Technical Note

AgroTutor: A Mobile Phone Application Supporting Agricultural Sustainable Intensification

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Abstract: Traditional agricultural extension services rely on extension workers, especially in countries with large agricultural areas. In order to increase adoption of sustainable agriculture, the recommendations given by such services must be adapted to local conditions and be provided in a timely manner. The AgroTutor mobile application was built to provide highly specific and timely agricultural recommendations to farmers across Mexico and complement the work of extension agents. At the same time, AgroTutor provides direct contributions to the United Nations Sustainable Development Goals, either by advancing their implementation or providing local data systems to measure and monitor specific indicators such as the proportion of agricultural area under productive and sustainable agriculture. The application is freely available and allows farmers to geo-locate and register plots and the crops grown there, using the phone's in-built GPS, or alternatively, on top of very high-resolution imagery. Once a crop and some basic data such as planting date and cultivar type have been registered, the app provides targeted information such as weather, potential and historical yield, financial benchmarking information, data-driven recommendations as well as commodity price forecasts. Farmers are also encouraged to contribute in-situ information, e.g., soils, management, and yield data. The information can then be used by crop models, which, in turn, would send tailored results back to the farmers. Initial feedback from farmers and extension agents has already improved some of the app's characteristics. More enhancements are planned for inclusion in the future to increase the app's function as a decision support tool.

Keywords: volunteered geographic information; agricultural intensification; sustainability; smart farming; citizen science; SDGs; decision support tool

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1. Introduction

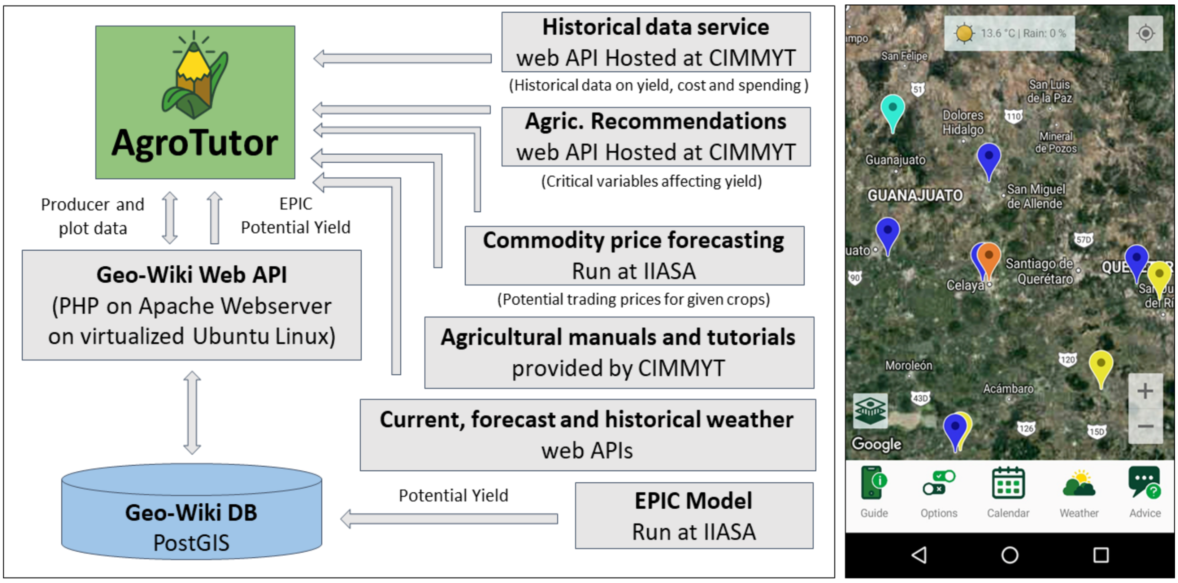
Sustainable agricultural intensification responds to the need for increased food production and improved ecosystem services while land availability is limited [1,2]. For agricultural inputs like fertilizers or pest control methods to be effective, the recommendations for their use need to be targeted to local conditions. Excessive input use due to generalized agricultural recommendations, apart from having damaging spillover effects in surrounding ecosystems [3], also increase the costs incurred by the farmer. Technology and knowledge for making agriculture more effective and environmentally friendly already exist [4]; however, across the world, farmers with low incomes do not tend to benefit from agricultural innovations and techniques [5]. Agricultural extension services are one of the most common responses for promoting and transmitting such knowledge, although in developing countries, agricultural extension services are usually over-stretched. Widespread mobile smartphone technology is one potential vehicle for promoting sustainable agricultural intensification, supporting existing agricultural extension services. The expected expansion of mobile phone use[1], especially smartphones[2], as well as the rise in crowdsourcing [6,7], have paved the way for involving farmers in a new information-rich economy, providing them data directly, while at the same time asking them to improve this information through locally-sourced knowledge inputs. For the International Maize and Wheat Improvement Center (CIMMYT) in Mexico, monitoring, evaluation and learning efforts are an integral part of innovation systems. Extension agents generate summary diagnostics in the existing data collection system, but farmers have been requesting feedback that is more detailed, benchmarking and more continuous access to recommendations than individual extension agents can provide in the current system. As a result, CIMMYT has identified the need to develop an openly available mobile app that draws upon the vast experience and information collected over the years, but also provides some of the functionality that can be found in proprietary apps. Working with the International Institute for Applied Systems Analysis (IIASA), a prototype smartphone application called AgroTutor was developed. The application is aimed at providing specific and timely agricultural recommendations for farmers across Mexico. It allows farmers to query information for crops at specific locations, providing targeted agricultural and benchmarking information. Here we present the technology behind AgroTutor and the information provided to its users, as well as initial feedback provided by farmers and extension agents on the application. We also briefly discuss how AgroTutor contributes to the implementation and measurement of several of the United Nations Sustainable Development Goals (SDGs).

2. The AgroTutor mobile app

Figure 1(a) provides a general overview of the application's current structure including the different components while Figure 1(b) shows a screenshot of the main landing screen of AgroTutor.

[1] https://www.statista.com/statistics/274774/forecast-of-mobile-phone-users-worldwide/

[2] https://www.statista.com/statistics/203734/global-smartphone-penetration-per-capita-since-2005/



(a) (b)

Figure 1. (a) AgroTutor data structure with its components and (b) a display of the main screen of the mobile application. Geo-Wiki is the current server at IIASA where data are stored and processed.

The current version of the app is built using Xamarin.Forms®, with Android and iOS versions. For building the architecture of the app, a modularity platform called Prism was chosen with a "Model – View – View – Model" (MVVM) approach [8]. The app is developed in two languages – English and Spanish – and allows for easy translation into other languages.

2.1. Information collected from the farmers

AgroTutor relies on the use of geo-location, allowing a farmer to register the position of a given plot, although a farmer can tap anywhere on the map display to query information or to register a plot. To store a plot in AgroTutor, a name is required as well as the planting date. If the crop is maize, the cultivar characteristics are also requested from the farmer (Table 1).

Table 1. Maturity classes and climate suitability options available in AgroTutor with their corresponding growing degree days (GDD) / Potential Heat Units (PHU) and base temperature (T_{base}) for maize (Adapted from Ruiz et al. (1998) and Capristo et al. (2007)).

Maturity class	PHU/GDD [°C]
Early	1680
Mid-early	1890
Intermediate	2100
Mid-late	2310
Late	2520

Climate suitability	T_{base} [°C]
Cold	4
Temperate/subtropical	7
Tropical	9
Hybrid	10

AgroTutor can also store cropping activities for each plot with their specific details, e.g., costs, dosage, price, etc. A list of available activities in AgroTutor can be found in Supplementary Table 1.

2.2. Information provided to the farmers

When pressing the Advice button (lower right corner, Figure 1(b)) and selecting a location and a crop of interest, a set of benchmarking information is displayed. The location and crop queried can then be stored as an agricultural plot, where the benchmarking information previously seen will also be shown but, additionally, all the stored plot information as well as weather information and a new menu with several actions will become available. Possible actions include adding cropping activities, adding videos and pictures, visualizing the crop calendar with plot activities and delineating the plot. The latter can be added using high-resolution imagery (from Google Maps) as a backdrop when online but also while offline, once a map layer has been downloaded[3].

2.2.1. Weather information

AgroTutor incorporates three types of weather information including: 1) current conditions, 2) a 10-day forecast, and 3) historical data. The information is specific to the queried location or field plot. The data are obtained from the API of aWhere[4]. The parameters shown include, amongst others, precipitation (mm), relative humidity (%), temperature (°C), and solar radiation (Wm^{-2}).

2.2.2. Historic yield potential

Based on the geo-location of the field and associated data (i.e., soil[5], climate [11], topography [12] and growing season [13]), selected representative cultivars based on Ruiz *et al* (1998), and water management (rain-fed or fully irrigated) farmers are provided with historic, non-nutrient and pest-limited yield potential estimates as a benchmark, derived *a priori* from crop model outputs for the time period 1980-2010. The results then provide information about the maximum yield potentially attained, but also the variability of these results for the selected location. Crop model simulations have been carried out with the well-established field-scale model, Environmental Policy Integrated Climate (EPIC) [14], within a spatial computational framework running the model for specific climate, soil, topography, and growing seasons in each pixel [15]. The yield potential provided is targeted to the farmer's plot locations but is currently limited to maize, although in the future, more crops could be considered if enough information is obtained from the field, e.g., using data entered by farmers into the application.

2.2.3. Benchmarking local information

Historical income, costs, profit and yield shown in AgroTutor are based on geo-tagged historical data from 197,714 experimental, demonstrative and pioneer farmers' plots across Mexico. A map of CIMMYT's support infrastructure is shown in Supplementary Figure 1 [16]. Since the historical data are geo-tagged, the information displayed is targeted to registered plots, crops and products, allowing the farmer to compare their own production costs, yields and profit against those from nearby fields to showcase their chances of improvement using real cases.

2.2.4. Windows of opportunity

Windows of opportunity are suggested 'best times' for executing agronomic management activities on the selected plot, based on known responses of a given cultivar type (Table 1). Currently, the system suggests the optimal nitrogen fertilizer split application for maize to the farmer, which allows for more efficient fertilizer use by minimizing losses compared to applying the full rate at planting [17–19]. This approach typically consists of a smaller start-up fertilizer dose applied at planting and a second larger dose once the crop enters a phase of rapid linear biomass accumulation, reached once the crop has accumulated 18-25% of the temperature requirement for maturing or

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[3] Layer is extracted from the "Mosaico Nacional" service available at http://WMS.SIAP.gob.mx/MosaicoNacional/

[4] https://developer.awhere.com/

[5] Soil profiles from the "Información Nacional sobre Perfiles de Suelo v1.2" service, produced by the Mexican National Institute for Statistics and Geography (INEGI), available at: http://www3.inegi.org.mx/contenidos/temas/mapas/edafologia/metadatos/ok_suelosesp.pdf

growing degree days (GDD) [20]. The windows of opportunity are then shown to the farmer in the AgroTutor calendar.

2.2.5. Recommended agricultural practices

The recommended practices are derived from analyses done by the International Center for Tropical Agriculture (CIAT-Colombia) on field data already collected by CIMMYT (see Supplementary Figure 1). Using machine learning algorithms, management practices related to higher yields are identified and subsequently shown as recommended practices for the area. The methodology used is based on previous studies on rice [21] and perennial crops [22] where random forest-based algorithms are used to assess the relevance of a set of predictor variables in explaining the output yield variability. The most frequent parameters highlighted for optimization are, e.g., cultivar sown, levels of fertilization, sowing density and some weather parameters. An example for the ranking of variables according to their importance as determined by the random forest model in Guanajuato is shown in Supplementary Figure 2.

2.2.6. Commodity price forecasting

This module provides farmers with direct information regarding projected prices at trading hubs for commodities such as wheat and maize, with predictions from 1 month to 12 months in advance. The method used to obtain forecasts of agricultural commodities is based on the estimation of an array of multivariate time series models making use of climatic, financial and macroeconomic variables, as well as market fundamentals corresponding to the particular commodity whose price is predicted (Crespo Cuaresmca et al., 2018; Cuaresma Crespo et al., 2017). The estimated models are validated making use of out-of-sample forecasting exercises with respect to historical data and both loss- and profit-based performance measures. Supplementary Figure 3 shows a comparison of actual and predicted corn price with confidence intervals for the year 2016.

2.2.7. Communication, data recording, accessibility, and user experience

Farmers can receive relevant messages on an ad hoc but targeted basis, e.g., training sessions in the area, or messages linked to motivation to participate, e.g., encouraging farmers to add information to the app. Features that allow farmers to document their plots, crops and practices using photographs and video are also included in the application. Documentation and messaging should also encourage farmer-to-farmer and farmer-to-expert discussions similar to that in the Digital Green project [23]. Since overall user experience and accessibility are crucial for technology uptake, the use of visual language, i.e., icons with few colors, simplified benchmarking information graphics, and direct access to information directly from the main map was emphasized during all stages of development of AgroTutor. Additionally, ensuring that basic smartphones (using the Android operating system) could employ the app was prioritized, since these are most common in the target rural agricultural areas. Based on smartphone penetration in Mexico[6], it was determined that AgroTutor should be available for Android versions 19 (4.4 KitKat) and later. Finally, since AgroTutor is the result of a non-profit collaboration, all information provided, including benchmarking and geo-located points of service, is free of charge.

3. Preliminary tests and farmers willingness to adopt

To promote AgroTutor amongst farmers, CIMMYT is preparing a deployment strategy that will include advertisement strategies as well as incentives for technicians and farmers alike. Nevertheless, initial feedback was already provided by 27 farmers and field technicians (extension agents). Some of the comments were recorded in four interviews and a workshop lead by a co-author (JMM) that took place in the CIMMYT offices in Guanajuato on February (n=10), while others were sent back via

[6] http://gs.statcounter.com/android-version-market-share/mobile-tablet/mexico/#monthly-201904-201904-bar

email after downloading the application (n=5) in September 2019, and the rest (n=12) were recorded on a two-day visit by CIMMYT personnel to farmers in 2 areas: Moroleón and Purísima del Rincon, in the state of Guanajuato, Mexico in October 2019. The feedback was provided for earlier iterations of the application, so some of the issues mentioned were already incorporated into AgroTutor, e.g., weather inconsistencies, app not responsive, bugs, app crashing, map not loading, etc. IIASA and CIMMYT are currently updating the application and including new features based on the feedback provided. Table 2 summarizes the comments received.

Table 2. Direct feedback for AgroTutor received from farmers and field technicians in Guanajuato

Positive characteristics	Challenges and suggestions
• Nice interface	• Loading map problems and storing parcel problems
• Good design	• Location problems, cascading problems - weather, benchmarking
• Friendly icons/design	• Historical weather problems /high data load requested
• Great characteristics such as windows of opportunity, weather, parcel delineation and registration, producer profile, benchmarking information	• Some activity fields are repetitive, some units are not fully matching field measurements (e.g., kg/bags)
• Would highly recommend it	• Too broad commercialization activity concept: Allow individual activities, e.g., transport, contract agriculture.
• Good that no individual farmer characteristics or information are shown	• Pest and disease activity: Allow for broader set of options, not only insecticide or fungicide
• Very useful for programming fertilization	• Some bugs and crashes happening with benchmarking data. Slow rendering sometimes. Slow loading.
• High useful for programming irrigation	• General flow and look: to fill in forms use an arrow rather than Enter. Add font size change (older farmers)
	• Share back with testers the changes or modifications made
	• Calendar - synchronize with telephone calendar for alerts
	• Allow the possibility of downloading reports
	• Employ more customization to engage user - to welcome the producer
	• Add guides to identify weeds, pests, and nutritional deficiencies - pictures/labels
	• Add tips section
	• Add activity: Soil identification (characteristics)
	• Add fruit trees
	• Maturity type is confusing. Better explanation needed
	• Allow exporting parcel location - map with coordinates
	• Add selling points with local prices
	• Add a calculator allowing conversion of units and transformations

Additionally, to investigate the farmers' willingness to adopt the AgroTutor app, a survey based on the Unified Theory of Acceptance and Use of Technology (UTAUT) [24–26] was conducted as part of a separate study. Although the full set of results is soon to be published, preliminary findings show that intentions to adopt the app were predicted by the app's perceived usefulness, how farmers believe that technical infrastructure exists and by the expectation of the farmers using the app to acquire new knowledge. These findings are useful for providing relevant feedback from the field to the app designers and developers as well as providing additional insights into ways of encouraging adoption.

4. AgroTutor and the Sustainable Development Goals: Current and potential contributions

AgroTutor was built to promote sustainable intensification of agricultural production, contributing directly to achieve food security, end hunger and to improve the nutritional status of farmers while at the same time increasing productivity of the land. The recommendations provided by the app on the use of pest and disease control, which help to ensure overuse of agrochemicals does not happen, will protect and regenerate the soil, and avoid contamination of the water table, restoring peri-agricultural ecosystems and protecting the surrounding environment. Recently, AgroTutor was mapped as a citizen science project that could potentially contribute to two SDG Tier III indicators [27], i.e., 2.4.1 Proportion of agricultural area under productive and sustainable agriculture, and 12.3.1 (b) Food waste index[7]. Recommendations of harvest and post-harvest management, which are being incorporated into the app and which are already accessible via links to CIMMYT's manuals and best practices, will contribute to avoidance of food waste and enhance financial gains for smallholder farmers.

Furthermore, AgroTutor has the potential to contribute to other SDGs as the range of services is expanded and refined based on stakeholder feedback in an iterative process. For example, since the app already allows for the delineation of parcels, it can potentially be adapted to contribute to initiatives such as FAO's Voluntary Guidelines for the Responsible Governance of Tenure [28]. This would support a crowdsourcing approach for collecting tenure-related details by farmer communities, thereby contributing to the monitoring of indicator 5.a (b) Share of women among owners or rights-bearers of agricultural land, by type of tenure [27]. Similarly, these features, together with farmer characteristics, can also potentially support the indicator 4.4.1 Proportion of youth and adults with information and communications technology (ICT) skills [27]. The youth participation in agriculture is a pressing challenge worldwide and specifically in Guanajuato, Mexico, where the pilot test of the app showed an average farmer age of 65, whereas close to 40% of producers in Mexico are between 46 and 60 years old [29].

By providing free access to high-quality recommendations to small farmers who cannot afford consultancy services, thus helping them to reduce costs and increase profits, AgroTutor provides a direct contribution to ending poverty (SDG 1). Also, the financial recommendations, such as expected commodity price forecasts, have the potential to empower farmers, especially female farmers, who may exploit this information to achieve higher profits for the sale of their produce and thereby enhance their self-reliance and the budget management of their families. Finally, the provision of environmentally friendly recommendations, e.g., guidance on how to perform conservation agricultural practices that store soil moisture, will help farmers to cope better with impacts from climate change such as recurring droughts, thereby strengthening their resilience and adaptive capacity to climate-related hazards and natural disasters (SDG 13, Target 13.1). Supplementary Table 2 provides a summary of the actual and potential contributions of AgroTutor to the SDGs.

5. AgroTutor and crowdsourcing with small farmers

This technical note has outlined AgroTutor, a mobile application developed to support sustainable agricultural intensification. The application was built with the understanding that small and medium farmers require decision support tools to strive for sustainable intensification that translates into higher profits for their families while having the lowest possible environmental

[7] Note that since the publication of [27], Tier III indicators no longer exist and both 2.4.1 and 12.3.1(b) are now Tier II indicators.

impact. Deployment of the app is currently under way in Guanajuato, Mexico, but a refinement of features as well as an understanding of how much information farmers can contribute, will depend on the additional feedback elicited by CIMMYT technicians after some seasons of testing in the field.

Even though the potential of citizen science data for monitoring the SDG indicators is being recognized [27], potential synergies and trade-offs arise when focusing on small farmers and agriculture [30]. When dealing with smallholders, satisfaction of basic needs is a priority, which may sometimes put them at odds with being promoters of sustainable development [31]. Moreover, it is very important to maintain privacy standards for crowdsourcing applications, especially in agriculture, so as to avoid potential issues or additional barriers that may hinder participation [32] or even set participants at risk by revealing critical information to the public. Hence, citizen science applications should not only focus on obtaining the data but in managing it fairly and not harm nor infringe upon any of the SDGs. In the best case, these applications should support smallholder basic needs and promote inclusiveness. The design of suitable, low-cost and simple technological solutions, which leaves no one behind, should be the core of agricultural citizen science projects and apps such as AgroTutor.

Supplementary Materials: Table S1: List of agronomic management tasks and activities currently available in AgroTutor, Table S2: Potential and current contributions of AgroTutor to SDGs, Figure S1: CIMMYT support infrastructure across Mexico, showing research platforms, modules, extension and impact areas. More information at http://bem.cimmyt.org/Inicio/Default.aspx (in Spanish), Figure S2: Output ranking of variable importance from the random forest model in Guanajuato - rainfed maize , Figure S3: Actual and forecasted corn prices with 1 and 2 standard deviations upper and lower (UCL, LCL) confidence intervals. Model forecasts shown for the year 2016.

Author Contributions: Juan Carlos Laso Bayas, Andrea Gardeazabal, Bram Govaerts, Luis Vargas, Michael Obersteiner and Steffen Fritz conceptualized the research; Mathias Karner, Luis Vargas and Christian Folberth organized the database; Mathias Karner, Moemen Saad and Anto Subash developed the application; Christian Folberth, Rastislav Skalský, Juraj Balkovič, Sylvain Delerce, Jesús Crespo Cuaresma and Jaroslava Hlouskova contributed with data and analysis for the different app modules. Janet Molina-Maturano and Luis Vargas contributed with the field feedback summaries. Janet Molina and Linda See contributed with additional insights into the SDG contributions of AgroTutor. Linda See edited the manuscript. All authors wrote different sections of the manuscript and contributed to manuscript revision. All authors read and approved the submitted version.

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