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Pronosticos AClimateColombia: A system for the provision of information for climate risk reduction in Colombia

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ABSTRACT

Climate variability poses major risks to agricultural production around the world, including in Colombia. Despite progress, major gaps still exist for the continuous provision of climate services for the Colombian agricultural sector. These gaps include lack of capacities in farming communities and technical assistants to understand and use seasonal forecast information, as well as the systematic provision of agro-climatic information. Here, we describe a user-centered digital agro-climatic forecast system that addresses several of these gaps. The system, named, "*Pronosticos AClimateColombia,*" and available at https://pronosticos.aclimatecolombia.org, formalizes the processing of climate and crop information from quality control, forecasting, and tailoring to crop-specific decision-making processes. The design, development and evaluation process captured user needs through regular engagement with key stakeholders ranging from the Ministry of Agriculture, the National Meteorological Service (IDEAM), as well as farmer organizations and farmers in a range of agricultural areas. We describe the process of design, testing and deployment of the system, in which forecast generation is performed as a series of automated steps, with agro-climatic forecasts issued on the 7th day of every month with a rolling lead-time of six months. We show that the constant gathering of user requirements and feedback resulted in users expressing substantial interest in using the system, though with some limitations on the level of understanding of the provided information. The limitations indicate a need for improved capacity at the local level. This underscores the importance of cyclical, continuous, feedback and discussion processes for climate services.

1. Introduction

Climate variability poses major risks to agricultural production around the world, especially in tropical developing countries where crops are grown primarily under rainfed conditions, in small to medium-sized farms, and by producers with limited access to resources (Iizumi et al., 2014; Rickards, 2012). In Colombia, climate variability is substantial (Poveda et al., 2010), impacting staple crop yield and agricultural livelihoods (Delerce et al., 2016; Ortega Fernández et al., 2018).

Systematic efforts to address climate variability in Colombia have been increasing over the last five years. One clear indication of this is that, as part of Colombia's Intended Nationally Determined Contribution (INDC), 15 Local Technical Agro-climatic Committees (LTACs) are being established across major agricultural areas (IDEAM and UNDP, 2017; Loboguerrero et al., 2018). These LTACs, led by

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farmers organizations and the public sector, develop and disseminate recommendations that provide farmers with options to respond to expected seasonal variations in climate (Loboguerrero et al., 2018). At the same time, Colombia's national meteorological service, the *Instituto de Hidrología, Meteorología y Estudios Ambientales* (IDEAM), generates and disseminates seasonal climate forecasts. Recent research indicates that these forecasts are suitable for agricultural decision-making in many regions (Esquivel et al., 2018; Fernandes et al., 2020). Furthermore, farmers organizations have started to use more Information and Communication Technologies (ICTs) to deliver agronomic advice and climate information to their farmers (Ramirez-Villegas et al., 2018).

Climate services are defined as the systematic provision of climate information to support decision-making (Hewitt et al., 2012). Climate services involve the production, translation, transfer and use of information for climate risk management (Vaughan et al., 2018; Vaughan and Dessai, 2014). While there has been substantial progress in the establishment of climate services for agriculture in Colombia (see Section 2.1), several challenges remain. In general, these various challenges can be synthesized as follows (Blumenthal et al., 2014):

1. The slow pace of meteorological data and information delivery such that received information is no longer timely and actionable;
2. The inability of decision makers, including farmers, to understand and apply climate data;
3. The poor quality of much meteorological data in terms of completeness and accuracy;
4. An unavailability of certain types of climate data on the spatial scale needed by users;
5. The inability to access available datasets held by public and private sector;
6. The lack of skill of seasonal forecasts for certain variables especially in areas where teleconnections are weak.

These limitations impede the correct extraction of relevant and timely information from web portals or mobile applications. In an effort to mitigate some of these challenges, climate services are evolving to increase access to and usability of new meteorological information, and to better leverage new technologies in meeting demand (Kolstad et al., 2019; Lourenço et al., 2016). Many recent advances and is associated with a shift from a science- or supply-driven perspective to a more holistic understanding of the "*servicescape*" (i.e. the landscape of existing services) and the importance of demand-side considerations from the outset (Alexander and Dessai, 2019). Several studies have demonstrated the value of web-based services for information provision, especially where user needs and capacities are at the center of the development process (Fraisse et al., 2006; Minet et al., 2017).

Here, we describe the development of a digital agro-climatic forecast system designed to provide highly automated climate services for agriculture in Colombia. The system, named "*Pronosticos AClimateColombia,*" formalizes the understanding of demand, then leverages this understanding to produce tailored information to support crop-specific decision-making processes. We developed the system for rice and maize crops, since these are the two most important staple crops in Colombia (FAO, 2018), and because they are substantially affected by climate variability across large parts of the Colombian territory (Delerce et al., 2016; Jiménez et al., 2019). We focus on describing the general context of climate services in Colombia (Section 2.1), and the development of the system including its software architecture and its usability from a user perspective (Sections 2.2 and 2.3).

2. Materials and methods

This paper describes the development of a system for the provision of climate services for agriculture in Colombia – *Pronosticos AClimateColombia*. System development was a co-creation process, implemented in consultation and collaboration with various next-users (farmers, extension agents, farmer organizations) and information producers (e.g. IDEAM). Developing the system began with a clear understanding of the context of climate services in Colombia, so as to result in a tool that integrates with other ongoing processes. The below sub-sections describe the overall context (Section 2.1), the system components (data, climate predictions, and crop predictions; Section 2.2), and the process of system development (Section 2.3).

2.1. Overview of AClimateColombia within the context of climate services in Colombia

The *Pronosticos AClimateColombia* system sits between the generation of forecasts and their use by agricultural stakeholders in decision-making (Fig. 1). Seasonal forecasts in Colombia are generated by IDEAM and other organizations using Canonical Correlation Analysis (CCA), implemented through the Climate Predictability Tool (CPT) software package (Ruiz and Melo, 2019). These forecasts are generated on a monthly basis with lead-times of 0–6 months, issued in the first week of the month, and provided in the form of probability maps. Seasonal forecast skill is generally considered sufficient for agricultural

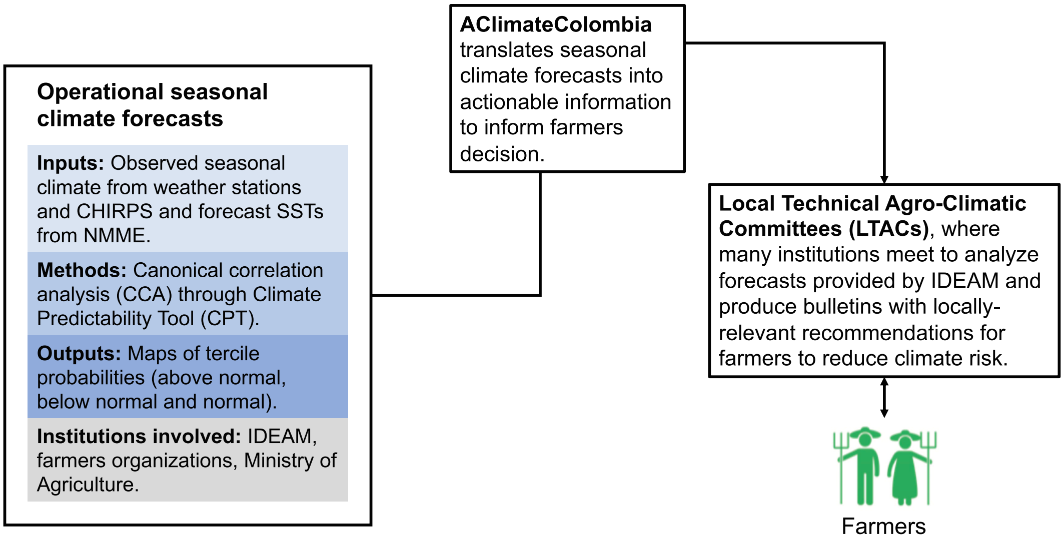

Fig. 1. Diagram showing the process of production and use of seasonal agro-climatic forecasts. CHIRPS: Climate Hazards Infra-Red Precipitation with Stations; SSTs: Sea Surface Temperatures; NMME: North-American Multi-Model Ensemble; IDEAM: Colombian Meteorological Service.

decision making (Esquivel et al., 2018; Fernandes et al., 2020). Dissemination of forecasts is made at the central level by IDEAM through a National Climatic and Agro-Climatic Bulletin (Bouroncle et al., 2019). These predictions and bulletins are used as inputs into a network of LTACs, which in turn make recommendations that are then delivered to farmers through bulletins, social media, TV, radio, local newspapers, and extension agents (Loboguerrero et al., 2018).

The *Pronosticos AClimateColombia* system role is to serve as an interface for translation and transfer of forecasts generated by IDEAM and disseminated through the LTACs. Being a web-based platform, the system also facilitates direct access to both general and context-specific climate information when users have sufficient capacity to understand and use the same. In *AClimateColombia* we implement seasonal climate forecasts using methods and configurations consistent with those in use by IDEAM (see Section 2.2.2), and connect these with crop simulation models of maize and rice (Section 2.2.3), to provide actionable information for decision-making related to the choice of planting dates and cultivars.

The system was initially developed and implemented for four departments (equivalent to states or Administrative Level 1 subnational boundaries) of Colombia where maize and rice are crops of primary importance (Fig. 2). The system was piloted in six localities across the four departments, and then scaled out to cover 34 localities across nine departments.

2.2. Climate and crop predictions

2.2.1. Meteorological and crop model data

Data required for developing the system included: (i) local level meteorological data from IDEAM's network of weather stations; (ii) crop experiment data for crop model calibration; and (iii) crop management data for seasonal crop forecasts.

We gathered local level meteorological data from 104 meteorological stations from the meteorological station network of IDEAM located in four departments, namely, Cordoba, Casanare, Valle del Cauca and Tolima (Fig. 2). The quality control for the observed meteorological data was done following Esquivel et al. (2018) by using the RClimTool software (Llanos-Herrera, 2014). The procedure involved three filters aimed at flagging and removing wrongly reported values based on a range check, outlier detection, and constant values. Data gap filling was performed at the monthly scale by means of a linear regression model that combines the Climate Hazards Infrared Precipitation with Stations (CHIRPS) (Funk et al., 2015) and the observed weather data from IDEAM (Esquivel et al., 2018).

Crop model data included experimental data for crop model calibration and evaluation, as well as crop management data and soil profile information for seasonal crop forecasting for the study sites. Crop experiment sites differed from the sites where the system was developed because of the logistical requirements of crop experiments (i.e. proximity to a research station or University with a laboratory to process samples). Sites for system development, on the other hand, were needs driven and chosen by the farmers' organizations.

Following calibration and evaluation, rice and maize modeling (see Section 2.2.3) for the system implementation in the four departments of interest required the definition of management practices (i.e. cultivars, planting dates, planting density, fertilization, and irrigation) and of typical soil profiles for each locality of interest. Management practices were defined following standard management by the rice and maize

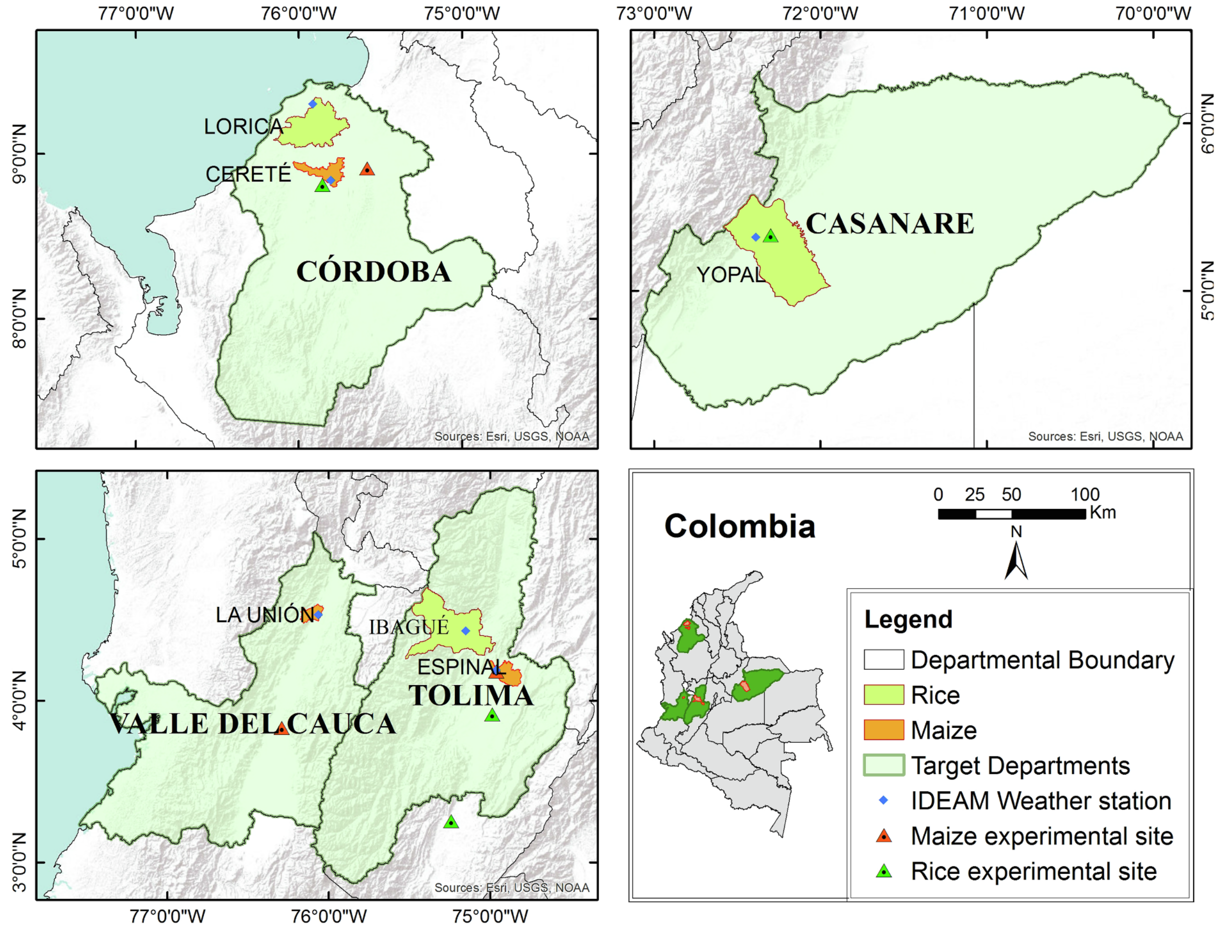

Fig. 2. Areas where the *Pronosticos AClimateColombia* forecast platform was deployed.

Table 1
Agronomic management at each site for which the system was developed.

Site	Weather station	Soil texture	Sow start (doy)	Sow end (doy)	Crop and system	Cultivar	Sow density (plants/m^2)	Nitrogen (kg/ha)
Lorica	La Doctrina	Loamy	295	30	Irrigated rice	Fedearroz 2000, 733, and 60	135	120
Yopal*	Yopal	Clay, Loamy	80	180	Rainfed rice	Fedearroz 174, and 2000	130	128
Ibague	Ibague	Loamy	1	365	Irrigated rice	Fedearroz 2000, 733, and 60	140	240
Cerete*	Turipana	Silty Clay Loam	122	305	Rainfed maize	Dekalb DK234, Pioneer P30F35	6.25	120
Espinal*	Nataima	Sandy Loam	275	138	Irrigated maize	Delakb DK7088, Fenalce FNC3056	6.25	166
Buga*	La Unión	Clay Loam	172	349	Irrigated maize	Pioneer P30F35	6.25	162

* Crop experiments were conducted at these sites (see Supplementary Table S1).

farmers' organizations (FEDEARROZ and FENALCE, respectively). At each site, soil samples were collected and analyzed at the soil laboratory of the International Center for Tropical Agriculture (CIAT) to determine the parameters necessary for crop simulation. Table 1 shows agronomic management and soil parameters for the six localities where the system was implemented.

2.2.2. Seasonal climate predictions

The seasonal climate forecasts produced within the *Pronosticos AClimateColombia* forecast system are generated through Canonical Correlation Analysis (CCA) (Goddard et al., 2001), implemented via the Climate Predictability Tool (CPT) software package (Mason and Tippett, 2017). The CCA relates Surface Sea Temperatures (SSTs) with local climate patterns to develop probabilistic forecasts, expressed in three categories (terciles): below normal, normal and above normal. Our implementation of the CCA model optimizes the initial (typically rectangular) predictor domain in the CCA. A first pass serves to identify the areas (i.e. pixels in the SST dataset) with most weight in the CCA, and then a second pass that uses only those areas. This results in a CCA model that maximizes both physical plausibility and forecast skill. All climate predictions are performed using the National Centers for Environmental Prediction (NCEP) Climate Forecast System version 2 (CFSv2) SST forecast (Saha et al., 2014) as the predictor variable, and seasonal precipitation as the predictand. The NCEP-CFSv2 model produces predictions with a 9-month lead-time, and with four initial conditions (starting at 0000, 0600, 1200, and 1800 h UTC), every fifth day.

The incorporated crop simulation models (see Section 2.2.3) for rice and maize require daily meteorological data as inputs. We compute daily weather data for all variables (i.e. precipitation, maximum and minimum temperatures, and solar radiation) by resampling the observed record for the season of interest (e.g. June-July-August) with replacement following the probabilities specified by the precipitation forecast for each tercile category (Capa-Morocho et al., 2016). To ensure having sufficient weather data for the crop model simulations, we concatenate the immediately following season (e.g. September-October-November, if the forecast is for June-July-August). The resampling is repeated 99 times to explicitly capture uncertainty in the resampling process. Because of the resampling process, 99 weather realizations with 180 days (i.e. for the next six months) are produced for use in the crop models (see Section 2.2.2).

2.2.3. Crop modeling

The included rice and maize crop models help translate seasonal climate forecasts into actionable information in support of two agronomic decisions, namely, the choice of planting dates and cultivars for each site of interest for any given seasonal forecast.

For rice, we used the ORYZAv3 crop model (Li et al., 2017). ORYZAv3 is an eco-physiological model that simulates growth and development of the rice crop under a variety of environmental and management conditions (Li et al., 2017, 2013). The ORYZAv3 crop simulation model allows simulating rice yield based on the soil–plant-atmosphere dynamics under potential, water-limited and nitrogen-limited conditions. The model has been evaluated in a number of climate and production situations (Li et al., 2013). For maize, we used the Crop Environment Resource Synthesis (CERES) maize model within the Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003) software package. The CERES-maize model has been in continuous improvement during the last three decades and is commonly used by the agriculture research community to simulate growth and development of maize in response to climate, soils, genotypes and agronomic management (Basso et al., 2016).

The calibrated and evaluated crop models were then used into the system to perform crop simulations (see Supplementary Text S1). The next step is, for each weather realization of a given seasonal prediction, to run the crop models for 45 planting dates starting on the first day of the forecasted season for all calibrated cultivars and using standard management for each site (Table 1). Outputs of the simulations then provide information (including uncertainty) to aid decisions on optimal planting dates and cultivars for each site and forecast situation, thus translating the seasonal climate information into the base of a context-specific agro-climatic service.

2.3. System development

The development of the *Pronosticos AClimateColombia* platform involved the collection of requirements and prototyping of the system, as well as a cyclical design and learning process, based on the life cycle and evolution model (Pressman and Troya, 1988). During each development stage, we gathered feedback from relevant stakeholders, and developed a new prototype. This process, developed and implemented jointly with IDEAM, the farmers' organizations, technicians and farmers (Fig. 3), helped assure consideration of user priorities and needs.

As shown in Fig. 3, we created an initial design of the system and its workflow, and prototypes for climate and crop forecast visualization (see Supplementary Fig. S1). We then carried out six workshops (one in each locality of interest in Table 1) with farmers and technical assistants to determine information needs at the local level and assess the visualization prototypes. These workshops had a duration of three hours, and consisted of four parts: (i) explaining basic concepts on climate variability and seasonal forecasting; (ii) present and discuss crop model outputs; (iii) creation of a calendar of crop activities; (iv) discussion and assessment of visualization options. The workshops identified priorities for system development, most notably the key decisions that required climate information, the timing of these decisions, and the preferred approaches to visualizing the results.

We then developed a complete list of requirements of the system; these were classified by their nature (user, system, functional and nonfunctional requirements) and by their function (backend, frontend). Using the full list of requirements, we then designed the system (architecture, frameworks, databases and programming languages) and developed a beta version. The beta version then went through two cycles of testing and improvement. The first cycle was done with a group of experts from the project, including the development team and crop-climate modeling experts at CIAT (International Center for

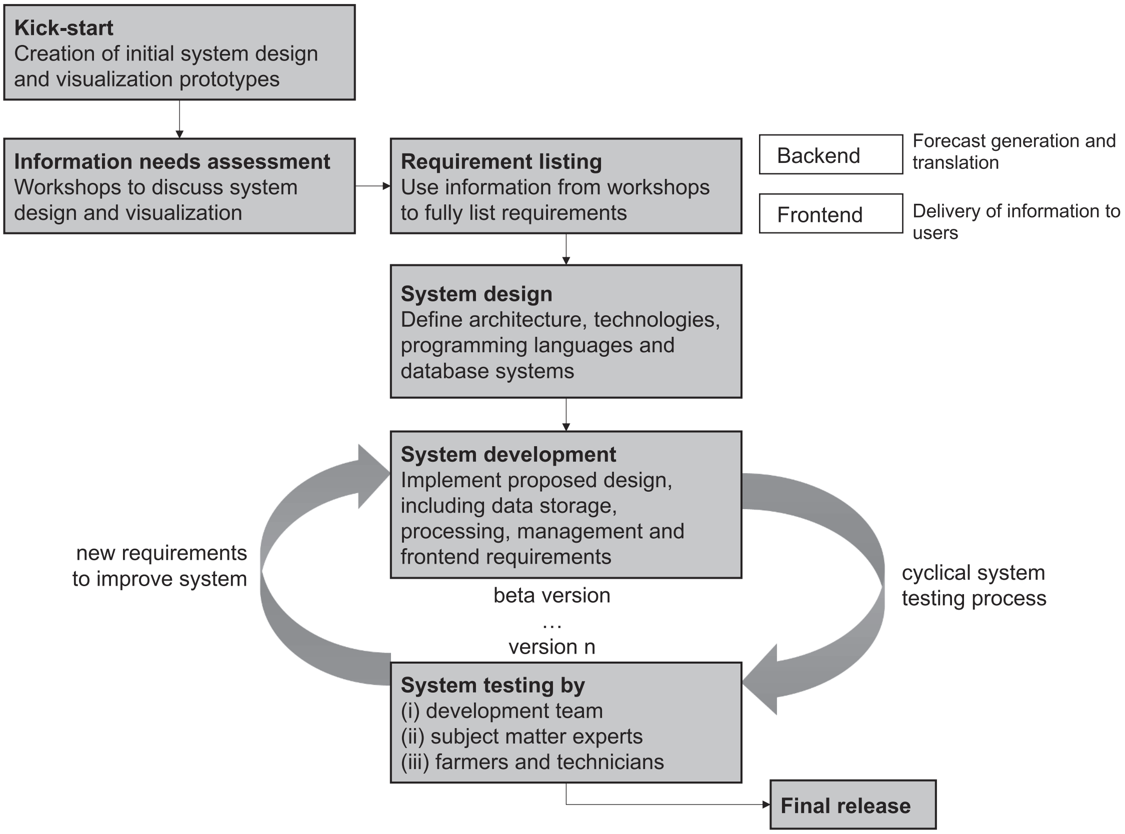

Fig. 3. Process of system development.

Tropical Agriculture), FEDEARROZ, FENALCE and IDEAM. The implementation of the additional requirements gathered by the first testing cycle led to the development of a pre-release version. This version needed to be fully functional since it was going part of the usability testing by users outside the project including farmers, technicians, farmer organizations, and IDEAM.

The usability study used a web-based survey and targeted relevant stakeholders for climate and crop information production and use for maize and rice. Surveyed users (192 in total) included farmers, farmer organizations' professionals, technical assistants, IDEAM staff, public institutions staff (e.g. from Ministry of Agriculture), Universities and other academic institutions, and private sector entities. The survey included a total of 21 questions to users and aimed at understanding (1) their capacity to extract information in the interface, (2) their perception of the interface usability and (3) recommendations on how to improve the interface. The complete questionnaire is presented in Supplementary File S2. Finally, once the results of the usability testing were analyzed, we implemented changes into the system in order to increase usability of the final release.

3. Results

3.1. Overview of the system architecture and operation

The launched version of the *Pronosticos AClimateColombia* system was the result a co-creation process and addresses multiple next-user needs and capacities to access, understand, and use information. The platform is accessible through a web browser either via a computer or a mobile phone with internet. The requirements were transformed into components (i.e. functional pieces of software), and all components collectively form the basis of the system. These components connect through explicitly designed interfaces that serve to standardize data flows. The connection of all components with the interfaces then enables a robust digital platform to provide agro-climatic forecast information.

3.1.1. System operation

The release version of the system, after incorporating results from the usability study (Section 3.2), is currently operational at https://pronosticos.aclimatecolombia.org. Its operation is illustrated in Fig. 4. Forecast generation is performed as a series of automated steps, with agro-climatic forecasts issued on the 7th day of every month, with a lead time of 0 to 6 months. The system first downloads NCEP-CFSv2 SST data and uses it together with meteorological station monthly precipitation data (stored in the '*climatic_data*' table of the database, see Supplementary Fig. S2) into CPT to compute the probabilistic forecast. Once the probabilistic forecast is done, the system creates weather scenarios that are then written in weather input files for ORYZAv3 (.CLI) and DSSAT (.WTH). The platform then performs agro-climatic forecasts through a set of files for soil, management practices and model parameters required by the DSSAT-CERES-Maize V4.6 and ORYZAv3 models. The structure allows the addition of new cultivars, soils and climatic data to expand the coverage of the climate service.

The system provides the end-user with probabilistic forecast information, interpreted results in terms of expected precipitation, temperature and solar radiation, as well as crop simulation results that allow selecting appropriate sowing dates and cultivars for maize and rice in the areas for which the system has been configured (Fig. 5).

3.1.2. Layers, components and deployment

Three types of layers, namely, frontend, database system, and forecast generation, support the operation of the system (see Table 2 and Supplementary Fig. S3). The foundation of the system is the database, which was built using the Mongo database engine (NoSQL technology, Supplementary Fig. S2). We used NoSQL due to the nature of the weather data (daily, multiple variables), which for a large number

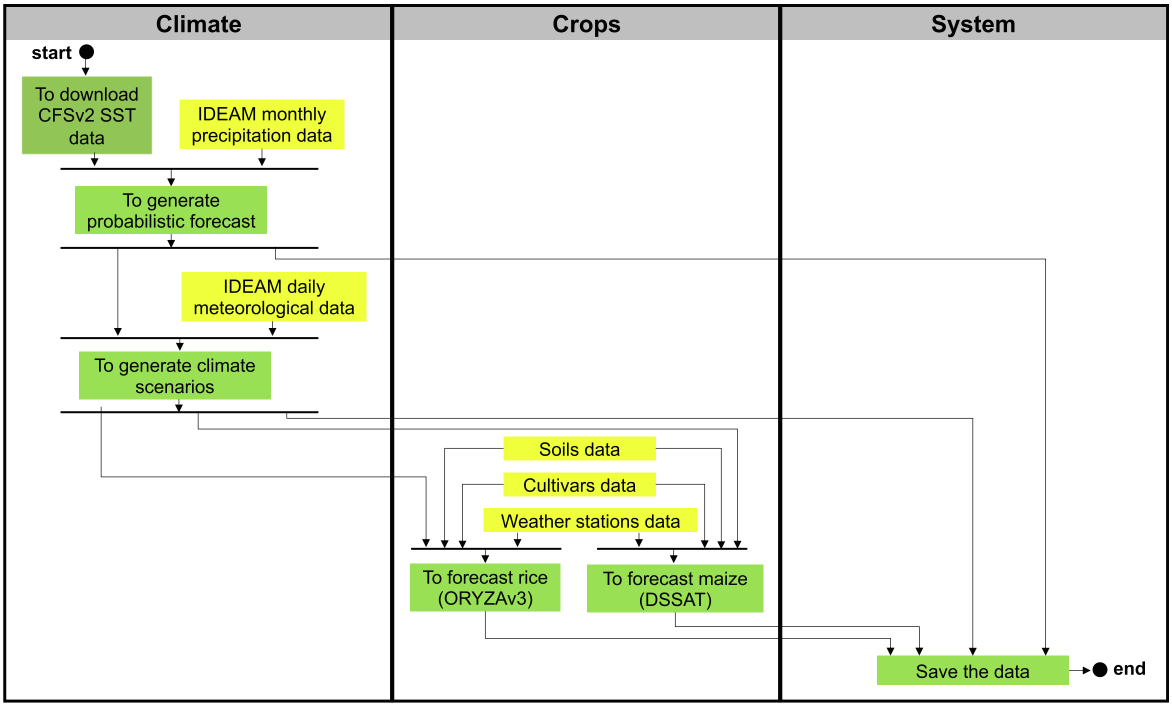

Fig. 4. Seasonal forecast generation diagram. Green boxes indicate major processes, and yellow boxes indicate data inputs.

of weather stations would be impractical or inefficient to implement in a standard SQL database. The 'Data Layer', which is a library built in C#, allows accessing the database for reading and writing. This layer includes functions and queries to retrieve data. Both layers compose the data management system. The 'Forecast App', which is a console application, allows data to be exported from and imported to the database, and serves as the interface between the database and the forecast generation process ('Forecast Generator').

Forecast generation is orchestrated by the 'Forecast Generator', managing the models described in Section 2.2. It takes the raw data and parameters (crops and weather) from the database and makes them available to the rest of the forecast process. The 'Probabilistic forecast (CPT)' generates a probabilistic forecast for a given season (as described in Section 2.2.1). Probabilistic outputs are then used to generate weather scenarios that are then used by either the 'Rice forecast (ORYZAv3)' or the 'Maize forecast (DSSAT)' layers to predict the performance of rice and maize crops for a given forecast situation.

Our use-case analysis illustrated the need to consider the user experience for two types of users. Expert-level users manage the system ('WebAdmin' layer), for example by changing crop varieties, soils or management used for crop simulations. The second type of user is an 'end user,' who accesses information for decision support. The 'Website' layer offers information to these users for visualization and reading. The 'Web API' layer exposes historical and forecast data through a REST (Representational State Transfer) web service for end-users who wish to use the data for analysis. Other apps can be connected to access historical and forecast data using the 'Web API' layer. Supplementary Fig. S4 shows a more detailed deployment view, including protocols and infrastructure required by the system.

The components are deployable in different servers in order to take advantage of available resources. The applications for generating forecasts must be deployed on a server using the Windows operating system, allow communication with the database, and allow for the storage of a relatively large number of temporal, log and configuration files. The 'Forecast.WebAdmin' and 'Forecast.WebAPI' require a web server exposed to the internet and connected to the database, whereas

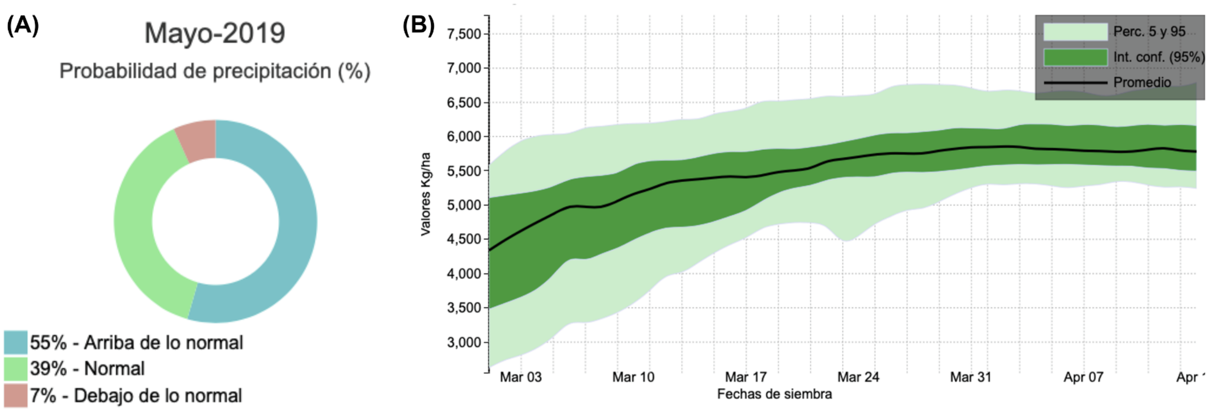

Fig. 5. Visualization of forecasts in the *Pronosticos AClimateColombia* forecast platform. (A) probabilistic forecasts; (B) variation in yield across a set of planting dates for rice.

Table 2

Detailed description of system components and their functionality.

Module	Component	Description
Frontend	Forecast.WebAdmin	Website which was built with ASP.NET Core MVC (Model-View-Controller). This website allows the management of parameters that affect the entire system. Users can use this to add new locations, cultivars, and soils, including the import of historical data (weather climate and crop performance). Additionally, this component is used to set the parameters of the execution of the forecast.
	Forecast.WebAPI	REST web service which was built in .Net Core. This service exposes the data of the platform (forecast and historical information). Users can choose two formats either JSON (JavaScript Object Notation) or CSV (Comma-Separated Values) depending on their needs.
	Forecast.Web	Website built in ASP.NET Core. This website allows displaying forecast and historical information (climate and crops). Users can get this information in many ways, including interactive graphics, texts, and tables. The design of these formats was driven by requirements from farmers and technical assistants.
Database System	Mongo DB	Scalable database component designed using the Mongo Database System that stores all the necessary data for the platform. It does not directly store configuration files that can be required by other components (e.g. files required by ORYZAv3, DSSAT or CPT), but it stores the paths where these files can be found.
	Forecast.Data	Dynamic-link library (DLL) built using .Net core. This component is an ORM (Object Relational Mapping) to connect the applications and the database. This component contains and drives all database queries.
Application for forecast generation	Forecast.ForecastApp	Console application built in .Net Core. This application interfaces between the R Scripts (Run main, Rice model, Maize model, probabilistic forecast, and forecast resampler) and the database. Exports parameters and historical data to generate the forecasts, and imports forecast results and stores them in the database.
	Run main	R script that orchestrates the forecast generating process. It calls all applications and scripts required in a specific order. This component, in each step, makes the inputs available for each function and stores the outputs for the next steps. At the end of each forecast, it stores the results in the database.
	Probabilistic forecast	R script. This component takes CFSv2-predicted SSTs and monthly precipitation data from weather stations to perform CPT run. Once the CPT run is completed, this component will extract the probabilistic precipitation forecast for the locations of interest.
	Forecast resampler	R script responsible for generating of daily weather scenarios. To do this, it resamples from the historical data following the precipitation probabilities predicted by CPT.
	Rice model	R script. This script performs rice crop model runs using the ORYZAv3 model, forced with weather scenarios generated by the forecast resampler, and the corresponding cultivars, soils and agronomic management data.
	Maize model	R script. This component takes the weather scenarios, model parameters (cultivars, species, ecotype), soils and agronomic management and executes DSSAT to generate the maize crop model run for a given forecast.

the 'Forecast.Web' is a website that uses services from the 'Forecast.WebAPI' to retrieve historical and forecast data. Users then access the website via a standard web browser.

3.2. Use, usability and suggested improvements

The web-based survey implemented here (see Section 2.3) informed our understanding of two key aspects of the system: (i) the users' capacity to extract information from the interface (5 questions); and (ii) the users' perception of the interface usability (10 questions). The survey also provided specific pointers on how to improve the system. The complete set of results is presented in Supplementary Table S2.

The first part of the survey (capacity to extract information) simulated actual system use, with potential next users going through the information provided and making simulated decisions based on their interpretation of the "season" in question. Results indicated that roughly half of farmers and non-farmers (i.e. national growers' association staff, technical assistants, and meteorological agency staff) interested in both crops (rice and maize) were able to identify and interpret information in the interface (Fig. 6). More specifically, 62 (52) percent of farmers interested in rice (maize) were able to find the information requested (see Supplementary Table S2 for question-specific results). Many (between 40 and 60% depending on the crop and type of user), however, were not able to find the information asked, answered that they did not know or provided a wrong answer. These findings underscore the importance of capacity strengthening, as well as the need for continuous improvement in the usability of the *Pronosticos AClimateColombia* system. It is noteworthy that professionals had similar or in some cases worse results in terms of interpretation of seasonal forecasts than farmers. This tends to confirm the general lack of training for both farmers and professionals on agro-climatology and seasonal forecast information interpretation in the regions where the system is deployed.

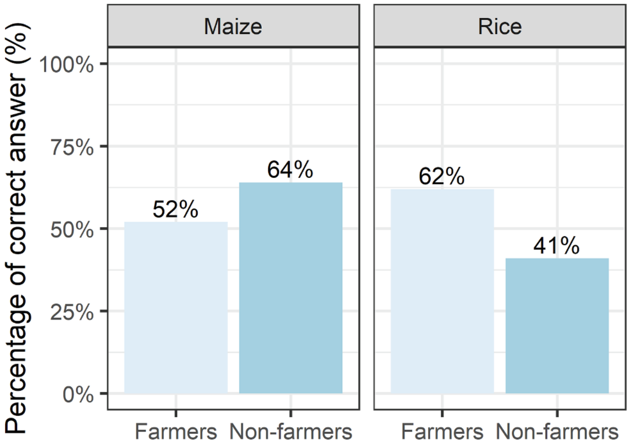

Fig. 6. Percentage of correct answers in the survey by maize and rice farmers and non-farmers. 'Non-farmers' refers to national growers' association staff, local technical assistants, and meteorological agency staff. Individual question results are shown in Supplementary Table S2.

After navigating the *Pronosticos AClimateColombia* forecast platform, we asked participants to share their perception on the interface and specifically on the use of the interface. This included questions regarding their interest in using the interface in the future and their perception of the interface's reliability. The survey respondents gave mostly positive feedback on the interface (Supplementary Table S2), confirming that the initial user requirement gathering process prior to system design and development was extremely useful. However, some survey respondents shared that they will need some support to use the interface. For instance, 53% of farmers agreed or strongly agreed that they would need such support. This confirms that training is required locally to enhance system usability. This is further confirmed by the fact that ca. 62% of farmers agreed or strongly agreed with the affirmation, "I need to learn a lot of things before I could get going with this interface."

Based on a synthesis of the results we conclude that farmers and non-farmers share a similar level of understanding and use of the interface. The majority of surveyed users expressed that they would need training to better use the interface although they already feel some level of confidence in using the presented information. Based on the usability test the team made several adjustments to the platform and developed a tutorial video to improve understanding of how to use the interface. The video is available in the platform's website at https://pronosticos.aclimatecolombia.org.

4. Discussion

4.1. Key lessons learned to maximize climate services usability and sustainability

We have developed a digital agro-climatic forecast system that addresses a key gap in the systematic provision of climate services in Colombia. The development of the system for delivering climate services for agriculture had to resolve the challenge of differing capacities between the climate service providers and its users. Specifically, the large quantity, detail and complexity of the information that a researcher or developer (i.e., the provider) intends to offer in a climate service needs to be tailored to the user and made accessible and understandable. Throughout the system development process, we addressed this challenge by continually capturing and incorporating user feedback, while maintaining a robust science-based set of modeling approaches and outputs as the backbone of the system itself. This counters the more typical 'loading-dock' or science-centered model for climate services production, whereby user perspectives and needs are rarely taken into account (Kolstad et al., 2019; Vogel et al., 2017). Here, we draw some lessons learned from this process as they are useful to maximizing climate services usability.

The development and refinement of the *Pronosticos AClimateColombia* climate services platform leveraged successive development cycles that involved not only the project team but also key stakeholders (farmers associations, IDEAM) and next-users (farmers and technicians) which were helpful in offering advice to improve the selection of information shared and the visualization thereof. We expect that this co-production process will enhance the adoption of the technology at different levels (Vaughan and Dessai, 2014). Notably, the similar level of understanding of the platform's information between farmers and non-farmers suggested that it was not necessary to create a distinct and more complex visualization of the forecasts for technicians or professionals. Clear and simple communication between information producers and users is key in ensuring effective use of climate information for decision making (Klemm and McPherson, 2017).

Importantly, we found that all participants to the usability test agreed on the need for complementary training to better use the interface. Such training (e.g. on agro-meteorology and/or interpretation of seasonal forecast information) will be important in reducing the risk of ineffective decision-making and mal-adaptation. Indeed, the current content of the portal assumes the understanding of climatic and even mathematical concepts, such as probability, forecasts, historical averages, among others. Limited understanding or capacity to interpret or apply forecasts, as well as perceptions of low forecast accuracy can severely limit the use and usefulness of seasonal predictions (Mase and Prokopy, 2014). Here, we find that despite feeling comfortable using the system, about half of the users failed to correctly extract information from the interface (Fig. 6). A further question (not addressed here) is whether once extracted, information is correctly used. Recent research suggests that increased use and usability is achieved when forecasts are provided early in the seasonal farm planning process, with sufficient lead time, and where they are tailored to specific decisions (e.g. planting date) (Klemm and McPherson, 2017). Therefore, while the platform addresses this (e.g. by providing an instructional video), training for farmers and technicians to be able to effectively use and act on a seasonal forecast remains important.

Finally, the development, implementation and scaling up of digital climatic services is useful when infrastructure requirements are fulfilled that facilitate its adoption and long-term continued use. These include internet connectivity, connection to the energy grid, computer availability, penetration of mobile phones, and general skills regarding use of computers and the internet. These challenges have been raised in multiple projects involving ICTs and will remain a key consideration for some time to come. Indeed, the non-adoption of a technology is often related to the lack of consideration of farmers' conditions and context, including their access to services. As infrastructure continues to improve in Colombia, continuous investment in climate services by the Ministry of Agriculture, farmers organizations, and IDEAM ensures the system is online and well-maintained.

4.2. Scaling up climate services in Colombia and beyond

Scaling up climate services requires addressing a number of challenges associated with the salience, legitimacy, access and equity of the climate information being delivered (Tall et al., 2014). This includes enabling inter-institutional links between the national meteorological services, national research organizations, farmers, and other stakeholders in alignment with principles of good practice from organizations at the global level including the World Meteorological Organization (Tall et al., 2014; Vaughan and Dessai, 2014). Moreover, the consideration of farmers' needs, the correct and timely capture of user feedback, and the increased and clear dialogue between information producers and users, are also critical elements to enable successful climate services (Tall et al., 2014).

We believe that the design elements taken into account for the development of the *Pronosticos AClimateColombia* forecast platform are relevant to allow scaling across Colombia and beyond. Foremost, during the development process, we fostered clear and continuous dialogue between a range of institutions and users. As a result, the system has been adopted in many instances as the starting point in participatory processes such as the previously mentioned Local Technical Agroclimatic Committees (LTACs) (Loboguerrero et al., 2018) (as envisioned in Fig. 1) and other processes using the Participatory Integrated Climate Services for Agriculture (PICSA) method (Ortega Fernández et al., 2018). In this way, the platform supports information-based dialogue between different types of users.

The technical components of the system are designed with scaling in mind and will lend themselves to other crops and the inclusion of additional data sources. For example, the use of the NoSQL database system allows storing large amounts of daily weather data from both historical information as well as system-generated forecasts. This structure readily enables the addition of more localities or more weather data sources. Similarly, other crop models can be added to generate new agro-climatic forecasts. We also note that while the system can be accessed through web browsers in mobile phones, mobile-specific applications can also be added to the system, therefore allowing multi-channel communication (Tall et al., 2014).

Finally, the system can also be implemented in other countries and regions, provided some effort in data identification and conversion and some level of consistency in forecast methods (i.e. use of CCA). In these cases, we suggest that additional requirements be determined from users and other stakeholders in these contexts. This will allow identifying appropriate weather, soil and management data sources; relevant crops; deployment areas; and modifications to language and delivery formats (e.g. inclusion of geographically-explicit data). Currently, there is an effort to tailor the *Pronosticos AClimateColombia* climate services platform to Ethiopian agriculture, addressing decision making for teff, wheat and maize crops led by the Ethiopian Institute for Agricultural Research (J. Said, personal communication). Potential for scaling also exists throughout Central America, in coordination with the Central America Climate Outlook Forum (CACOF).

4.3. Limitations and future work

While the *Pronosticos AClimateColombia* forecast platform is operational, improvements are still possible, and development is ongoing. Most notably, while we included feedback in the development of the system, it currently does not capture real-time feedback, which could be relevant for the continuous improvement of delivery formats, as well as for the monitoring of forecast skill. Continuous feedback from technicians and farmers can also help identify development outcomes when they occur. For instance, although not captured directly by the system, a recent review of outcomes in Colombia suggests that the use of agro-climatic seasonal forecasts, including from *Pronosticos AClimateColombia* has indeed helped reduce climate risk (Giraldo et al., 2019; Young and Verhulst, 2017). Real-time feedback can also help identify opportunities for capacity building, or for expansion of the system into new areas or crops. Capacity building, in particular, was herein identified as a clear user need. We note that the inclusion of more crops, as well as more localities (currently an ongoing process) would address information needs for more farmers across the region, in connection with already-ongoing participatory processes (e.g. LTACs).

Planned improvements to the platform include the incorporation of improved seasonal climate forecasts (e.g. from high-resolution dynamical climate models), especially for regions where skill of CCA models is limited (Esquivel et al., 2018), or where large-scale drivers other than SSTs have been identified (Fernandes et al., 2020). Similarly, the integration of forecast information at other timescales (e.g. sub-seasonal, weather) as these become available or translated in agricultural terms. Sub-seasonal forecasts, for example, may allow making shorter-term decisions such as may be relevant to irrigation and fertilization. Technical improvements may also be possible in the system including the parallelization of forecast generation in a cluster or server farm, and the inclusion of capabilities to display geographically-explicit information.

5. Conclusions

Climate services for agriculture seem to offer a great deal of potential for improving the resilience of agriculture to climate variability. In order for climate services to be effective, however, they must carefully consider next-user needs and the specific issues faced by the decision makers. In the development of a climate services platform for Colombia (available at https://pronosticos.aclimatecolombia.org), we show that a wide cross-section of users have a lot to offer to the design process. User involvement throughout the development process will ultimately be key in ensuring adoption and impact (Young and Verhulst, 2017). At present, maize and rice farmers and technicians generally respond favorably to the use of the system. We note the general limitations on the level of understanding and encourage others delivering climate services for agriculture to consider carefully the role of next-user training. This underscores the importance of cyclical continuous two-way feedback processes for climate services, including continuous training and improvement of delivery formats, as well as diversification of delivery channels.

CRediT authorship contribution statement

Steven Sotelo: Software, Writing - original draft, Investigation. **Edward Guevara:** Data curation, Software. **Lizeth Llanos-Herrera:** Data curation, Software. **Diego Agudelo:** Data curation, Software. **Alejandra Esquivel:** Data curation, Software. **Jeferson Rodriguez:** Data curation, Software. **Leonardo Ordoñez:** Data curation, Software. **Jeison Mesa:** Software. **Luis Armando Muñoz Borja:** Methodology. **Fanny Howland:** Methodology, Investigation. **Sebastian Amariles:** Software. **Alexander Rojas:** Resources, Writing - review & editing, Software. **Jhon Jairo Valencia:** Resources, Writing - review & editing, Software. **Cristian Camilo Segura:** Resources, Writing - review & editing, Software, Investigation. **Freddy Grajales:** Resources, Writing - review & editing, Software. **Francisco Hernández:** Resources, Writing - review & editing, Investigation. **Fabián Cote:** Writing - review & editing, Software. **Enrique Saavedra:** Resources, Writing - review & editing, Investigation. **Franklyn Ruiz:** Resources, Writing - review & editing, Software. **Julieta Serna:** Resources, Writing - review & editing, Software. **Daniel Jimenez:** Writing - review & editing, Conceptualization. **Jeimar Tapasco:** Writing - review & editing, Conceptualization. **Steven D. Prager:** Conceptualization, Supervision, Project administration, Writing - original draft, Writing - review & editing. **Pete Epanchin:** Supervision, Writing - review & editing. **Julian Ramirez-Villegas:** Conceptualization, Supervision, Project administration, Methodology, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.compag.2020.105486.

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