	http://www.farmcarbontoolkit.org.uk/carbon-calculator
Farm Futures	http://marketing.farmprogress.com/brands/crop/farm-futures
FarmConnect	https://www.rubiconwater.com/usa-farmconnect
Fasal	http://fasal.co/
FieldPrint Calculator (Field to Market)	https://calculator.fieldtomarket.org/fieldprint-calculator/
Foodshed	https://www.foodshed.io/
GDA Nursery Assessment	https://apps.bugwood.org/apps/
Geospatial Guide for Residential Pesticide Application (Wickliffe et al. 2016)	www.sccoastalpesticides.com
GreenSeeker (Trimble)	http://www.dasnr.okstate.edu/apps[to be used with N Rate Calculator, same site]
HelloTractor	http://www.hellotractor.com/
iCow	http://www.icow.co.ke/
IrriFresa: (González Perea et al. 2017)	https://www.innocentdrinks.co.uk/blog/2016/july/we-won-an-award https://doi.org/10.1016/j.agwat.2016.07.017
IveGot1 (Wallace et al. 2016)	https://apps.bugwood.org/
John Deere App Center (John Deere)	http://www.deere.com/en_US/services_and_support/technology-solutions/technology-solutions.page?
LandPKS (USAID, USDA)	https://www.landpotential.org/landpks.html
LoGOFF	http://www.nycurbanproject.com/logoff-movement/
MilkCrate for Communities	http://mymilkcrate.com/
MMP360 (AgSolver)	http://www.efcsystems.com/index.php/agronomicplanningandsustainability/
OpenIoT	http://www.openiot.eu/
Organicgirl mobile assessments	https://www.iloveorganicgirl.com/
Plantix (PEAT)	https://plantix.net/
PlantVillage (The Pennsylvania State University)	https://plantvillage.psu.edu/
Plantwise Knowledge Bank	https://www.plantwise.org/
Pocket Spray Smart	http://www.agrible.com/
Profit Zone Manager (AgSolver)	http://www.efcsystems.com/index.php/agronomicplanningandsustainability/

Table 2 (continued)

App, (reference or sponsor if known)	Internet or developer web address
Seafood Watch	http://www.seafoodwatch.org/
Seasonal Food Guide	https://www.seasonalfoodguide.org/
Smart Scout	http://www.taranis.ag/
SmartOysters	https://www.thundermaps.com/
SmartRain (BAUER GmbH)	https://www.bauer-at.com/en/
The Cattle Tags App (Cattlesoft, Inc.)	https://www.cattletags.com/cattle-tags-app
The Nitrogen Index (USDA)	https://www.ars.usda.gov/research/software/download/?softwareid=426
Trringo	https://www.trringo.com/
Twitter	https://twitter.com/
Veg Pest ID	http://ahr.com.au/news/pest-and-disease-identifier-released/
WOCAT SLM (Knowledge for Sustainable Land Management)	http://www.wocat.net

Some of the links provide contact information only, or dead ends presumably from apps that are no longer being updated or funded

"agriculture" (Fig. 3) into Table 3 classifications. For iOS, we found that about one-third were related to information management, which includes weather, markets, news, and recordkeeping apps. Games and equipment optimization apps (such as irrigation sensor management or product manuals) each made up 18% of the offerings. About 22% were geared to agronomy reference (13%) or consumer education (9%). Key differences in Android options compared to iOS apps were that Android had far more games (38%) and fewer equipment optimization apps (5%).

Development costs and time are two reasons for potential differences in numbers and types of agriculture apps discovered on iOS vs Android consumer searches. Costs for iOS development are somewhat higher than Android on average (e.g., 27,000 USD compared to 23,000 USD, respectively in 2012; Dogtiev 2018), and Android apps require less review or debugging prior to public release but may take longer to develop version compatibility (Bilyk 2018). Regardless of operating system, costs and time invested depend on the complexity of each app and market characteristics and are not explicitly addressed in this paper.

Many apps are developed to link specific products such as GPS-guided crop implements or soil moisture sensors within Internet-of-things (e.g., AgSense, Fasal), oftentimes to web, cloud, or desktop software tools. Others are geared at food product security, for example individual animal (The Cattle Tags App, SmartOysters) or produce batch (CropTracker) tracking devices. Some of these programs are designed for field or farm-level agronomy reference or decision support, especially for nutrient (The Nitrogen Index, AgPhD, Crop Nutrient Calculator), pest (Plantwise, Plantix, Smart Scout, Veg Pest ID), spray applications (Pocket Spray Smart), and water management (SmartRain, CropX, FarmConnect, IrriFresa). There are a growing number of mobile networking tools that connect farmers to equipment (e.g., Trringo, HelloTractor), markets (e.g., FarmFutures, Fasal, AgriMarket, Agri Marketplace), or agronomic resources (iCow, Digital Inputs Financing Toolkit by AGRA). Potential exists for apps related to ethical and sustainable consumption (Seafood Watch, Seasonal Food Guide), which may influence producer decisions (Nghiem et al. 2016), but these approaches do not explicitly involve farmer to farmer exchange of knowledge regarding practices that improve sustainability of farms and landscapes.

Nearly all of the apps we found can be characterized as "single solution" approaches that provide limited data to improve one specific aspect of efficiency—and often sustainability—but they are not effectively designed to integrate sustainability concerns from multiple dimensions or themes of indicators for sustainable agricultural landscapes (Eichler Inwood et al. 2018). Within "agriculture" tagged apps for iPhone and Android, only three contained "sustain*" in the description or title. A full search within the Appstore.org engine for iPhone returned 11 apps for "sustainable agriculture," 9 for "agricultural sustainability," and 2 for "landscape sustainability," and those generally emphasize environmental or economic issues in agriculture using a farm business management or consumer perspective. An essentially identical selection was available for iPad devices. We did not identify a mobile app that links end users such as farmers, extension personnel, resource managers, or policy-makers with information that relates to landscape sustainability concerns across environmental, social, and economic dimensions although below we discuss other types of software that attempt to do so.

Many of the peer-reviewed reports on apps related to sustainable agriculture or agricultural efficiency consist of technical descriptions and case studies for individual software programs, primarily for sensors (Wu et al. 2016), Internet-of-things (Jayaraman et al. 2016; Krintz et al. 2016; González Perea et al. 2017), GPS and/or GIS (De Filippis et al. 2013; Yu et al. 2017), marketing (Sevenster et al. 2014; Aker 2016; Nghiem et al. 2016), or agronomic reference (Delgado et al. 2013; Schröer-Merker et al. 2016). Many Web of Science

Table 3 Common categories of software tools for agriculture including example programs

Tool purpose	Example tool (developer)	Theme	Platform	Target audience
Regulatory compliance	MMP360 (AgSolver)	Water resource protection, manure management	Web	Farm manager (livestock), Iowa, USA
Equipment optimization	John Deere App Center (John Deere)	Manufacturer to consumer instruction	Mobile	Equipment operators, global
Information management	Agriculture Survey App (Fulcrum)	Digital recordkeeping, data collection, sharing	Web, Mobile	Farm manager, assessors, global
Agronomy, profitability	Profit Zone Manager (AgSolver)	Scenario comparisons; field management, profitability calculator	Cloud-based data processing	Farm manager, crops integrating GPS based precision systems, USA
Agronomy, reference information	Climate FieldView (The Climate Corporation, Monsanto)	Data management; climate/ weather, field management	Mobile	Farm manager, yield prediction and fertilization timing for crops, USA, Canada, Brazil
Agronomy, sensed data	GreenSeeker (Trimble)	remote or micro sensed biological data for crop management	Web	Farm manager (crops), global
Product tracking	The Cattle Tags App (Cattlesoft, Inc.)	RFID management of livestock	Mobile (iOS)	Farm manager (livestock), global
Pest identification	Plantix (PEAT)	Diagnosis and treatments for plants using machine learning	Mobile (Android)	Gardeners, farmers, extension agents, global
Emissions accounting	Farm Carbon Calculator (Farm Carbon Cutting Toolkit)	Life cycle analysis approach for farm practices to cut costs and carbon footprint	Web	Farmers, UK
Benchmark, marketing compliance claims	FieldPrint Calculator (Field to Market)	Supply chain sustainability assessment, field/ farm/ watershed; downstream manufacturing	Web	Production manager, marketing, (commodity crops) USA

citations are from conference proceedings and present concepts for use of apps in agriculture rather than available and functioning apps, indicating that the topic of apps in agriculture is both recent and of broadly growing interest. We identified additional references for sustainability-related software that are mobile- and web-based, for example, invasive species reporting (Wallace et al. 2016), resource management (Ochola and Kerkides 2004; Fegraus et al. 2012; De Sousa et al. 2015; Quaranta et al. 2017), residential property management (Wickliffe et al. 2016), and remote sensing (Tripicchio et al. 2015; Xin et al. 2016).

We found several iOS programs for agronomic decision making, and these are often related to nutrient or water management for fields. A much larger, similarly categorized selection of programs was found in the Android Apps store, though a wider variety of languages is available than in the Apple Store. It is important to note that apps within the virtual stores are not cataloged and thus cannot be searched with the same reproducibility as a reference library. Therefore, we do not consider this an exhaustive review, and it is possible that some apps escaped our notice despite multiple searches, keyword combinations, and use of third-party app listing tools. Furthermore, it is not practicable to determine if an app is still being updated or supported, or if a new name or developer has taken over for the hundreds of apps identified through the app store searches. The vast majority of apps we found do not have a peer-reviewed publication, and many do not have an operational developer web link.

Although we did not uncover literature or app store items that explicitly describe integrated mobile apps related to agricultural landscape sustainability issues, there are several software tools related to information provisioning and community knowledge exchange in agriculture. These are generally web-based and intended for use through a computer rather than a mobile device. We discuss specific exceptions below. Efforts to coordinate knowledge sharing around agricultural techniques are not new but are not yet a major presence in mobile-specific tools. For example, eXtension.org offers a website for sharing US Cooperative Extension Service products including live and recorded webinars on a wide variety of topics related to farms, energy, family, and environment but does not yet have a mobile app. WOCAT Knowledge for Sustainable Land Management (WOCAT SLM, iOS app) is a recent educational app that acts as a unidirectional digital reference. Its web portal however (wocat.net) is an established network that provides opportunities for interaction between academics, development agents, and land managers. WOCAT focuses on soil and water conservation, encompassing ecosystem issues from local to regional and national levels with a limited ability to address social and economic sustainability concerns for farmers or local communities.

We identified two tools that focus on multidirectional knowledge transfer. LandPKS consists of a web portal

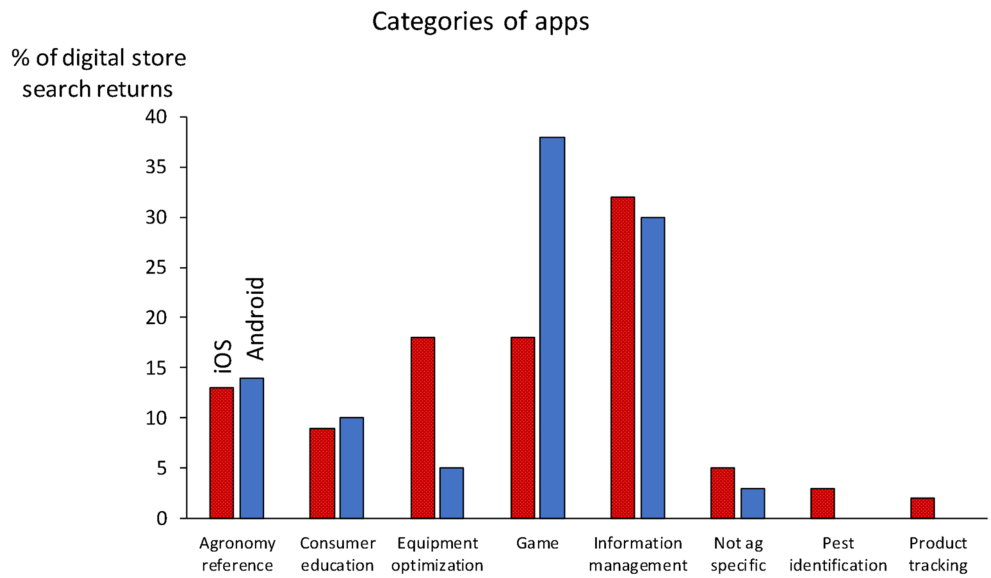

Fig. 3 Recategorization of the first 100 apps returned from an "agriculture" search from iOS and Android stores according to the authors' categories listed in Table 1. The iOS search was completed via theapplestore.org on Nov. 13, 2017; the latest Android search was completed through the Google Play store via a Dell laptop computer on Sept. 2, 2018

(landpotenital.org) for sharing knowledge focused on soil, climate, and productivity expectations for land use planning and decision making. Modules are being developed as individual apps that help resource managers assess site conditions including soil and land cover characteristics and in the future will allow sharing of information with other farmers facing similar land management opportunities and challenges (Herrick et al. 2016). LandPKS is working toward building a digitally linked network of users and have made major strides in using mobile devices for collecting geo-tagged indicator data by app users after minimal training (Herrick et al. 2017). PlantVillage (plantvillage.psu.edu) is a web-based platform to link farmers to other farmers, extension agents, and researchers through digital forums discussing plant diseases. The Plant Village platform was designed to mimic the Stack Exchange (stackexchange.com) process for open-access information sharing in which the reputation of forum participants changes based on the usefulness of their information as scored by fellow participants. An app (AI Assistant Nuru available in GooglePlay) for identifying cassava diseases through an Android camera was recently released by PlantVillage and additional app modules are planned. The goal of PlantVillage is to apply machine learning techniques (Ramcharan et al. 2017) to educate farmers on disease identification while at the same time using geo-tagging of the phone images to monitor spread of plant disease (Ramcharan et al. under review; D. P. Hughes, personal communication). This approach could facilitate landscape-scale responses to plant disease pressures if the network of users grows sufficiently.

In addition to the virtual-focused tools above, Plantwise Knowledge Bank connects trained crop plant health extension workers with farmers through in-person, web, and tablet-based training systems for knowledge sharing. Although its outreach program is farm-focused, preliminary efforts are underway to explore how Plantwise farmer information requests (e.g., focused on a specific pest in a particular location) can be used to predict regional or landscape crop threats (Powell 2017). Plantwise is included with Global Open Data for Agriculture and Nutrition (GODAN), an effort launched in 2013 to address the lack of access to agriculture and nutrition information across all actors in the food system (Powell 2017). A suite of Crop Specific Mobile Apps using Bluetooth technology among low-literacy rural smallholders in India shows high potential for new extension/outreach methods that train more farmers with lower costs (Castillo et al. 2015). However, its application to broader landscape sustainability concerns—beyond improving regional average yields and thus farm household food security—is not clear and individual apps were not available for review. Camacho-Villa et al. (2016) discuss the need for adaptive information systems such as Mexico's MasAgro Hub framework in order to foster agriculture innovation in heterogeneous agro-environments via evolving, demand-driven, advisory services, including the use of Short Message Service (SMS) text alerts. Agroportal provides Greek farmers with a single access point for agriculture government and extension services and its in-development Android mobile platform facilitates chat and email communication between users and service providers (Karetsos et al. 2014). While pilots, prototypes, and case studies are available, public mobile apps to improve multidirectional (i.e., information that can transfer both to and from the app) agriculture knowledge exchange are extremely limited; we describe five such programs in Table 4.

Social networking platforms have transformed the way we communicate. Not surprisingly, we found some apps that provide social networking for agriculture, but these are focused on data sharing for business/project management (e.g.,

Table 4 Software for information sharing in support of improved sustainability across agricultural landscapes

Tool name	Purpose	Target audience/location	Description	Platform	Application to decision support tool for sustainable landscapes
CROPROTECT	Extension, networking; non-profit research sponsor	Growers, agronomists, UK	Provide guidance and knowledge exchange on pest, weed and disease management, IPM	Web, iOS, Android	UX, GIS integration of farm data, curated data; custom info delivery within community of interacting users, pest prevalence tracking
WOCAT	Education, decision support tool for SLM; UN-FAO and global partners	SLM specialists, national/regional policy, extension, land managers; global	Promote practices to reverse land degradation and improve livelihoods; digital SLM tool being developed	Web, iOS educational app	Multi-media, community exchange of practices (WOCATpedia), curated reference material; open-access, user-built global database
LandPKS	Education, data management, USDA and global sponsors	Local land managers, piloted in several sites across Africa and west Asia, available globally	Provide free, user-friendly access to SLM knowledge and technology training, sub-component assessment modules	Web, iOS, Android	Geo-referenced data collection and sharing, identify risks and ecosystem service potentials (e.g., productivity), open-source mobile apps linked to cloud global database, crowdsource data
PlantVillage	Extension, networking, university sponsor	Growers (especially smallholders), global	Democratizing access to knowledge for increased food production	Web, Android	Geo-referenced plant disease surveillance, knowledge exchange focused on diagnosis and response, crowdsource data, offline functionality
eFarm* (Yu et al. 2017)	Crowd-sourced geo data	Managers/farm households	Crowd sourcing and human sensing tool for geo-tagged images, management history of ag lands, parcel and higher	Desktop, Android	Various basemap sources (public, private), integrate bio-physical and socio-economic information at fine resolution via VGI
Land Quality Manager* (Ochala and Kerkides 2004)	Database management for (research) integrated agro-ecosystem	Researchers, land managers, policy-makers, Kenya	Desktop decision support tool integrating GIS with farmer supplied data for land quality assessment	Microsoft Windows, prototype	Indicator-based decision support tool, UX, custom dashboard, farmer-led modular assessment, GIS/ spatial analysis, interactive output maps and diagrams

* Website or app not available for further review

GIS geographic information systems, *UX* user interface, *VGI* volunteered geographic information, *SLM* sustainable land management

Agworld for iPhone) or food marketing (e.g., Foodshed) rather than on integrating environmental and socio-economic dimensions of sustainable agriculture. Bruce (2016) highlights the need for systems that combine formal scientific reporting and informal farmer knowledge networks based on social networking so that farmers can share "what works." The CROPROTECT project is being developed to facilitate farmer and research information exchange through a web- and mobile-based digital extension network. There are apps that explicitly address social well-being related to food and agriculture through social networking. We categorized these as consumer education apps (LoGOFF, MilkCrate for Communities, DoneGood: Ethical Shopping App) rather than farmer or land-manager knowledge sharing tools. We did not identify an app for social networking geared at exchanging knowledge about farmers' resource discovery or practical agricultural techniques for improving sustainability indicators.

Furthermore, we did not find mobile apps that support integrated triple-bottom-line sustainability assessment support. It is possible that desktop or web-based assessment tools such as SAFA (Food and Agriculture Organization (FAO) and SAFA 2013), MESMIS (Speelman et al. 2007; Astier et al. 2011), or SMART-Farm Tool (Schader et al. 2016) could be transferred to mobile platforms, but these tools are geared toward professional, trained assessors rather than mobile users in general and do not emphasize knowledge exchange per se. Ochola and Kerkides (2004) designed a spatial decision support tool within Microsoft Windows based on land quality indicators in Kenya, called Land Quality Manager. Farmers were involved in developing the prototype tool, which emphasizes assessment and classification of landscape quality, and identification of potential management solutions (Ochola and Kerkides 2004). The Environmental Sustainability Dashboard is a web-based decision support tool that combines GIS, field, remote sensing, and household survey data to compute metrics and visualize levels of ecosystem stress for a pilot Tanzanian agriculture assessment project (Fegraus et al. 2012). We identified apps that facilitate agriculture environmental assessments (EnviroWalk, GDA Nursery Assessment) or compliance-related inspections (organicgirl mobile assessments), but these tools do not integrate farmer knowledge or practical land management solutions.

4 Opportunities and challenges for apps supporting sustainability in agricultural landscapes

Significant technical challenges involved in digitally connecting diverse sources and outputs of information have been identified. For example, Jayaraman et al. (2016) compare Internet-of-things management software in the context of smart farming and created SmartFarmNet in a free, open-source platform called OpenIoT to include features that permit bring-your-own-sensors as well as big data analytics. Other hybrid cloud architectures that combine private-user data input with cloud-based databases have been conceived for sustainable agriculture (Xin et al. 2016) and landscape management (LandPKS, Herrick et al. 2016; Environmental Sustainability Dashboard for Tanzania, Fegraus et al. 2012). These programming architectures are optimized for biophysical and environmental data and may not address potential socio-economic data resources or data ownership/security issues, a topic of increased interest for researchers (Bronson et al. 2016). Nevertheless, technological advances in computing have improved trust and increased use of digital tools by farmers, especially for financial transactions (Babcock 2015). There is a burgeoning research community surrounding questions of access and ownership of information that argues that knowledge should be managed cooperatively as a "commons"—a type of public good (Hess et al. 2007), if we are to assess and ultimately manage socio-ecological systems (Ostrom 2009) and global resources (Carattini et al. 2017) more sustainably.

Beyond technical challenges surrounding data security and access, which are solvable given sufficient resources, there are socio-behavioral considerations in how and how much agricultural apps could be used. Rose et al. (2016) offer a checklist of features that can improve uptake of digital agriculture decision support tools based on an extensive survey of UK farmers and consultants. Lessons learned from implementation (or lack of implementation) for decision support tools related to agricultural climate risk management are described (Hochman et al. 2011; McCown et al. 2012) and include suggestions for conditions needed prior to undertaking design of decision support tools. Ochola and Kerkides (2004) report feedback from testers of a prototype decision support tool and suggest areas for improving a full release version. The lessons learned fall into performance, reliability, and user experience concerns as summarized in Fig. 4.

Decision support tools should be not only useful and effective but also flexible to farmers' enormously varied situations, in which compliance concerns may instigate change in practice. Tailoring the tool for a specific target (age, experience, farm type) can improve uptake to an extent, whereas development of a more generic platform with user-customizable functionality may reach a broader audience. The *platform* model enables value-creating interactions between producers and consumers of information (Parker et al. 2016) rather than directly suppling information. Users often try new tools based on peers' experiences, which reflects trust in both the science and the community of stakeholders including developers, researchers, extension agents, and marketers. Developers must be prepared to assure the sustained usefulness of the tool so as to warrant users' investment in time and money. Users appear

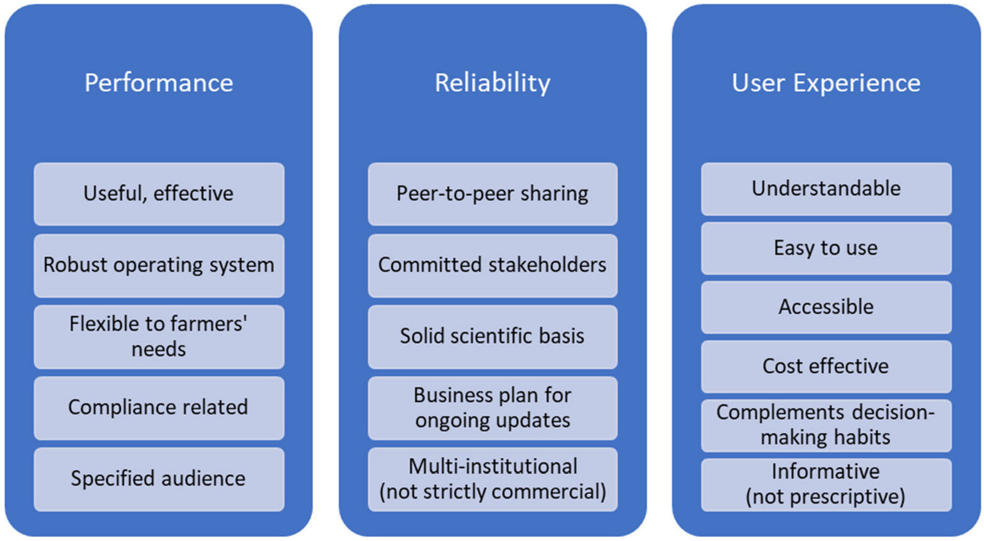

Fig. 4 Design of a digital decision support tool for improved sustainability in agricultural landscapes should consider performance, reliability, and user experience at the earliest development stage to enhance uptake by farmers and resource managers. Summarized from Rose et al. (2016), Hochman et al. (2011), and Ochola and Kerkides (2004)

skeptical of strictly commercial decision support tools. Developers should consider the user experience and user interface at the outset of tool design. Users seem to prefer a decision support tool that offers information to assist decision making rather than a prescription that replaces user knowledge and agency. For example, McCown et al. (2012) detail how Australian farmers used the decision support tool FARMSCAPE to improve their holistic intuition for making farm-level management decisions by recalibrating simple soil indicators to more complex simulation models of crop production under climate change. Further research is needed regarding what types of information would be honestly shared between farmers and other decision support tool users, who may also be competing for limited resources in marginal markets.

Provisions that balance transparency with personal security need to be carefully constructed to encourage dispersal of information and knowledge resources. Xin et al. (2016) propose a hybrid multi-cloud architecture for smart farming that allows both virtual and physical compartmentalization of privately derived data. Krintz et al. (2016) argue that data security and ownership concerns inhibit broader adoption of existing agriculture decision support tools, which often require farmers to relinquish rights to the data, and instead propose an on-farm "data appliance" called SMARTFARM to integrate farmer-generated data with cloud databases. On the other end of the spectrum are tools that rely heavily on volunteered geographic information, crowd sourcing, and "human sensors" to acquire bio-physical (e.g., IveGot1, Wallace et al. 2016) and/or socio-economic data (e.g., eFarm, Yu et al. 2017).

Agricultural landscapes are not always readily defined geographically: the system boundary depends on the process of interest. For example, water quality decisions within an agricultural landscape should consider the watershed in which agricultural production occurs and account for upstream and downstream activities. Likewise, marketing information may encompass a different set of geographic boundaries. This complexity creates challenges in identifying, finding, and visualizing contextual information (Schader et al. 2016). Furthermore, information needs of farmers and other agricultural actors are highly context specific to location, crop type, season, markets, production system, and equipment access. These information needs relate to goals for improving sustainability as well as boundaries within which stakeholders may operate. Designing software that automatically and correctly identifies those multiple system boundaries of agricultural landscapes is difficult to engineer and requires that users input contextual information. Thus, digital computing methods that incorporate GPS and Earth observation systems databases, as well as capacity for dynamic "smart" forms or questionnaires for user input, can reduce information overload by passing data through user-defined filters to quickly yield relevant information. Apps should provide a clear indication of current capabilities as well as the objective behind the app functionality.

We identified several agriculture apps that have a resource discovery component in the sense that users can digitally search for information themes (e.g., Agroportal, WOCAT SLM, Plantwise). LandPKS is being updated and expanded to include capacity for networking users to each other for peer-to-peer learning and to site-specific resources based on user input of farm contextual information and resource needs. It is presently focused primarily on soil bio-geophysical properties and land cover characteristics for management or restoration planning in efforts to improve sustainability (Quandt et al. 2018). The functionality available in the mobile assessment modules could be readily developed for improving sustainable agricultural landscapes by connecting socio-economic information to the user, based on geo-tagging. For example, if a farmer queries information on cover crops for improving land cover indicators, it would be useful to return information

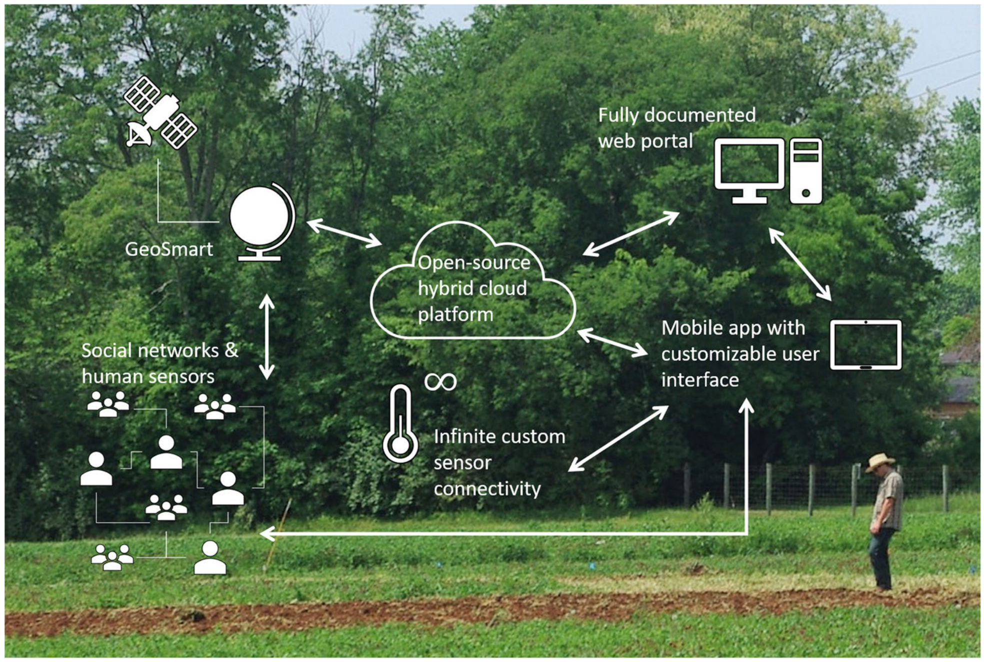

Fig. 5 Software design features recommended for a broadly applicable knowledge sharing system for improving sustainability of agricultural landscapes are illustrated: provision of a fully documented web portal linking digital cloud databases, geographic information systems including volunteered and crowd-sourced data, private sensors, and social networking platforms may improve performance, reliability, user experience, and thus uptake by development workers and farmers

on the varieties suitable for their plant hardiness zone and link to information regarding planting methods of those varieties—including neighboring farmers or extension offices and local seed suppliers or even online markets for seeds.

We summarize key features for an app that supports management decisions toward sustainable agricultural landscapes (Fig. 5). Clearly, compilation of GPS, GIS, remotely sensed, and geo-tagged micro-sensor data are necessary for successful agriculture landscape knowledge exchange. A hybrid multi-cloud server architecture can address the resulting big data processing needs. Less obvious perhaps is the method by which this compilation should be accomplished. A broadly applicable and adaptive knowledge sharing system based on robust science requires open source, infinite sensor integration with open data standards such as OpenIoT (e.g., as in SmartFarmNet, Jayaraman et al. 2016). Rather than a stand-alone app, a "deep" web portal linked to a mobile app allows for better documentation of a committed network of stakeholders and facilitates maintaining user/farmer ownership and access to uploaded data (Krintz et al. 2016; Xin et al. 2016). "Living system" design that undertakes continual adaptation and updates of app functionality would ensure its relevance over the long term. Ease of use issues may be addressed through an intuitive, farmer-centered, user interface (UX) with icon-based customizable "dashboard" display so that even low-literacy users can quickly access their priority information themes (Castillo et al. 2015; Herrick et al. 2016; Rose et al. 2016; Xin et al. 2016). Effective social networking for knowledge exchange in agriculture relies on establishing an adequate level of transparency with an emphasis on interpersonal relationships (Wood et al. 2014). Therefore, incorporating existing social media platforms (e.g., Twitter) and other direct communication capabilities (chat, text) within an app would be important for widespread adoption of a tool supporting sustainable landscape management.

An extensive, interconnected information provisioning system that includes environmental as well as social and economic aspects of agricultural sustainability requires multiple public and private institutional partners (e.g., as in LandPKS) and thus an innovative funding mechanism to ensure usefulness over the long term. In order to build a unified and broadly beneficial agricultural knowledge sharing app, it is important for software developers to understand the lessons learned from pilot projects and studies examined in this paper.

5 Conclusion

This review highlights the lack of mobile device or web-based applications that address sustainability across agricultural landscapes. Sustainability goals vary by stakeholder values and resources, and also influence the selection of a mobile decision support tool for use. There have been efforts to connect "big data" to farm management decisions, but these generally focus on agronomic or environmental compliance concerns within a single topic. Apps that connect farmers, extension agents, and other agricultural actors to information relevant to the ways in which farm management decisions affect landscape sustainability are still needed. Such an app should be capable of filtering cloud-based information using GPS inputs cross-referenced to GIS resources, generic Internet-of-things sensors, volunteered geographic information, crowd-sourced data, and social networking for broad knowledge exchange and peer-to-peer learning. Furthermore, a useful app can provide a straightforward user interface with dynamic smart forms for user data input and customizable data visualization.

Transparency regarding information ownership and use, as well as personal/ cyber security, is essential. Developing an app that is targeted initially to agriculture outreach professionals and policy makers may lay a foundation for later participation by a broader collection of agricultural landscape decision-makers including farmers, retailers, and government resources. Given a target end-user of extension/ outreach and policy personnel, app developers need to consider how the information can best be delivered, used, and exchanged with extension clients especially farmers. Because there are millions of apps available, and they are difficult to search or document systematically, it is useful to have an external website that can be easily shared with target audiences through a variety of outlets, rather than only through an app store. Without a web link, a niche app for agriculture is likely to get lost in the constantly evolving field of apps, and reliability and trust by potential users may be compromised.

By emphasizing knowledge exchange and resource discovery rather than Internet-of-things connectivity, an integrated sustainability app could help farmers identify practices that improve environmental, social, and economic indicators of sustainability on their farms within the context of the broader agricultural landscape in which they operate. The role of such apps is to support farmers' ability to make adaptive decisions based on available information, changing conditions, and evolving concerns rather than to simply provide prescriptive services. While an app with these features presents technical engineering and design challenges, the rapid pace of innovation in cloud-based data and open-source mobile applications suggests those barriers can be overcome. Major research efforts are needed to identify end-user information requirements, social networking preferences, and the usefulness of sensed data within specific agro-ecosystems in order to design a broadly relevant mobile app for improving social, economic, and environmental conditions of agricultural landscapes.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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