Possibilities for Growing Switch-grass (*Panicum virgatum*) as Second Generation Energy Crop in Dry-subhumid, Semiarid and Arid Regions of the Argentina

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Abstract

Panicum virgatum (swich-grass) is cultivated in some countries to obtain biomass used in the production of heat, fiber, electricity and second generation ethanol. Currently, in Argentina, this species is used for forage and as an ornamental. The aim of this work was to design an agroclimatic zoning model for swich-grass in Argentina, both for upland and lowland ecotypes, based on its bioclimatic requirements and employing a Geography Information System. The variables taken into consideration were: average temperature during growing period and reproductive period, frost free days and rainfall during growing season. This work demonstrated that an ample region of the country is agro-climatically suitable for the implantation of switch-grass in rainfed conditions or with complementary irrigation. The agroclimatic zoning for the upland ecotype shows that suitability reaches latitudes of up to 46ºS, while the lowland ecotype can be grown up to 40ºS. Thornthwaite's Moisture Index equal to zero was overlapped to the Argentinean agroclimatic zoning for upland and lowland types, to obtain the potential growing areas under dry-subhumid, semiarid to arid climates. The areas where switch-grass should be effectively tested are those categorized as optimal, very suitable, suitable, and very suitable/suitable with irrigation, located to the West of TMI equal to zero, which include dry-subhumid (0<TMI<-20), semiarid (-20<TMI<-40) and arid (-40<TMI<-60) climates. This agroclimatic zoning model can be applied to any region in the world, using the same bioclimatic indices and the classes delimited in this paper.

Keywords: agroclimatic zoning model, Argentina, bioclimatic requirements, dry-subhumid to arid climate, energy crop, switch-grass, Thornthwaite's Moisture Index

Introduction

Bioenergy has become essential for energy security, but it also crucial in diminishing carbon dioxide emissions (CO_2) from fossil fuels. For instance, the chemical energy enclosed in the biomass of lignocellulosic crops may be transformed into bioethanol or alternate fuels by direct combustion or by pyrolysis. Ethanol can be obtained from crops with high sugar contents, through fermentation.

In the 1980´s *Panicum virgatum* (switch-grass) was singled out as a model energy crop in the U.S.A. Since then, it has been developed mainly for production of second generation ethanol. Switch-grass is composed of more than 60% lignocelluloses, which are the preferential components of a good bioenergy crop (Samson et al., 2005). When switch-grass is used for production of second generation ethanol, it is estimated that greenhouse gasses (GHG) emissions are reduced in a range of 43 to 79% compared to the fossil alternative (Skinner et al, 2012). According to De Vries et al., (2014), second generation biofuel crops contribute much more to GHG emission reduction, had much higher net energy yields and better resource use efficiencies; soil erosion and N leaching were also lower than first generation biofuel crops.

Currently, the main unsolved issues of energy crops concern the competition with lands for food production and the possibility that conversion of arable land to energy crops may lead to indirect land use changes (ILUC) and, therefore, GHG emission. The use of cellulosic materials, such as wood by-products, and crop residues can help avoid this problem. Another option is the exploitation of marginal or abandoned land for biomass production (Fritsche et al, 2010). Switch-grass has been shown to be productive under low input conditions and may play a role in using this option for ILUC free biomass production on marginal lands.

Characteristics of *Panicum virgatum*

Panicum virgatum L. is known as “pasto varilla” in Spanish and “switch-grass” in English. It is a C_4 species, and it fixes carbon through various metabolic pathways, using water very efficiently (Moss et al., 1969; Koshi et al., 1982). It is a wind-pollinated perennial tallgrass native to prairies, savannas, and coastal habitats ranging from Florida and New Mexico in the south to Saskatchewan and Nova Scotia in the north. It can also be found in the remaining prairies, native pastures and also on roadsides (Mc Laughlin and Kszos, 2005). Geographically, it is currently distributed South of 55ºN and found in different territories: U.S.A, Russia, India, East and South Africa, Southeast Europe and the Middle East (Christian, 1996; Theriault et al., 2003). Current data on switch-grass grown in Europe suggest that it may be grown further North than in North America (Elbersen et al., 2001).

There is a strong signal of climatic and latitudinal adaptation across the species’ range, as evidenced by higher survival of local ecotypes in reciprocal transplants and by phenological differences (Casler et al, 2004). Natural selection has given rise to two major ecotypes of switch-grass: lowland and upland. Upland ecotypes are commonly octaploids. They are fine-stemmed and the leaf blades have different amounts of pubescence. This ecotype is semi-decumbent and broad based, with heights of 92 to152 cm and adapted to drier habitats. The lowland ecotypes are usually tetraploid and are coarse stemmed, erect, glabrous, more robust, and found in bunches in moister sites, with heights of 61 to 305 cm (Cortese et al, 2010). The upland ecotypes demonstrated considerably higher lignin (14.4%) compared with lowland genotypes (12.4%), while hemicellulose was higher in lowland compared with upland (Bhandari et al, 2014)

Arundale et al, (2014) found that yield initially increased until it reached a maximum during the fifth growing season and then declined to a stable, but lower level in the eighth. The mean yields observed over this longer term period of 8–10 years were lower than the yields of the first 5 years.

Situation in Argentina

In Argentina, the ecotypes found have not yet been classified as upland or lowland, but the morphology is consistent with the upland denomination (Cortese et al., 2010). Switch-grass is widely used as a forage species but does not tolerate frequent defoliation. It is cultivated either alone or together with big bluestem (*Andropogon gerardii* Vitman) for direct grazing or haymaking (Mitchell et al., 2001). When it is employed for grazing, it must be used before the floral stems develop because it is when the forage reaches its maximum quality and palatability. It is recommended that 15 to 20 cm should remain at the end of the growth season and every time it is used. Severe defoliation after autumn results in a poor spring outbreak, a decrease in bush vigor and loss of specimens. Since its forage yield is extremely high, it is particularly useful for haymaking or other forms of conservation (Whyte et al., 1959). For haymaking, the crop has to be harvested before the panicles emerge so as to promote subsequent regrowth. The apical growing points and many of the axillary buds remain above-ground and are thus in danger of being eliminated with mechanical cutting or grazing. In sub-humid areas of Argentina, switch-grass can be found as a fodder crop, but there are no reports of it being tested as an energy crop.

Uses

This species is used mainly in soil conservation, grounds, as an ornamental plant and fodder. Recently, switch-grass has begun to be studied in U.S.A and Europe as a potential biomass crop to produce electricity by direct combustion. It also holds great promise for lignocellulosic bioethanol production, although development of improved switch-grass through genetic manipulation is needed to enhance cellulosic ethanol production (Kausch et al, 2010). Other uses include fiber production and wildlife habitat improvement (Christian et al., 2010).

When switch-grass is grown for biomass (energy, fiber, etc), delayed harvest in winter/early spring is recommended. The biomass must be harvested 2-3 weeks after frosts (- 2.2 ºC for 4 hours or more) because it freezes and loses water. If the crop is harvested before senescence, winter survival will be lower and spring re-growth will be reduced, possibly leading to stand loss (Christian et al., 2010).

The first commercially available varieties that were developed as bioenergy cultivars were lowland EG 1101 (improved Alamo ecotype), EG 1102 (improved Kanlow ecotype) and upland 2101 (Cave in Rock-type). These varieties have 5-30% more biomass than regular ones. Other varieties include switch-grass lowland ecotypes, such as Alamo and Kanlow, and upland ones, such as Blackwell, Cartago, Cave-in-Rock, Dacotah, Forestburg, Nebraska 28, Pathfinder, Shawnee, Vivienda and Summer. Some of these varieties were plants selected from wild populations in the 1940´s.

This research was conducted to explore the possibility of switch-grass cultivation for biomass production in Argentina. The aim of this paper consisted in demarcating the potential growing areas for upland and lowland ecotypes under dry-subhumid, semiarid and arid regions of Argentina as a second generation energy crop.

Materials and methods

Study area

The area studied was the Argentine Republic. The country borders to the North with Bolivia and Paraguay; to the South with Chile and the Atlantic Ocean; to the East with Brazil, Uruguay and the Atlantic Ocean and to the West with Chile. As a result of its vast territory, Argentina presents exceptional climatic diversity. Various geographic factors influence the climatic characteristics of the different regions. One of these is latitude, since the Argentina is characterized by its great latitudinal development: 21º46' in the North to 55º03' S in the South.

Figure 1 shows Argentina´s political map, with the names of the provinces. This map is useful when delimitating the classified areas with different grades of agro-climatic suitability. Thornthwaite's Moisture Index was used to demarcate arid, semiarid, sub-humid and humid areas in Argentina (Falasca y Forte Lay, 2004). Figure 1 also includes the distribution of the moisture regions of Argentina and shows the lands that could be used to produce energy crops, without encroaching on lands used for traditional agriculture. Those areas were defined by the Thornthwaite's Moisture Index (TMI) equal to or less than zero. They include dry-subhumid (0<TMI<-20), semiarid (-20<TMI<-40) and arid (-40<TMI<-60) climates.

Ecological requirements

Two major types of switch-grass have emerged through natural selection. In the US, different ecotypes have been found according to local climate and soil conditions. Some varieties are adapted to high-humidity in the East and South, while others grow well in dry climates in the West and the North. The majority of lowland ecotypes arose in southern United States, while upland ecotypes tend to have originated, and are better adapted, in more northerly latitudes (Casler et al., 2004). The upland ecotypes are adapted to soils with coarser textures and semi-arid climates. The lowland ecotypes grow better in heavier soils with higher water availability. Furthermore, they produce higher amounts of dry biomass than the upland cultivars.

The ecotypes respond differently to latitudinal effects, thus giving rise to northern or southern upland and northern or southern lowland strains (Casler et al, 2004). When lowland and upland ecotypes have the same chromosome number, they can be crossed to obtain viable switch-grass seed (Martinez-Reyna and Vogel, 2002). The F_1 hybrids derived from this crossing have increased biomass yields compared with the parental lines (Vogel and Mitchell, 2008). Latitude of origin is the most important factor that determines the area of adaptation for different switch-grass varieties.

According to Parrish and Fike (2005), there is a strong correlation between latitude of origin and yield. In the U.S, the varieties from the South have higher potential yields than the ones from the North. Commercial varieties are differentiated by their latitude of origin from 28º to 44ºN. This species is very sensitive to photoperiod and, although the response depends on the variety (Benedict, 1941), it usually needs short days to induce flowering. When the species is grown to the North of its area of adaptation, it is exposed to longer photoperiods and, consequently, its growing period is longer, thus producing more biomass than the population original to that latitude. Instead, if it is grown to the South of its adaptation area, it will produce less biomass than in the original region because of early flowering (Casler et al., 2004). It has a photoperiod response which is modified by growing degree days (Moser and Vogel, 1995). Decreasing day-length induces flowering in early summer.

There are two other factors that influence adaptation: temperature and moisture. The varieties that develop well in dry areas are more susceptible to fungal diseases when grown in humid conditions. The growth cycle depends on the cultivar, but it is usually relatively short, from 90 to 150 days (USDA, 2008).

The minimum temperature compatible with germination is 10.3 ºC (Hsu et al., 2007). The species requires temperatures above 20 ºC for optimum germination (Hsu and Nelson, 1986). Shoots emerge in spring when soil temperature rises above 10 ºC (Christian et al., 2010). The base temperature for growth varies between 4.5 and 7.3 °C, according to the variety (Madakadze et al. 2003). Consequently, in statistical growth models for different cultivars, it is essential to use different base temperatures. Nevertheless, in growth models, the base temperature considered for both the vegetative and reproductive stages is 10 ºC (Sanderson and Wolf, 1995).

During the vegetative period, the minimum temperature should not be lower than 10 ºC (Elbersen et al., 2004), and the optimum temperature should range from 24 to 32 ºC (Gesch and Johnson, 2010). During the reproductive period, all physiological processes cease with temperatures below 15 ºC. Suitable temperatures are those above 21 ºC, but they are deemed very suitable in the 24 to 29 ºC range (Gesch and Johnson, 2010). Although switch-grass growth is benefited by high soil temperatures, the survival of plantlets can diminish significantly if edaphic temperatures rise above 40 °C (Vogel, 2003).

According to USDA (2008) and Elbersen et al. (2001), water requirements depend on the variety. Table 1 shows the specific bioclimatic requirements for some varieties cultivated in the USA.

The agroclimatic zoning

The biophysical potential to grow bioenergy grasses varies with time and space due to changes in environmental conditions (Song et al., 2015). Plants need a minimum as well as a maximum offer from the climate in order to satisfy its physiological requirements. Beyond such limits, they are negatively affected. The term “ideal temperature” was coined by Ometo (1981), and it depicts the range between these two values and represents the energetic level that plants need for their physiological complex to work efficiently.

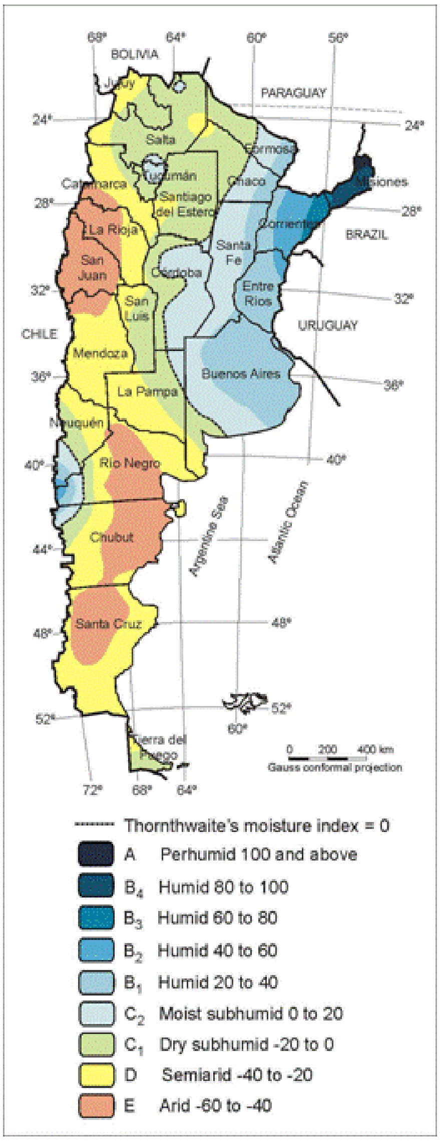

Figure 1. Argentina´s political map including the Thornthwaite's Moisture Index equal to or less than zero (TMI = 0) according to Falasca and Forte Lay (2004)

Agroclimatic zoning refers to the division of an area of land into climatic resource units. These units have a singular combination of climatic characteristics, which render a specific range of potentials and constraints for land use. The successful cultivation of switch-grass depends on the careful description of bioclimatic requirements for this crop and, consequently, the identification of the appropriate regions for cultivation.

First, the analysis of climate characteristics of native areas and the regions of successful cultivation around the world was crucial to determine the requirements, limits and bio-meteorological tolerance and conditions for both ecotypes. The resulting bio-climatological indicators were extrapolated to the Argentine territory. Growth aspects, such as development and death chances by excess or deficiency, were also taken into account. To define the agroclimatic fitness for switch-grass in Argentina, the climate data used was the one collected in all the meteorological stations around the country in the period spanning from 1981 to 2010. In parallel, an agro-climatological inventory was performed based on available climatological statistics. When all the information was gathered, the data were evaluated.

Table 1. Bioclimatic requirements of different ecotypes and latitude of origin[a]

Varieties	Ecotypes	Rainfall mm	Mean minim. temper.	Frost free days	Origin
Alamo	lowland	508-1016	-23.3 ºC	150	South Texas 28º
PAVI2	upland	304-1524	-42.0 ºC	120	------------------------
Kanlow	lowland	508-1016	-33.3 ºC	160	Central Oklahoma 35º
Blackwell	upland	457-1270	-36.0 ºC	135	Northern Oklahoma 37º
Cave in rock	intermediate	610-1524	-36.0 ºC	145	Southern Illinois 38º
Path Finder	upland	406-1143	-36.0 ºC	150	Nebraska/Kansas 40º
Shelter	upland	762-1143	-30.5 ºC	145	West Virginia 40º
Trail Blazer	upland	330-1067	-36.0 ºC	150	Nebraska 40º
Summer	upland	330-1143	-36.0 ºC	140	South Nebraska 41º
Nebraska 28	upland	406-1143	-33.3 ºC	145	North Nebraska 42º
Forestburg	upland	355-1143	-36.0 ºC	100	South Dakota 44º
Grenville	upland	355- 762	-30.0 ºC	180	New Mexico 36°
Dakotah	upland	406-610	-42.0 ºC	90	North Dakota 46º

[a] Elbersen et al., 2001 and USDA, 2008.

The number of frost-free days was the first parameter considered. These had to be above 150 to ensure the length of the growing period, which is 90 - 100 days for short cycle cultivars and an average of 140 - 150 days for the rest of the cultivars (USDA, 2008). The length of the growing period is one of the main factors because it refers to the number of days within the period of temperatures above base temperature when moisture conditions are considered adequate.

The moisture factor was analyzed by plotting the 430 and 500 mm average isohyets that correspond to the growing period. These two isohyets represent, respectively, minimum water requirements for upland and lowland ecotypes. Other lowland type cultivars with higher water requirements were not considered because the lands involved are more appropriate for food production.

To study the thermal factor, the vegetative and the reproductive periods were analyzed separately. For the vegetative period, the following classes of thermal suitability were described: non suitable area, when the temperature of the growing period <10 ºC, marginal area from 10 to 14 ºC, suitable area from 14 to 24 ºC, and very suitable from 24 to 32 ºC. In Argentina, the vegetative period for the upland ecotype extends from September 15th to December 15th, and for the lowland ecotype from September 1st to February 28th. The reproductive period for the upland ecotype extends, on average, from December 15th to February 28th, and for the lowland ecotype from February 28th to April 15th (Petruzzi et al, 2005). For the reproductive period, the following classes of thermal suitability were described: non suitable area when the temperature of reproductive period is <15 ºC, marginal area from 15 to 20 ºC, suitable area from 20 to 24 ºC and very suitable from 24 to 29 ºC.

To design the agroclimatic zoning model, the seven classes of suitability defined for upland ecotypes presented in Table 2 were considered. The seven classes of suitability characterized for lowland ecotypes were the same as for upland ecotypes, with the exception that annual average rainfalls > 500 mm were taken into account.

Each map was obtained by using a set of bioclimatic variables that were previously interpolated and subsequently processed by the GIS tool provided by the program Arc-GIS 9.3. The climatic interpolations were carried out applying the “Interpolate to Raster” tool, within the “3D Analyst” extension includes in the Arc-GIS program, using the interpolation method Ordinary Kriging. The mapped variables were obtained through multivariable integration geoprocessing, employing the “Raster Calculator” tool found in the “Spatial Analyst” extension of the program mentioned above. Each suitability class was defined by the geographical limits set for the different variables. The assigned aptitude classes were maintained for each intersection process.

Hence, the agroclimatic zoning contains the information from all the intercepted variables. In other words, by overlaying the four maps described above, agro-climatic zoning, for both upland and lowland ecotypes was achieved. As a result, seven classes of agroclimatic suitability were classified as optimal, very suitable, very suitable with complementary irrigation, suitable, suitable with complementary irrigation, marginal and non suitable. Thornthwaite's Moisture Index = 0 was then overlapped to the agroclimatic zoning for upland and lowland ecotypes, to obtain the potential growing areas under different moisture regimes.

Results

In Argentina the distribution of mean dates of first frost (autumn) and last frost (spring) is characterized by a dispersion of approximately 30 days. As a result, the first frost or last frost may take place 30 days before or 30 days after the mean date. The dispersion is due to the combination of two phenomena: the great asynchronous variability of temperature and the insufficient thermal tension when frosts occur. The easy entrance of polar air masses in the South-North direction and the scant annual thermal amplitude (since Argentina is under maritime influence) are responsible for this. Figure 2 shows the frost free days > 150. The suitable area includes a large part of the national territory and represents the duration of the switch-grass growing period. Agricultural activities can only be carried out in areas with at least 150 frost-free days. Thus, farmers can avoid or reduce damages caused by frost if they are aware of the probable dates of frost free days.

Table 2. Agroclimatic suitability classes for upland ecotype

Agroclimatic Suitability classes	Rainfall growing season (mm)	Frost free days	Temperature growing period (ºC)	Temperature reproductive period (ºC)
Optimal area	> 430	>150	24-32	24-29
Very suitable area	> 430	> 150	14-24	24-29
Very suitable area with irrigation	< 430	> 150	14-24	24-29
Suitable area	> 430	> 150	14-24	20-24
Suitable area with irrigation	< 430	> 150	14-24	20-24
Marginal area	> 430	> 150	10-14	20-24
Non suitable area	< 430	< 150	< 10	< 20

Figure 3 shows the temperature of growing period for upland ecotype. Different areas can be identified: very suitable, suitable, marginal and non suitable. The very suitable area covers only part of the Northern provinces: Jujuy, Salta, Chaco, Formosa, Santiago del Estero, San Juan and La Rioja. The suitable areas can be found up to 46º South. Marginal areas cover the center and the south of Buenos Aires province and Patagonian sectors.

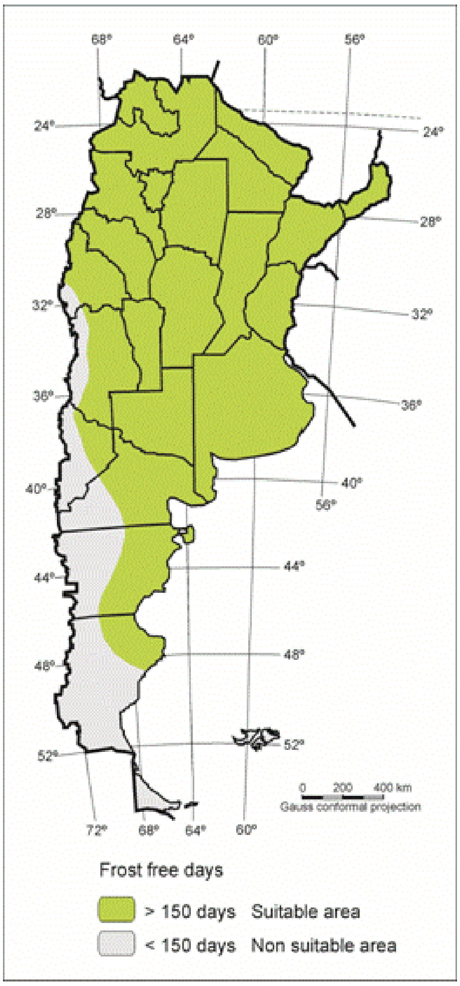

Figure 2. Frost-free days > 150

Figure 4 shows the temperature of reproductive period for upland ecotype. The same suitability classes described above were identified. The very suitable areas cover all the North, the East and the center of the country, except for the NOA (Northwest of Argentina). The suitable areas reach 45º S.

Figure 5 and figure 6 present the annual average rainfall during growing season for both ecotypes. North of the Colorado River, the isohyets exhibit the humidity trend along the E-W gradient due to the “Atlantic” influence. Warm winds prevail during the warm season, and this results in abundant rainfall until desiccation in the west. In the cooler seasons, the strength of the southern dry winds increases and a large part of Argentina lacks rain, except for the eastern regions. As a result, the northeast and central east (temperate pampas) regions of Argentina are humid environments with evenly distributed rainfalls. However, south of the Colorado River, humid air masses are introduced from the South Pacific Anticyclone.

Southerly winds are always prevalent in the Patagonian territory. Annual precipitation ranges from western territory to more than 2,000 mm in the area of Andean Patagonian forest to 150 mm in the driest parts of Patagonia. Figure 5 shows the rainfall during growing season for upland ecotype while Figure 6 shows the rainfall for lowland ecotype. Two suitable areas can be observed: the eastern one, which covers the east, the north and the center of Argentina, including a large part of Salta and Jujuy, and limiting to the West with the provinces of La Rioja, Catamarca, San Luis, La Pampa and the south of Buenos Aires. The other suitable area is located in the Andean-Patagonia area, covering part of Neuquén, Río Negro and Chubut.

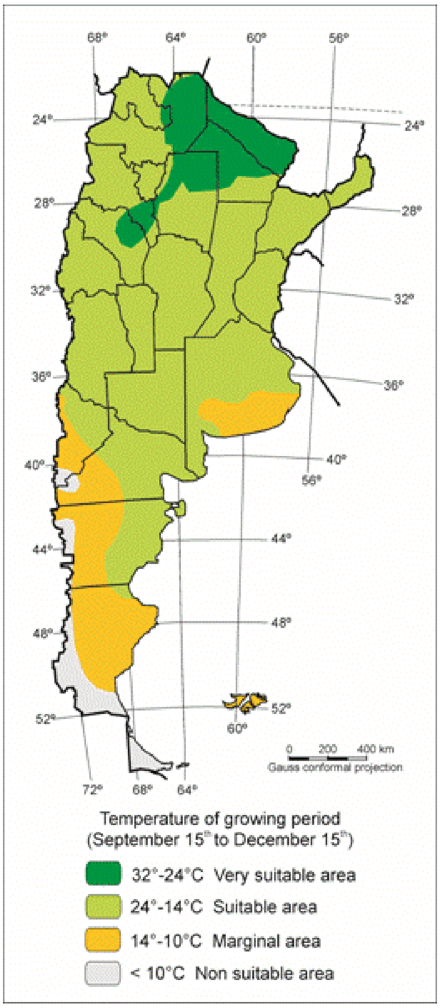

Figure 3. Temperature of growing period for upland ecotype

Figure 7 shows the temperature of growing period for lowland ecotype. Four classes of suitability can be detected. The optimal areas cover part of the provinces of Jujuy, Salta, Santiago del Estero, Formosa, Chaco, La Rioja and Catamarca. The suitable area encompasses the north, the east and the center of the country, reaching Neuquén, Rio Negro, Chubut and North of Santa Cruz.

Figure 8 shows the temperature of reproductive period for lowland ecotype. Four classes of suitability can be detected. The optimal areas cover part of the provinces of Jujuy, Salta, Chaco, Formosa, Santiago del Estero, Santa Fe, Corrientes, Entre Ríos, Misiones, Tucumán, San Juan, La Rioja and Catamarca. The suitable area surrounds the former, and reaches Mendoza, east of Neuquén, La Pampa, Rio Negro and the south of Buenos Aires. Marginal areas appear in North Jujuy and in large areas of Patagonia. Only small extensions of the Argentine territory are deemed non-suitable due to thermal constraints.

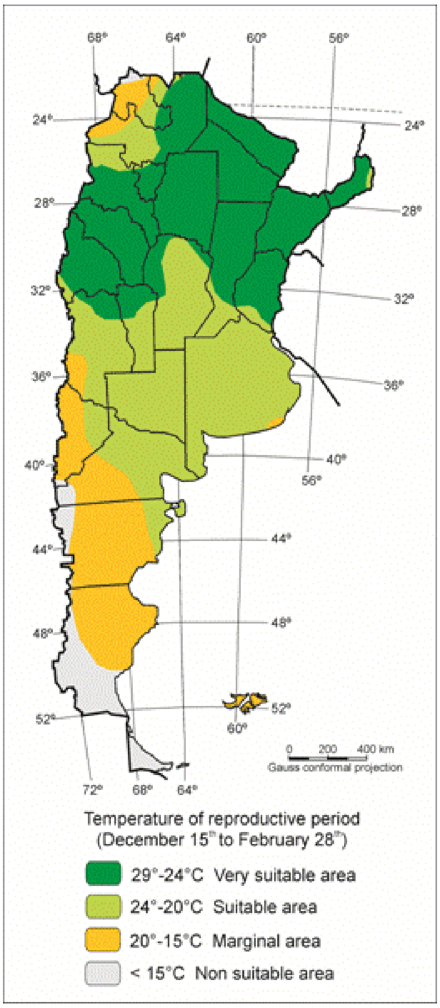

Figure 4. Temperature of reproductive period for upland ecotype

The agro-climatic zoning for uplands and lowlands ecotypes was then obtained by overlaying the previous maps. Moisture regions map (Figure 1) was superimposed on the Argentinean agroclimatic zoning for each ecotype of switch-grass, to obtain the potential growing areas. Figure 9 shows the potential growing areas for upland and lowland ecotypes, under different moisture regime, defined by the isoline of TMI equal to zero. Although the agroclimatic zoning for upland ecotype presents seven classes of suitability, the interesting ones are those located west of isoline of TMI equal to zero. The optimal areas cover a large part of the provinces of Salta, Formosa, Chaco, Santiago del Estero and part of La Rioja, Catamarca and the east of Jujuy. Very suitable areas comprise a large portion of Santiago del Estero, part of La Rioja province, Catamarca, Tucumán, Salta, Jujuy, San Luis and Córdoba. Towards the South, a suitable area can be found, and it covers part of the provinces de Cordoba, San Luis, Mendoza, La Pampa, Rio Negro and Buenos Aires. Another suitable area stands out in the north, encompassing part of the provinces of Jujuy and Salta.

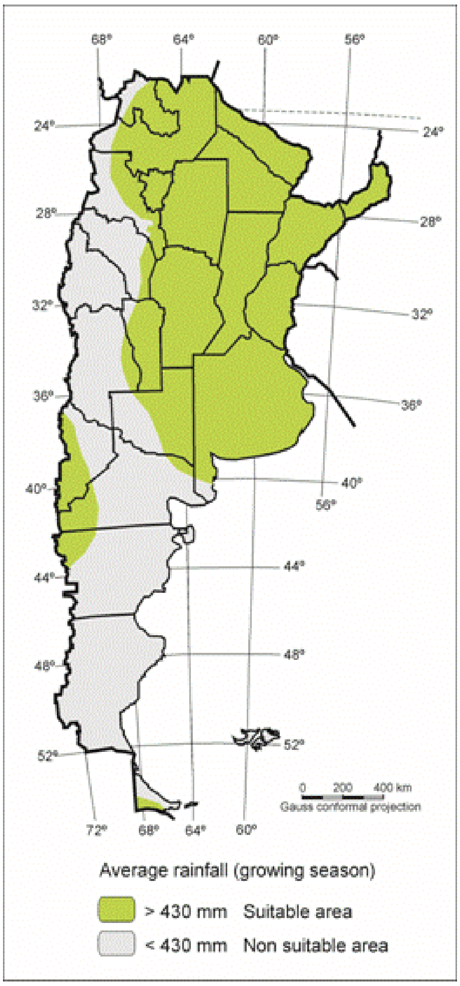

Figure 5. Rainfall during growing season for upland ecotype

West of the optimal, very suitable and suitable areas, two very suitable and suitable areas with irrigation can be discerned. However, complementary irrigation can be recommended only if residual water, i.e. water not useful for human or animal consumption or for edible crops, is available. These areas that require irrigation cover the Central-West part of the country and the North and Eastern of Patagonia, reaching 46ºS.

In the agroclimatic zoning for the lowland ecotype, the optimal area covers part of the provinces of Formosa, Chaco and the northwest of Santiago del Estero, Salta and Jujuy. Very suitable areas extend to the south and west of the former region, comprising part of Tucumán, Catamarca, La Rioja, Santiago del Estero, Córdoba, Salta and Jujuy. Suitable areas are located to the South of Buenos Aires province, encompassing part of Santiago del Estero, San Luis, Córdoba, La Pampa and Buenos Aires. Towards the West, two areas with irrigation can be discerned: very suitable and suitable.

If the two agroclimatic suitability maps are compared, it can be observed that the optimal, very suitable, suitable, and suitable with irrigation areas reach higher latitudes for uplands ecotypes than for lowlands ecotypes. The optimal areas occupy similar regions, but the upland type reaches the South, occupying part of the provinces of La Rioja and Catamarca. Very suitable areas also reach higher latitudes (Córdoba and San Luis provinces). For uplands ecotype, the suitable area with irrigation approaches the province of Chubut while the lowland ecotype only reaches the province of Río Negro.

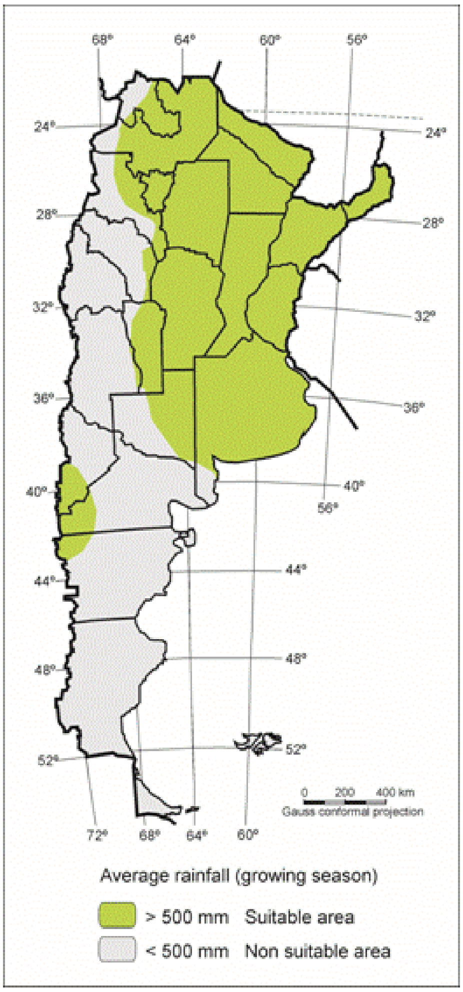

Figure 6. Rainfall during growing season for lowland ecotype

Discussion

This work demonstrated that a broad region of Argentine territory is agro-climatically suitable for the implantation of switch-grass in rainfed conditions or with complementary irrigation. Agro-climatic zoning for upland ecotype shows that the agroclimatic suitability reaches latitudes up to approximately 46ºS, while the map for lowland ecotype reveals that it can be grown up to approximately 40ºS. These results are in agreement with the data presented by Elbersen et al, (2001), which was used to compose Table 1.

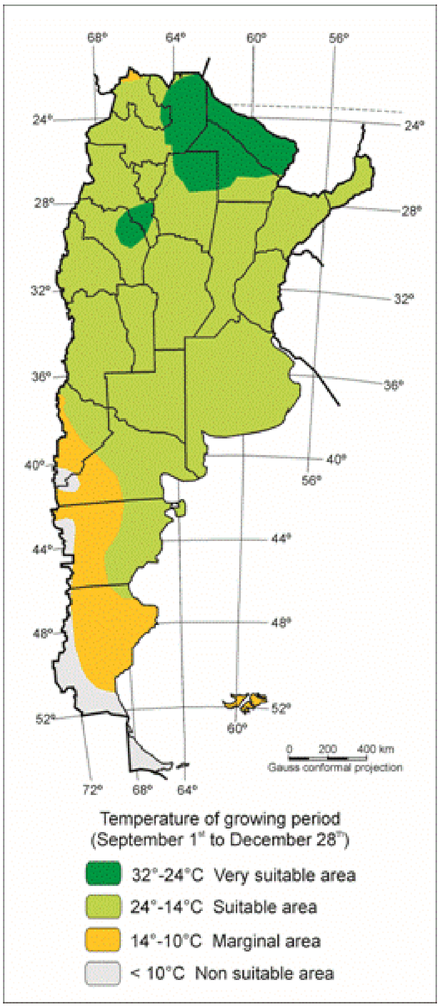

Figure 7. Temperature of growing period for lowland ecotype

In Argentina, the species has been detected (Discover Life, N/D) at median latitudes (34.5ºS/63ºW; 37.5ºS/57.0ºW; 36ºS/60ºW; 36.47ºS /64.18ºW). However, its growth at higher latitudes has been reported. For instance, according to (Discover Life, N/D), there are examples found in Quebec (60ºN/95ºW), Germany (52.02ºN/8.42ºE), Spain (40.5ºN/3ºW), Hungary (47.36ºN/19.88ºE) and Greenland (72ºN/40ºW). Furthermore, there are reports of cultivation in Europe at higher altitudes than the ones mentioned for the U.S.A (Elbersen et al., 2001).

To the East of the isoline of TMI equal to zero (moist-subhumid, humid and per-humid climates), only food crop cultivation is recommended. The implementation of switch-grass cultivation would be appropriate only for special cases, as in recovering soils exposed to hydric erosion or contamination. Therefore, cultivation is recommended to the West of this isoline, thus ensuring that the lands allotted to the proposed energy crop are located under dry sub-humid, semiarid or arid climate.

The information presented on the Agroclimatic suitability map for upland and lowland ecotypes at 1:500,000 scale is important for plans at the national level, since it allows a broad and sweeping view of the expansion potential of this energy crop in Argentina. However, this small scale zoning should be considered as reference for the production phase. Switch-grass may be the first among many perennial feedstocks for the emerging lignocellulosic energy industry in Argentina.

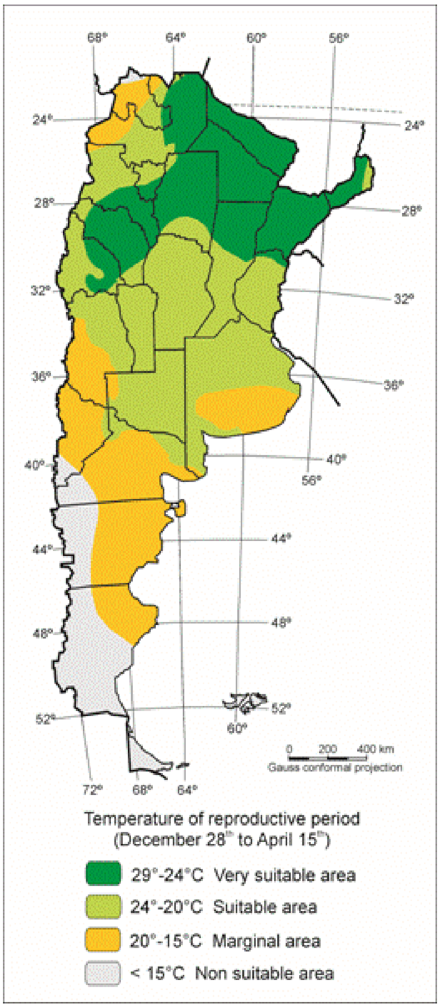

Figure 8. Temperature of reproductive period for lowland ecotype

Decisions on land use could then be based on field scale and empirical or process-based models to estimate the productivity of cellulosic feedstocks. Consequently, economic decisions can be taken based on gross margins and total cost, which include opportunity costs related to cultivation of other crops. However, other factors could weigh in on the final decision. High cost of technology is seen as the primary barrier to full commercialization of cellulosic biofuels. Morrow et al. (2014) found that droughts reduced modeled biorefinery capacity factors, on average, by 47%, raising biofuel production costs by 35% between a modeled dry and wet year. For instance, perennial grasses have several environmental benefits: they reduce erosion processes, improve soil structure, increase organic matter and reduce pollution because they need less pesticides and fertilizers compared to annual cultivars.

According to Masters et al (2016) cultivation of switch-grass on land formerly used for row crops may reduce the need for nutrient additions and potential losses of nutrients to groundwater and the atmosphere. Furthermore, if it is harvested after senescence, it can re-translocate nutrients for future use, with potential longer periods of productive soil fertility and biomass production.

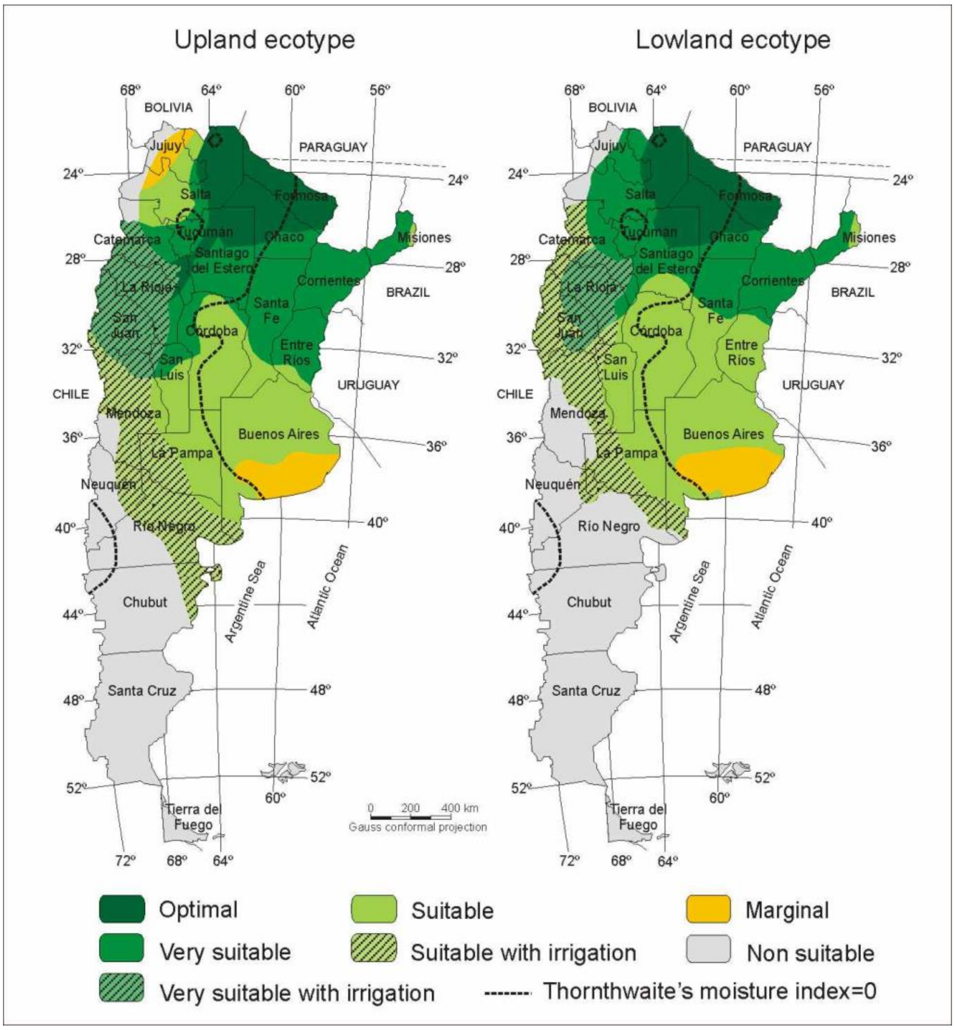

Figure 9. Agroclimatic zoning for upland and lowland switchgrass ecotypes

This species tends to store carbon in the root zone in higher proportions than the majority of crops, particularly annual ones (Mitchell et al., 2008). According to Mc

Laughlin and Walsh (1998) the rate of soil carbon sequestration is approximately 20-30 times higher than annual crops. According to some researchers (Frank et al., 2004; Lee et al., 2007), approximately 80% of total switch-grass biomass persists in soil in U.S.A. Carbon sequestration by switch-grass is evidenced across a wide range of growing conditions at a rate of 1.7-10.1 ton ha^{-1} yr^{-1}, which is equivalent to 6.2-37.0 ton CO_2 ha^{-1} yr^{-1} (Frank et al., 2004; Lee et al., 2007).

Species that have this pattern of carbon sequestration can counteract the total greenhouse gas emission and reduce total emissions on a life cycle basis. Thus, environmental mitigation potential of low-input non-food crops can be added to the list of factors deciding the suitability of land for biofuel.

Switch-grass production in the southern Argentinean prairie should utilize the U.S.A. cultivars from northern latitudes or adapted Argentinean cultivars should be developed. Long term geographic trials in various sites and the actual observation of where the crop gets grown by producers would be the best validation for this model. However, this extended and expensive field work can be avoided by using GIS technology.

Conclusions

The authors developed an agroclimatic zoning model for both ecotypes of switch-grass. This agroclimatic zoning model can be applied to any region in the world, using the same bioclimatic indices and the classes delimited in this paper.

This work demonstrated that an ample region of the country is agro-climatically suitable for the implantation of switch-grass in rainfed conditions or with complementary irrigation. The agroclimatic zoning for the upland ecotype shows that suitability reaches latitudes of up to 46ºS, while the lowland ecotype can be grown up to 40ºS. The areas where switch-grass should be effectively tested are those categorized as optimal, very suitable, suitable, and very suitable/suitable with irrigation, located to the West of TMI equal to zero, which include dry-subhumid (0<TMI<-20), semiarid (-20<TMI<-40) and arid (-40<TMI<-60) climates.

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