# Agroclimatic zoning methodology for agricultural production systems in dry Caribbean region of Colombia

## Metodología de zonificación agroclimática para sistemas de producción agrícola en la región Caribe seco de Colombia


**Fabio Ernesto Martínez M.[1], Leidy Yibeth Deantonio F.[1], Gustavo Alfonso Araujo C.[1], Edwin O. Rojas[1], Douglas A. Gómez-Latorre[1], Diego F. Alzate[1], Lilia A. Ortiz[1], Elizabeth Aguilera G.[1], and José F. Boshell-Villamarin[2]**



### ABSTRACT

The agricultural sector in Colombia and especially, small-scale agriculture subsector in the Colombian Caribbean has been very vulnerable to the negative impacts of climate variability in part due to the poor existence and lack of access to agroclimatic information. The objective was to build a methodology for agroclimatic zoning for crops growing in Colombian dry Caribbean. To achieve this goal, a case study of tomato crop growing in the municipality of Repelon (Atlantico, Colombia) was selected. The methodology was based in the combination of crop-specific soil suitability assessment and the monthly probability of a humidity condition occurrence in the soil for tomato production under water deficit. Probability was constructed through water balances generated from the Palmer drought severity index, calculated for each month of crop production cycle during the 1980 to 2011 series. The resulting maps show defined areas called Productive Niches with lower limitations per soil and low probabilities of soil water deficit in the growth of tomato crop in the municipality. The methodology can be used to delineate areas suitable for planting tomato or other crops in climate variability events in the dry Caribbean region of Colombia.



**Key words:** agroclimatic risks, territorial planning, mapping, water balance.



### RESUMEN

El sector agrícola en Colombia, especialmente el subsector de agricultura a pequeña escala del Caribe colombiano, ha sido vulnerable a los impactos negativos de la variabilidad climática por causa de la escasa disponibilidad y acceso a la información agroclimática. El objetivo del estudio fue construir una metodología de zonificación agroclimática de cultivos en el Caribe seco colombiano. Para lograrlo fue seleccionado como estudio de caso el cultivo de tomate en el municipio de Repelón (Atlántico, Colombia). La metodología se basó en la combinación de la aptitud de suelos para el cultivo de tomate y la probabilidad mensual de ocurrencia de condiciones de humedad en el suelo de déficit hídrico. La probabilidad fue construida por un balance hídrico generado a partir del índice de severidad de sequía de Palmer, calculado para cada mes del ciclo de desarrollo del cultivo, con series de datos del período comprendido entre 1980 y 2011. Los mapas resultantes muestran áreas definidas llamadas “nichos productivos”, las cuales presentan bajas limitaciones por características del suelo y bajas probabilidades de déficit hídrico en el suelo durante el ciclo de desarrollo típico de tomate en el municipio. La metodología puede ser utilizada para delimitar áreas aptas para el tomate y otros cultivos bajo eventos de variabilidad climática en la región del Caribe Seco colombiano.



**Palabras clave:** riesgo agroclimático, planificación territorial, cartografia, balance hídrico.


## Introduction

The increase in the frequency and intensity of extreme weather events has led to frequent conditions of water excesses and deficiencies with negative impacts upon agricultural production (IPCC, 2012) due to the reduced growth and development of plants because of water stress (Moreno, 2009; Fischer *et al*., 2016) and increased incidence of pests, diseases, and weeds (Seidel, 2016; Corpoica, 2013). Water deficiencies and droughts, associated to the El Niño phenomenon of 1997-1998 and considered one of the most severe in recent years, generated losses in the national economy in the order of US$563.5 million, which represented close to 1% of the national Gross Domestic Product (GDP) for 1998 and affected negatively close to 0.5% of the country’s economic growth (UNGRD, 2014).

The Colombian Caribbean suffers even more prolonged dry periods. The most frequent occurrence of the events of warming and abnormal cooling of the surface waters of the equatorial Pacific Ocean (events known as “El Niño “ and “ La Niña”, respectively) will also cause more frequent


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[1] Tibaitata Research Center, Colombian Corporation for Agricultural Research (Corpoica). Mosquera (Colombia). femartinez@corpoica.org.co
[2] Consultant Corpoica. Mosquera (Colombia).

and severe periods of scarce or excessive rains. Repelon, located in Colombian dry Caribbean, derived much of its sustenance from agricultural activities like the tomato crop, an important and traditional product in the region, however the limited environmental offer of South of Atlantico department (tropical dry forest and arid soils) restrict the agricultural activities despite the existence of water sources and irrigation systems.

Given this scenario, agroclimatic zoning of the territory constitutes a risk management strategy that guides the implementation of prevention and adaptation measures upon adverse weather conditions (Brunini *et al*., 2010). It is a key tool to determine the agricultural potential, territorial planing, and soil management in agricultural production areas (Yazdanpanah *et al*., 2001; Brunini *et al*., 2009).

Currently, diverse agroclimatic zoning approaches has allowed the implementation of public policy for agricultural development. Those mainly include the assesment of agroclimatic risk through agroclimatic indices like proposed by Zullo *et al.* (1999). They employed water availability in reproductive states of cotton to zone agroclimatic risk in São Paulo (Brazil), especially against drought conditions. Yazdanpanah *et al.* (2001) defined areas with higher agroclimatic suitability for rain fed almond and the agroclimatic zoning of the province of Azarbayjan-Sharghi (Iran) by calculating indices. White *et al.* (2001) considered the relationship between rain and potential evaporation, minimum and maximum temperatures within the agroclimatic characterization of areas of wheat production in Ethiopia. Geerts *et al.* (2006) mapped the agroclimatic suitability for the quinoa crop in the Bolivian plateau from the reference evapotranspiration, the duration of the rain season, periods of drought, and risk of frost. Moeletsi *et al.* (2011) introduced the Poone Agroclimatic Suitability Index (PACSI) to integrate the most important climatic risks for maize production in Free State, South Africa.

In general, most agroclimatic zoning methodologies, which consider the soil within their analysis, include information from water-storage capacity parameters or from physical-chemical aspects, but not an integration of both. Due to the aforementioned, the aim of this work was to establish an agroclimatic zoning methodology that include the crop-specific soil suitability in terms of physical-chemical offer and water balance in terms, in this case, of water deficit for crop. Despite that the methodology was applied in the municipality of Repelón in the department of Atlantico it can use in all the territory and for different agricultural species in Colombia.

## Materials and methods

### Study zone

The municipality of Repelon (Fig. 1) is located to the west of the department of Atlantico, between coordinates 75°01' and 75°15' longitude west and 10°23' and 10°36' latitude north, with altitudes ranging between 30 and 540 m a.s.l. Its surface area covers 35,172 ha (10.6% of the total area of the department of Atlantico) and the predominant landscape is that of hills with 40% of the area, followed by flatlands with 31%. The Guájaro reservoir stands out, a lentic body of over 9,500 ha.

### Approach

Zoning of agroclimatic suitability was conducted by bearing in mind the definition of agroclimatic risks (IPCC, 2012), based on the crop's exposure to extreme weather events (defined by its location in the territory) and the species' sensitivity to water stress. The methodology was based on overlaying two types of analysis for the crop. The first for crop-specific soil suitability assessment (FAO, 1976) and the second for probability of occurrence of water deficit in the soil (Palmer, 1965) during the phenological stages of the crop. The areas of lower agroclimatic risk, denominated *Productive Niches* indicate agroclimatic characteristics (per soil and climate) of lower restriction for tomato production.

### Crop-specific soil suitability assessment

The methodology proposed by FAO (1976) was used at 1:100,000 scale, which confronted the edaphological requirements of tomato crop (Tab. 1) and the soil offer described in the units of land (UoL) presents in Repelon. Crop requirements were obtained from secondary sources and interviews with technicians, local farmers, and researchers from the Colombian Corporation for Agricultural Research (Corpoica). The characteristics of the UoL were obtained from the general study of soils for the department of Atlantico (IGAC, 2007). Characteristics related to the genesis and evolution of the soil units were used, as well as chemical pH variables, aluminum saturation, and salinity.

Thereafter, with this information decision trees were generated to qualify the suitability of use of the UoL for the tomato crop into three categories: "optimum" (A1): the characteristics of the soils evaluated are within adequate ranges; "moderate" (A2): the soils present one or two requirements that do not correspond to the most adequate values; "marginal" (A3): corresponds to soils with one or more restricted characteristics to establish the crop and the class "unsuitable"; (N): soils with very restrictive conditions for the crop's establishment and adaptability.

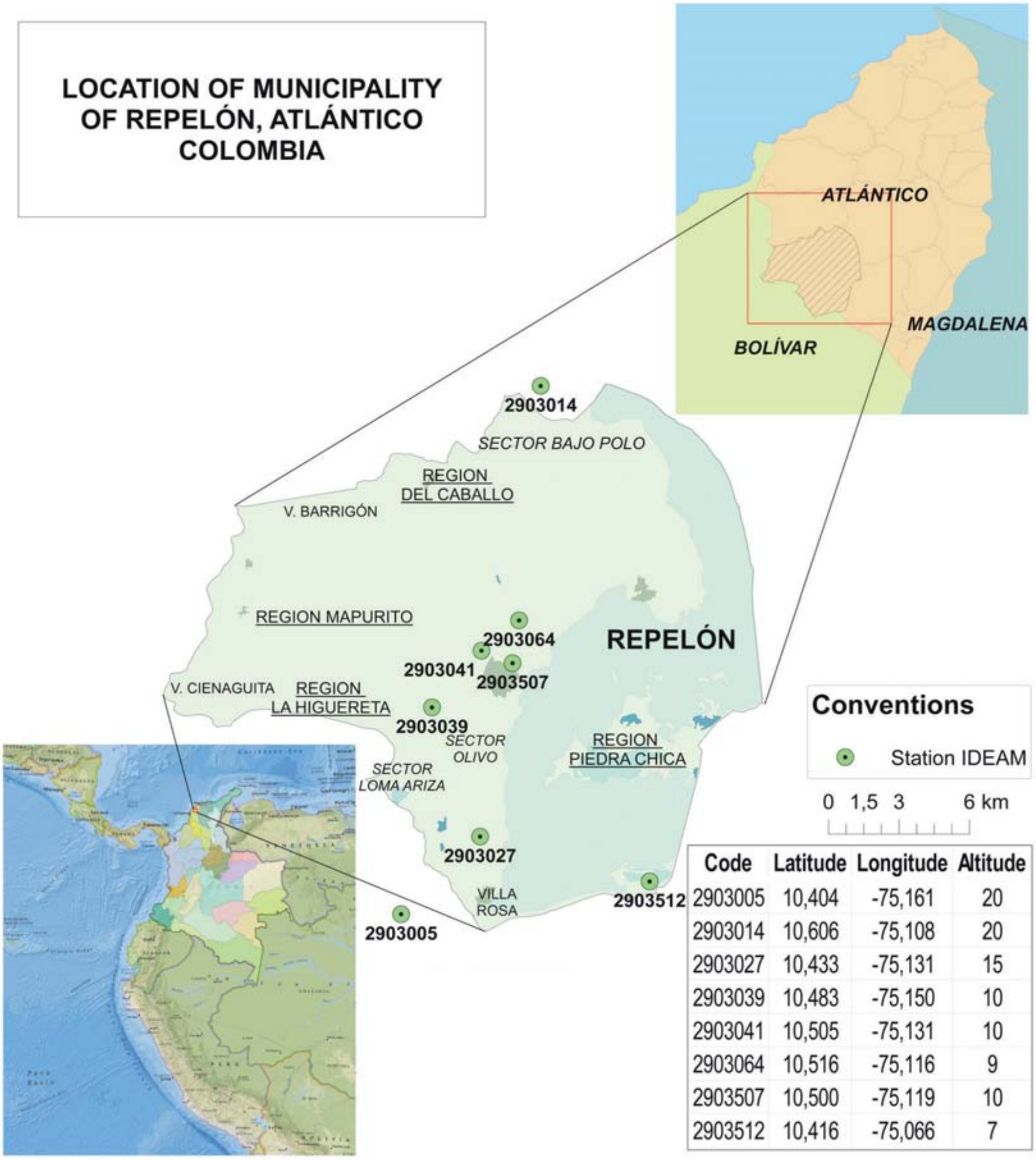



**FIGURE 1.** Location of municipality of Repelon, Colombia. Location and geographic coordinates of stations used in the study. Green dots indicate location of active weather stations.

**TABLE 1.** Edaphological requirements for the tomato crop, after Carrillo and Raish (1988) and García *et al.* (2004).

| Diagnosis factor | Unit | Ranges | | |
|---|---|---|---|---|
| | | Optimum | Moderate | Restricted |
| Class of soil drainage | Class | Good | Moderate | Imperfect to marshy |
| Slope | % | < 7 | 7-25 | >25 |
| Effective depth | Class | Moderate or deeper | Superficial | Very superficial |
| Texture | Class | Medium to coarse | Fine | Very fine |
| Reaction | pH | Slightly acid | Moderately acid | Strongly acid |
| Saturation of aluminum (SAI) | % | <15 | 15 | >15 |
| Salinity (CE) | ds $m^{-1}$ | <2 | 2 a 4 | >4 |
| Altitude (m a.s.l.) | M | 0 – 2,000 | 2,000 – 2,500 | >2,500 |

### Probability of humidity occurrence of water deficit in soil

The probability was calculated from the monthly historical series of the Palmer drought severity index (PDSI) (Palmer, 1965) during a 32-year period (1980 to 2011). The calculation of the Palmer index was generated by interpolating the monthly averages of precipitation and reference crop evapotranspiration rate (ETo) (FAO, 2006) calculated with the monthly historical series of the variables of mean maximum temperature, mean minimum temperature, relative humidity, and sun shine registered by eight stations belonging to the meteorological observation network of the Institute of Hydrology, Meteorology, and Environmental Studies (IDEAM) available in the area of analysis (Fig. 1).

The series were subjected to a quality process and complementation of missing data that included four stages: a) verification of the physical and statistic coherence (spatial and temporal) of the climatic series (Guijarro, 2011); b) homogeneity analysis of the series (Alexandersson test); c) complementation of missing data (Guijarro, 2011), and d) validation of the general quality control process (McCuen test).

The water storage capacity in the soil (required to calculate the PDSI) was determined from the texture and depth of the profiles and modal horizons of the soil units (IGAC, 2007) where each weather station is located. With the USDA-ARS tool (Saxton and Willey, 2005) the field capacity (FC), permanent wilting point (PWP), and saturation point (SP) values were assigned to each texture and modal class identified.

The PDSI qualifies soil humidity qualitatively at monthly level into 11 categories that range from extreme humidity to extreme drought (Tab. 2). Bearing in mind this qualification and the crop's sensitivity to the stress caused by water deficiencies in the soil (Rao *et al.*, 2000), the PDSI categories were defined, which indicate extreme restrictive soil humidity conditions for the crop (extreme deficiencies that cause partial or permanent damage to the crop). For tomato, it was considered that PDSI values below -2.0 indicate extreme water deficit (Tab. 2).

Monthly frequency of occurrence of extreme water deficit (PDSI < -2.0) values was determined per station for the 32 years of analysis (1980-2011) based on a sample that only included the PDSI categories corresponding to all water deficit conditions (slight and extreme water deficit, values < -0.5).

Based on the frequencies obtained per station, the monthly probabilities of occurrence of extreme water deficit in soil were determined for months corresponding to the productive cycles and modal phenological calendars of the tomato crop reported by technical assistants and producers from the municipality (Tab. 3).

**TABLE 2.** Regrouping of PDSI categories under slightly restrictive and restrictive soil humidity conditions for tomato crop.

| Humidity condition in the soil for tomato crop | PDSI categories | PDSI value | Index range and thresholds |
|---|---|---|---|
| Extreme water excess | Extremely humid | ≥ 4.00 | > 2.0 |
| | Very humid | 3.00 to 3.99 | |
| | Moderately humid | 2.00 to 2.99 | |
| Slight water excess | Slightly humid | 1.00 to 1.99 | 0.5 to 1.99 |
| | Incipient humidity | 0.50 to 0.99 | |
| Normal | Normal | -0.49 to 0.49 | -0.49 to 0.49 |
| Slight water deficit | Incipient drought | -0.50 to -0.99 | -0.5 to -1.99 |
| | Reduced drought | -1.99 to -1.00 | |
| Extreme water deficit | Moderate drought | -2.99 to -2.00 | < -2.0 |
| | Severe drought | -3.99 to -3.00 | |
| | Extreme drought | ≤ -4.00 | |

Source: adapted from Palmer (1965).

**TABLE 3.** Productive cycles and phenological stages of the tomato crop in Repelon (Atlantico).

| Phenological stages | Productive cycle 1: October transplant | | | | Productive cycle 2: November transplant | | | |
|---|---|---|---|---|---|---|---|---|
| | October | November | December | January | November | December | January | February |
| Initial vegetative | ■ | | | | ■ | | | |
| Flowering | | ■ | ■ | | | ■ | ■ | |
| Fruit filling | | | ■ | ■ | | | ■ | ■ |

Five levels were established to qualify the probability of occurrence of extreme condition to October-February. For each level was assigned a letter to facilitate the interpretation over the cartography: "*A*" very low (0 to 20%); "*B*" low (20 to 40%); "*C*" medium (40 to 60%); "*D*" high (60 to 80%), and "*E*" very high (80 to 100%).

### Monthly agroclimatic scenarios

To know the spatial variability of the soil suitability and extreme humidity conditions in the soil for the crop, overlaying was carried out of the mapping of *crop-specific soil suitability assessment* for tomato with the monthly probability mapping of occurrence of extreme water deficit. The total of cartographic outputs was established in function of the months corresponding to the productive cycles (October - February) and of the soil's humidity condition.

### Zoning of the agroclimatic suitability

Of the total of *monthly agroclimatic scenarios* generated for water deficit in soil, areas were identified that persistently registered: a) high probability of extreme water deficit and b) low probability of extreme water deficit in soil. One representative cartographic output was selected for extreme water deficit. Thereafter, to summarize the crop-specific soil suitability assessment outputs, three groups were established: optimum soils or with slight restrictions (A1 and A2), conditioned to practices of management and/or conservation of soils (A3) and unsuitable soils (N). After selecting the map and summarize soil outputs, the municipality's agroclimatic zoning for tomato crop was conducted according to the qualification matrix of Tab. 4.

Agroclimatic zoning presents six categories of which the "optimum productive niches or with slight restrictions" and the "productive niches conditioned to practices of management and/or conservation of soils" represent low risk for the crop, given that they present low or very low probabilities of water deficiencies, and optimum or moderate soils for the crop. The remaining categories indicate high agroclimatic risk because they present strong limitations due to soil and medium or high probabilities of restrictive humidity conditions for the crop.

### Mapping and geo-processing

The results of crop-specific soil suitability assessment and the probability of extreme water deficit were interpreted through functions of spatial analysis of the ArcGIS® 10.1 software and the central data visualization and exploration ArcMap™ tool.

### Field validation

The results obtained were validated locally with producers and technical assistants by using Participative Mapping through role play. From basic maps at 1:100,000 scale (watersheds, altitudes, landscapes, slopes, among others), producers and technical assistants zoned the crop-specific soil suitability, the susceptibility of the municipality to water deficiencies and, finally, areas of low agroclimatic risk of the prioritized production systems were identified, that is, optimum productive niches or with slight restrictions and productive niches conditioned to management practices. This methodology reflected the community's perception on the productive suitability of its territory under agroclimatic threats.

## Results and Discussion

### Climate characteristics

In Repelon, the average rainfall ranges between 700 and 1,300 mm year$^{-1}$ and it is mainly concentrated in the second semester of the year. Mean maximum, mean and mean minimum average annual temperatures reach values close to 34, 30 and 24°C, respectively. The average relative

**TABLE 4.** Qualification matrix and categories of agroclimatic suitability in a humidity condition of restrictive soil due to extreme hydric deficit for the tomato crop.

| Soil suitability of use (FAO) | Probability of extreme water deficit in soil | |
|---|---|---|
| | Very low and low (<40%) Letters A & B | Medium, high and very high (>40%) Letters C, D & E |
| Optimum soils or with slight restrictions (A1, A2) | Optimum productive niche or with slight restrictions: A1-A, A2-A, A1-B and A2-B | Areas with optimum soils or with slight restrictions and high exposure to water deficit: A1-C, A1-D, A1-E, A2-C, A2-D, A2-E |
| Conditioned to practices of management and/or conservation of soils[(1)] (A3) | Productive niche conditioned to practices of management and/or conservation of soils: A3-A, A3-B | Areas conditioned to practices of management and/or conservation of soils and high exposure to water deficit: A3-C, A3-D, A3-E |
| Unsuitable soils[(2)] (N) | Areas with unsuitable soils: N-A, N-B | Areas with unsuitable soils and high exposure to water deficit: N-C, N-D, N-E |

[(1)] Soils with severe restrictions due to slope, drainage, effective depth, risk of erosion, texture, pH, aluminum saturation.

[(2)] Marginal and unsuitable soils due to altitude, slope, drainage, effective depth, risk of erosion, texture, pH, aluminum saturation.

humidity ranges between 75 and 80%, with approximately 2,300 h $year^{-1}$ of direct sunshine.

### Tomato crop-specific soil suitability

A total of 60.6% (21,334 ha) of the surface of the municipality of Repelon (35,172 ha) has suitability "A1" (optimum) for tomato cropping. "A2" (moderate) correspond to soils limited principally by effective surface depth (5.7%). 2.85% (1,003 ha) correspond to areas "N" (unsuitable) due to superficial soils for tomato. The municipality of Repelon did not present marginal suitability (A3) for the crop. The remaining area corresponds to bodies of water (9,657 ha) (Fig. 2).

### Analysis of agroclimatic scenarios for the tomato crop under extreme water deficit conditions in the soil

A weather characteristic of the region is the frequent occurrence of completely dry periods; the study period (1981-2010) presented nine El Niño events lasting between 6 and 19 months. In Repelon, an El Niño event can cause an average of 36% decrease in rainfall during the dry season (December, January, February, and March) and below 12% during the rest of the year. The El Niño event for 1997 presented up to 31% decreased precipitation, which limited water availability for agricultural systems (Corpoica, 2014).

Under a scenario of water deficit in the soil (due to negative precipitation anomalies), a probability prevails below 40% of extreme water deficit in soil for the crop during the months of transplant – initial vegetative stage, and fruit filling (October and February), both in optimum, moderated and unsuitable soils due to effective depth (B-A1, B-A2, B-N areas) (Fig. 3). However, the probability of extreme water deficit for the crop reach 60% during the flowering and fruit filling months (November to January), mainly in optimum "A1" soils (C-A1 areas). The sector of "Bajo Polo" has the highest probability of occurrence of water deficit in the soil, with values up to 60% during November and January (D-A1 areas). Most of the months conserve a low probability of occurrence of extreme water deficit to the south of the municipality (Villa Rosa), as well as in the sectors of "Olivo", "Loma Ariza" and "La Higuereta".

In areas with slight soil limitations for tomato crop (A1 and A2), probabilities above 40% of occurrence of water deficit under rainfed farming, restriction in suitability is due to the higher risk of severe water stress for the tomato

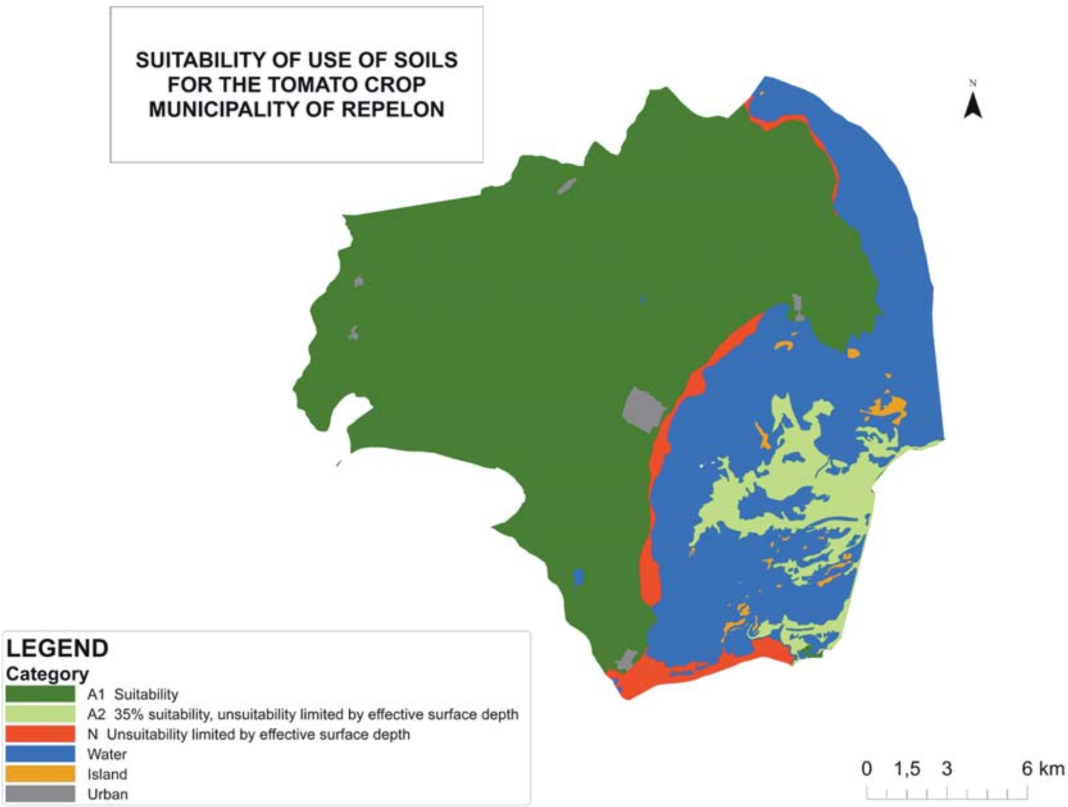



**FIGURE 2.** Suitability of use of soils for tomato crop in the municipality of Repelon.

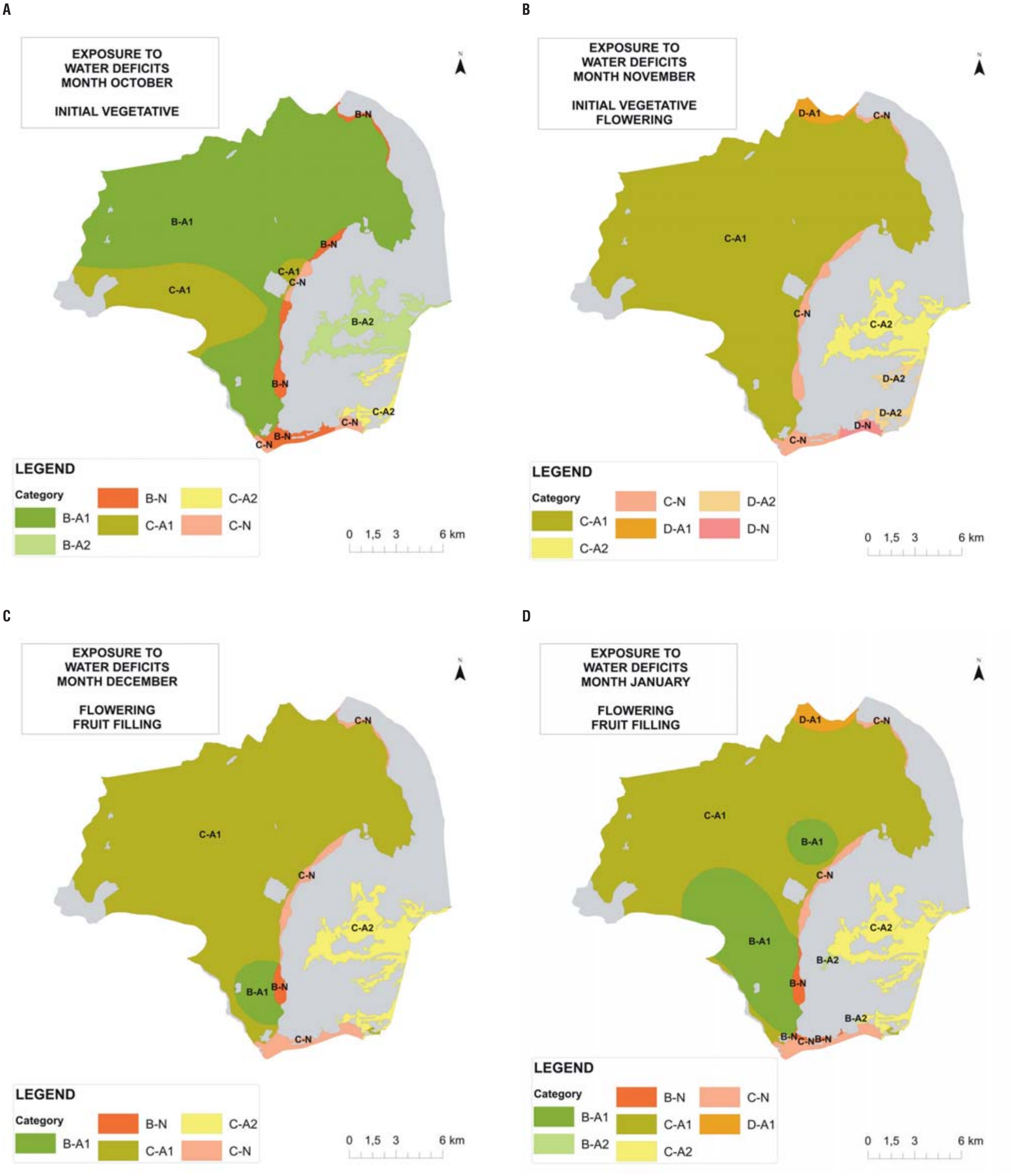
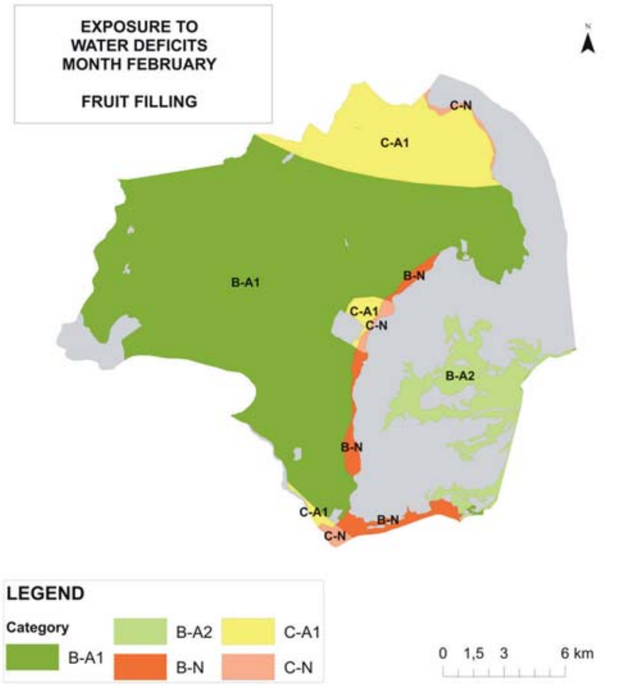



**FIGURE 3.** Monthly agro-climatic scenarios (October-February) under conditions of extreme water deficiencies in the soil for tomato crop growing in the municipality of Repelon. The first letter of the legend indicates the probability of occurrence of extreme water deficiencies in the soil for the crop: A (0-20%); B (20-40%); C (40-60%); D (60-80%); and E (80-100%). The second letter indicates tomato crop-specific soil suitability: optimum soils (A1), moderate suitability soils (A2), unsuitable due to very superficial soils (N).

E

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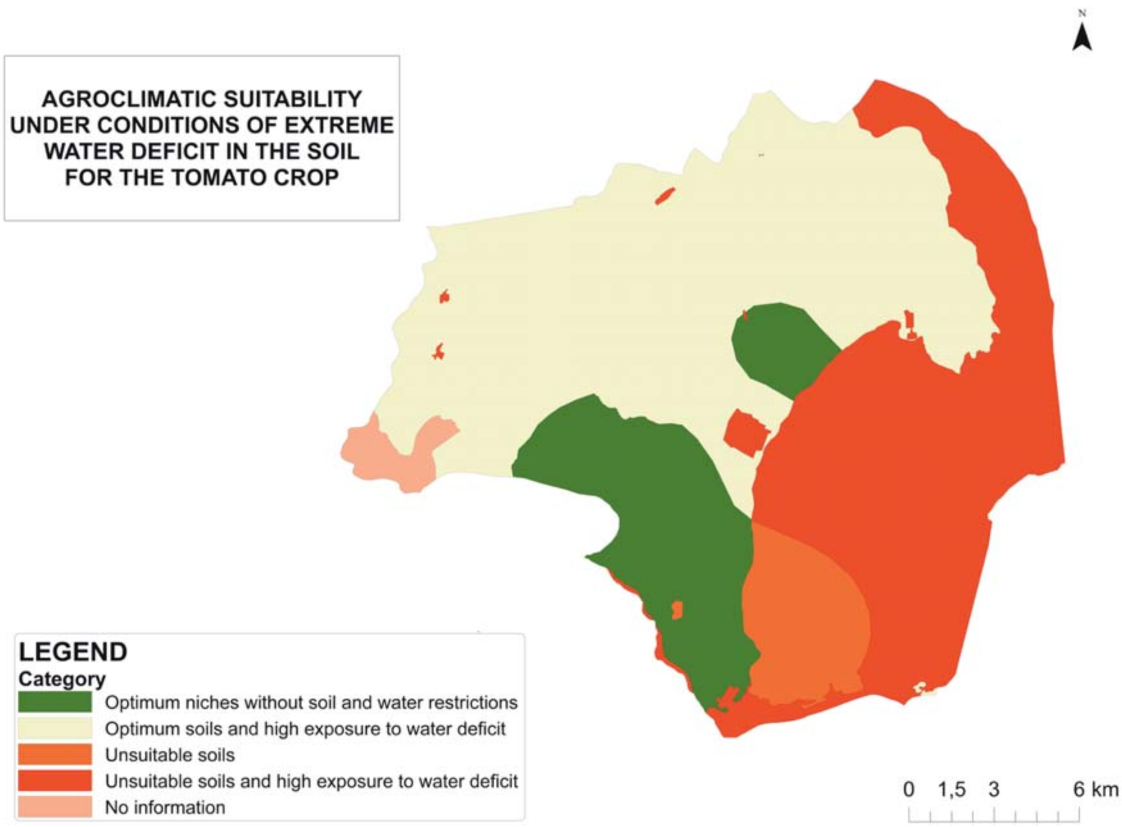


**FIGURE 4.** Agroclimatic suitability under conditions of extreme water deficit in the soil for the tomato crop in the municipality of Repelon, Atlantico.

crop. Rao *et al.* (2000) indicate that tomato is a species with high sensitivity to water stress, particularly the Rio Grande variety (cultivated in the zone) it presents higher sensitivity to water stress compared to other varieties. Under light stress, there is reduced foliar area and number of leaves, rapid decrease of total dry weight, and diminished number of flower buds (García *et al.*, 2004).

### Agro climatic suitability under conditions of extreme water deficit in the soil

Under extreme water deficit condition, 5278 ha were identified, corresponding to "optimum productive niches or with slight restrictions", which indicates 75% reduction of this area compared to the *tomato crop-specific soil suitability map* (Fig. 4). This area, considered of low agroclimatic risk, does not present restrictions due to physical-chemical characteristics of the soil and a low probability exists of severe humidity deficiencies for the crop during the growth period from October to February. It is located in the sectors of "La Higuereta", "Olivo", "Loma Ariza" and "Villa Rosa". Some 16,066 ha correspond to "areas with optimum soils or with slight restrictions and high exposure to water deficit"; these present a high probability of severe water deficit throughout the tomato growth season (October-February) and are mainly located in the sectors of "Polo Bajo, "Del Caballo", "Rotinet", "Mapurito", "Las Tablas", and "Cienaguita". In these areas it is important to implement highly efficient irrigation systems, like drip systems and micro-aspersion, and to plan the frequency of irrigation. Preparation of reservoirs to store water to provide irrigation during critical periods of the crop, use of living or dead coverage, minimum tillage, and use of organic fertilizers can mitigate the impact (UNGRD, 2014).

Other methodologies propose combinations of physical and chemical properties of the soil with the climate. Ceballos-Silva and López-Blanco (2003) defined the suitability of areas to cultivate corn and potato in central Mexico, by employing variables like minimum temperature, maximum temperature, precipitation, soil depth, soil texture, soil pH, soil slope, and altitude. Camargo and Ortolani (1964), Brunini *et al.* (2008) and Brunini *et al.* (2010) used annual and monthly weather records to determine parameters like current evapotranspiration, water deficit according to method Thornthwaite-Mather. Particularly, Brunini and Caputi (2001) include the storage capacity of different types of soils to improve the precision of the calculation of the water balance. Geerts *et al.* (2006), in turn, used the ETo estimated via the FAO Penman–Monteith methodology to determine the aridity index (AI) in the zoning of agroclimatic suitability of the Bolivian plateau for quinoa.

### *Field validation*

Prior to identifying productive niches, producers and technical assistants identified the municipality's susceptibility to extreme water deficit in the soil. In these zones it is not recommended to establish tomato crops under events of weather variability, given that this implies greater investment in irrigation infrastructure, along with a higher probability of loss of productivity and plants.

## Conclusions

The results contribute to identifying productive areas that could be more affected with decreases of precipitation due to weather variability events associated and not associated to El Niño Southern Oscillation (ENSO). Likewise, these results provide a risk picture that supports the implementation of public policies that promote issues ranging from the use of irrigation infrastructure to the application of agronomic management practices that mitigate the impact of events of hydric deficit.

This study presents a methodology to identify areas of low agroclimatic risk for agricultural systems through the combination between the suitability of soils (which employs the variables of drainage, slope, effective depth, texture, pH, aluminum saturation, salinity, and altitude) and the probability of the soil having restrictive humidity for the crop.

For tomato in Repelon, Atlantico, the agroclimatic suitability varies depending on the scenario. Upon an extreme event of water deficit in the soil, the suitable area (low agroclimatic risk) for tomato crop is 75% less than the suitable area found with *tomato crop-specific soil suitability assessment*. These areas should conduct with greater intensity practices and strategies of adaptation to improve the resilience of this production system.

The precision of this approach is conditioned to the availability of soil cartographic information that in Colombia is limited to scales of 1:100,000, to weather data – which is only available at monthly scale – to the index used to qualify the humidity in the soil, and to the availability of the crop's eco-physiological information. A closer look at the local reality would be possible by using weather information at daily scale, which permits designing indexes or improving the information with which the indexes applied to the agricultural sector are constructed.

With the participative cartography exercise it was possible to reflect upon the community's perception, knowledge, and experiences on its municipality's productive suitability under conditions of agroclimatic risk (through suitability and availability of water in soils). It was possible to corroborate the spatial location pattern of the areas denominated as "productive niches" for the tomato crop (mainly under events of water deficiency). This indicates that the methodology proposed presents a good approximation to the territorial reality and that the community effectively recognizes the resources, potentialities, and limitations of its territory.

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