Article

The sustainability and resilience of a rainfed agroforestry system for the semi-arid highlands of Mexico

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Abstract

The Environmental Policy Integrated Climate simulation (EPIC) model with a 100-year forecast horizon was used to evaluate the sustainability and resilience of an agroforestry system (SAF) rainfed for the rotation sorghum cultivation pattern with beans and live barriers to the outline of nopal (*Opuntia* sp.) and leucaena (*Leucocephala Glauca*) with the traditional system (ST) with monoculture. The erosion/productivity index (IEP) was used to measure the impact of erosion on the productivity of sorghum and beans. The historical change in the pattern of annual precipitation (PA) and the different phenomena associated with it (runoff Q, erosion E and yield $\bar{Y}$) was determined using the fractal dimension (D) of said parameters, applying the coefficient of Hurst (H), to determine if they show persistence. It was found that the perspectives of sustainability and resilience of the ST, measured using the productive life indexes (IVP), of productive loss (IPP) and equilibrium yield (ER), of the sorghum (IEP of 0.4) and the bean (IVP of 0.8 and IEP greater than 0.6) are low. In contrast, the SAF presented an IEP value of 1 that makes it sustainable and resilient, with better perspectives to resist or recover from extreme climates (droughts or heavy rains) compared to the ST, which is recommended to replace to avoid greater deterioration of the future productivity of the system in the semiarid Highlands region of Aguascalientes.

Keywords: crop rotation, fractal dimension, monoculture, resilience, simulation model.

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Introduction

In the agricultural systems of deficient weather in the region of the semi-arid highlands of Mexico, where resilience and subsistence are the main objectives for producers in this region. Improving the capacity of resistance and recovery of their productive systems to reduce the risk of losing the harvest altogether seems to be as important as increasing the nutritional potential and economic gains (Figueroa, 2011; Lin, 2011).

The basic crops (corn and beans) of rainfed land and forage production dominate the subsistence agriculture geographically in this region (Turrent *et al*., 2005; Paredes *et al*., 2010). Therefore, it is necessary to look for real alternatives that stimulate the capacity of agroecosystems to resist and recover from severe climatic events (eg. intermittent and unpredictable droughts). In this way, production is assured and producers' competitiveness is improved, maintaining quality and production levels within a sustainable agriculture (Osuna *et al*., 2000; Altieri and Nicholls, 2013).

In the semi-arid highlands, producers have generated with some success, a socio-ecological resilience (ability to retain their organizational structure and productivity after a disturbance) to face the natural constraints present in their environment, which deserve to be examined with attention to try to get the best results from them. The survival strategy of semi-arid farmers includes a wide range of activities that include the combination of soil and water management practices (use of surface runoff to ensure the availability of water in agriculture and livestock), hunting and manipulations synecological (relationship of native plant species).

This traditional knowledge and the indigenous practices of resource management are the basis of the resilience of the peasant agroecosystems. However, the implementation of agroecological practices for the design and management of agroecosystems would allow producers to adopt a strategy that increases resilience and also provides economic benefits, within a framework of minimization of risk in the face of uncertain climates (Altieri and Nicholls, 2013).

Among the main problems that limit the productivity of the traditional system are the scarce and erratic precipitation that causes long periods of drought, this results in the reduction of grain production and a forage deficit in the dry season of the year (Acosta-Díaz *et al*., 2003; Osuna-Ceja *et al*., 2015). In addition, two degradation factors are present, such as soil erosion, caused by rain, wind, and the sowing of annual crops on unsuitable land and the degradation of fodder and forest resources in the pastures, mostly caused part due to overgrazing, caused by the increase in the number of heads of cattle (Carranza-Trinidad *et al*., 2007). These problems result in the decapitalization and emigration of agricultural producers in the region, all of which puts at risk the sustainability and resilience of the traditional productive system.

In summary, when explaining the deterioration of natural resources, the concept of 'sustainable agriculture' is taken, which implies maintaining agricultural productivity and profitability indefinitely, while minimizing environmental impacts (Faeth, 1993; Villar-Sánchez *et al*., 2002). This is a 'process that allows meeting the needs of current producers without compromising the ability to meet the needs of future generations' (Fuentes-Castillo *et al*., 2015). Rescuing traditional management systems, combined with the use of agroecological practices, may represent the only viable and solid route to increase productivity, sustainability and resilience of agricultural production (Altieri, 2002).

Thus, the knowledge of sustainability and resilience within an agricultural system must be seen in a holistic, systemic way, of resistance and recovery, not only in terms of internal natural resources, but also with respect to relations with the market and others. socio-economic aspects (Andreoli and Tellarini, 2000). There is a deep gap between what is observed in physical systems and the dynamics of socio-economic patterns. Sustainability attempts to unite them within the Sustainable Agriculture triangle (Oleschko *et al*., 2004) and resilience seeks resistance to shocks (extreme events) and the system's capacity to recover (Lin, 2011). This approach establishes that 'sustainable production' is measured not only by the total exit in a short period of time, but by the exit of an infinitely long period (generations), which can be sustained and 'resilient' without affecting the base of natural resources on which production depends (Villar-Sánchez *et al*., 2002; Walker *et al*., 2002; Altieri and Nicholls, 2013).

To determine the sustainability within agricultural systems at the plot level, the physical changes in the soil that could result from applying different agronomic practices have been evaluated, for which the EPIC model was used, which has been fed with specific information to predict specific results (Faeth, 1993). This model allows to simulate the effects of the different techniques of crop production and rotation on surface runoff and soil loss in cultivated lands (Schröder, 2000; Larose *et al*., 2004).

The main components of this erosion model are based on a series of basic factors: physical-chemical characteristics of the soil, slope of the land, daily precipitation and its deviation, wind speed and direction, monocultures, crop rotation and tillage (Schröder, 2000). Currently EPIC has become a technological tool to describe with high degree of certainty the yield of crops with complex rotations and farming operations in more than 100 crops per year. Likewise, it can help, in an outstanding way, in the selection of soil and vegetation management strategies in order to increase the yields of specific crops and also stop the erosion process (Villar-Sánchez *et al*., 2002; Wang *et al*., 2006; Gaiser *et al*., 2010; Flores *et al*., 2014).

This new technology represents the 'state of the art' when it comes to modeling the effects of changes in soil characteristics associated with erosion. In addition, the impact of different crop management practices on soil erosion and long-term crop production can be predicted (Sharpley and Williams, 1990). The series of values of the response variables (annual rainfall, erosion, runoff, yield, among others) can be compared by means of a fractal analysis that allows to detect the properties of self-similarity and determine the fractal dimension (D). This technique measures how much complexity is repeated in each scale and in a series of time explains the relationship between increments (Breslin and Belward, 1999). The fractal dimension can be estimated by a variety of algorithms, one of them is the Hurst exponent, which is a measure of the trend or persistence of a data series and is linked to the fractal dimension D= 2-H (Mandelbrot, 1982).

The measures derived from the Fractal Theory favor a unified quantification of the dynamic and energetic aspects of a complex system. Many researchers (Breslin and Belward, 1999; Karambiri *et al*., 2000; Biaou *et al*., 2003; Amaro *et al*., 2004; Pérez *et al*., 2009) have used Fractal Theory as a valuable tool for the understanding of the pluviometric processes and the different phenomena associated with them.

The aim of this study was to evaluate and compare the sustainability and resilience of an agroforestry system rainfed cropping pattern sorghum brown midrib in rotation with beans and live the contour of nopal (*Opuntia* sp.) barriers and leucaena (*Leucocephala Glauca*) and the traditional system. In addition, we studied the fractal dimension of the series of values of the response variables (annual rainfall, runoff, erosion and yield), in order to determine if they show persistence, in the observed trends.

Materials and methods

This study was conducted at the Sandovales Experimental Site, Aguascalientes, Mexico. It is located at coordinates 21° 53’ 09” North latitude and 102° 04’ 14” West longitude, at a height of 2 049 meters above sea level, where an average of 300 mm of precipitation is recorded in the crop cycle; the average temperature is 16.3 °C and the crop cycle is 110 days (end of June to mid-October) (Medina *et al*., 2006). The soil is ≤ 0.4 m deep, with less than 1% organic matter, loamy sandy texture in the topsoil, 2% slope and pH 6.6 (Osuna-Ceja *et al*., 2015).

During the summer of 2014, a long-term study was established in an area of two hectares with contrasting antecedents: 1) area (one ha) with soil covered with natural pasture; and 2) area (one ha) with bare soil worked for more than ten years. In area 1, an agroforestry system (SAF) was established, where soil conservation practices, *in situ* water harvesting, rotation of grass and legume crops for forage and grain production with live wall barriers of nopal and leucaena and in area 2 the traditional system (ST) was established with monoculture planting in straight rows, without water collection.

In the 2015 cycle the study was continued, making the rotation in the SAF and the establishment of both species in monoculture in the ST. In both years the yield of MS for sorghum and of grain for beans in the two production systems evaluated was determined. The yield data (MS and grain), as well as the cultivation parameters (leaf area index, harvest index, maximum height of the crop, biomass-energy ratio, among others) were used to feed the EPIC model. In addition, the climatic data (maximum temperature, minimum temperature, daily precipitation and wind speed) required by the model were collected daily and were selected by the continuity criterion for a period of 43 years in the meteorological station of the Sandovales Experimental Site, located 300 m from the experimental area.

In order to know the response of the holistic and systemic management of natural resources and the identification of indicators, an assessment was made of the sustainability and resilience of the two sorghum-bean agrosystems in rotation and in monoculture. The methodology used was based on the simulation model Environmental Policy Integrated Climate (EPIC), version 5300) (Williams, 1990), which was used to measure the impact of erosion on the productivity of sorghum and dry beans in the region of the Semi-arid Highlands of Aguascalientes.

The simulations were carried out for the two management systems using the meteorological station of Sandovales, Aguascalientes, considering a forecast horizon of 100 years. The response variables: annual precipitation (mm), runoff (mm), erosion (t ha^{-1} $year^{-1}$) and crop yield of sorghum and beans (t ha^{-1}), were compared their series of values obtained with EPIC, by fractal analysis, to explain the relationship between increments (Breslin and Belward, 1999). The Hurst exponent (H) and the fractal dimension (D) were calculated for each of the series of values of the response variables, in order to study the long-term behavior of the fluctuations thereof (Mandelbrot and Wallis, 1968). For this, the method of wavelets (D_W) was applied, which is part of the commercial software ‘Benoit’, used in the present work. There are five techniques used by the Benoit package, to measure the fractal dimensions of the autoaffin sets, calculating the Hurst exponent from their values.

An H exponent above 0.5 reveals persistence phenomena: the variable is sensitive to its history and the strength of the persistence phenomenon increases when H approaches 1. Conversely, an exponent below 0.5 reveals an antipersistent phenomenon (Pérez *et al*., 2009).

Evaluation of the perspectives of sustainability and resilience of the two agrosystems with sorghum and beans in the study area

The evaluation of the effect of management practices for sorghum and beans in the two rainfed production systems to decide whether or not they are sustainable and resilient was necessary to use the long-term simulation scenarios (100 years). This evaluation was based on three main criteria: the productive life index (IVP), the productive loss index (IPP) and the equilibrium yield (RE), IVP and IPP are supported by the erosion/productivity index (IEP), concept introduced by Perrens and Foster (1984); Williams *et al*. (1984) and RE is the scope of performance variation, which are described below.

Erosion-productivity index (IEP)

This is defined as the relationship between the annual yield of a crop on eroded land and the annual yield of the same crop on a non-eroded land.

Productive life index (IVP)

This index, defined as the period of time to which a production system ceases to be sustainable and vulnerable by falling below a certain level of productivity (in this case IEP< 0.4 for the sorghum crop and 0.6 for beans, respectively), was considered important in this evaluation, to determine the productivity trends of sorghum and beans.

Productive loss index (IPP)

The magnitude of the loss of productivity of sorghum and beans due to accumulated soil erosion within the 100-year planning horizon was assessed by means of this index. This was defined as the slope of the curve obtained by plotting the IEP on the Y axis against the accumulated erosion on the X axis.

The evaluation criterion in this case was that, if the system presents IPP values close to zero, it would be sustainable and resilient since it is indicative of insignificant soil losses of yield. Threshold values that determined this criterion are not defined, therefore, as long as they are not determined for the conditions of the study area, the criterion of the researcher to characterize them is fundamental.

Balance performance (RE)

A sustainable and resilient system implies an equilibrium production in which the annual variation of the yield oscillates within a small amplitude. The evaluation of this equilibrium level means quantifying the amplitude of variation of the performance in relation to a ‘typical’ range of fluctuation in the environment of the study area. Therefore, the RE defined as the deviation of the yield with respect to the average value in time, was used to consider the seasonal variations of the climate of the region and the effect of the accumulated erosion, and its effect on the productivity of sorghum and beans in the time scale.

Results and discussion

Productivity of the sorghum-bean rotation in SAF

With the changes introduced in SAF (innovative system), it was possible to increase the productivity of sorghum and beans by 112 and 217%, exceeding the average commercial yield of 3 to 6.6 t ha^{-1} of MS in sorghum and from 0.57 to 1.4 t ha^{-1} in beans, respectively. Another difference between both systems is that the innovator proposes a crop production scheme different from conventional methods and an alternative productive soil management. Its contributions are significant in the increase of production, water retention, reduction of runoff and the production of sediments. However, beyond the productive criterion, two features of this system have an enormous ecological value: their capacity to resist and recover from extreme climatic events to sustain themselves over time (Figure 1) and explanation of the above, their ability to consider the interactions of natural resources (soil, water, plants, microorganisms), without destroying or deteriorating them, so that their resilience increases.

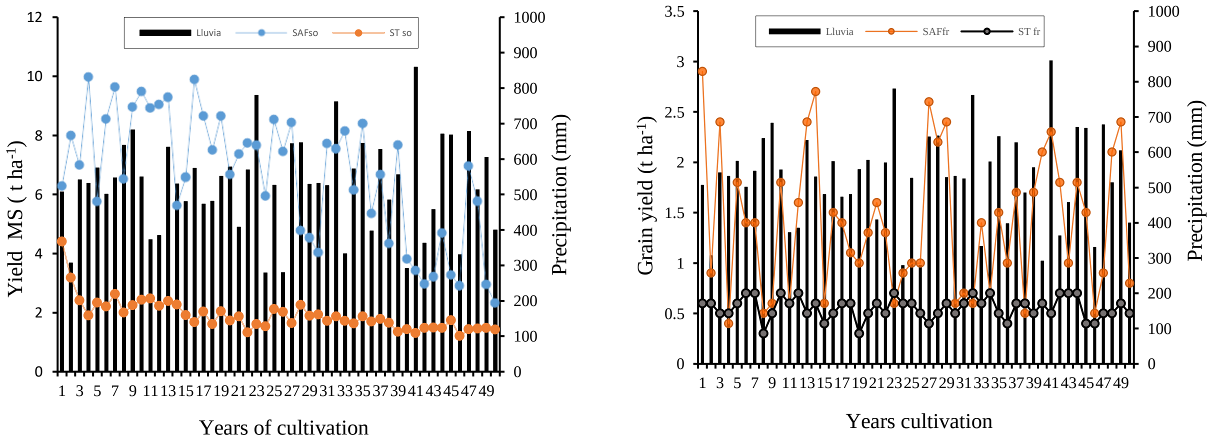

Figure 1. Yield of the rotation sorghum (a) and beans (b) simulated by EPIC in Sandovales, Aguascalientes, for a period of 100 years (50 years old sorghum and 50 years old bean).

In the traditional system (ST), a remarkable low productivity of the evaluated crops is observed, the yields of sorghum and beans in monoculture show a clear tendency to remain at a subsistence level with the passage of time, being more marked for sorghum, situation that is probably related to the tendency of runoff and erosion in the future as a result of using ST. This means that, under current production conditions, it is necessary to replace ST with a conservation one that reverses these trends and ensures greater resistance to climatic events, translating into less vulnerability and greater sustainability and long-term resilience, thus maintaining a high level of performance. sustained of the crops under these conditions of dry land production in the semiarid region. In addition, it can produce collateral benefits for subsistence and contribute to the reduction of poverty.

Variability of the productivity of sorghum and beans

With the integration of technological innovations, it is estimated that it is feasible to achieve an increase in the yield of sorghum and beans (Figure 1). The performance simulation analysis shows that the SAF productivity for the rotation sorghum and beans fluctuates less (with a CV= 30 and 16%) than the ST (CV= 32 and 47%). In both cases, this variation is probably due to differences in the amount and distribution of rains that occur between one year and another and during the growing season. However, even in the driest years, the production of the innovative system was higher ($p \leq 0.05$) than that of the traditional one.

Loss of soil and water for a 100-year scenario

In Figure 2, simulated runoff and erosion data are presented, with the EPIC model for sorghum and bean crops under the two production systems evaluated (SAF *vs* ST) for a period of 100 years, in which it is observed that the highest losses of soil and water were in the ST for both crops. The SAF significantly reduced runoff and erosion compared to the previous one. SAF, as expected, turned out to be a more efficient system to reduce runoff and erosion because, according to Figueroa-Sandoval *et al*. (2011), in addition to having the efficiency of the stroke to the contour, modifies two factors that influence the surface runoff and erosion, the length and the degree of original terrain slope; as well as the positive effect of the live nopal barriers and the plant cover of annual crops (sowing of sorghum and beans at high plant densities).

In general, the results obtained agree with what has been reported by other authors (Larose *et al*., 2004; Figueroa-Sandoval *et al*., 2011; Camas *et al*., 2012) regarding comparative efficiencies, since the absolute values of the soil and water losses vary considerably according to the rational management of soil and crops. Because conservation practices are designed to rationally use the land and properly manage runoff (Lal, 1991; Farahani *et al*., 1998). Reducing erosion and surface runoff are more evident and practically sustainable and resilient to the SAF's hedgerows, achieving almost total erosion control and utilization of rainwater and life spans of 100 years, taking into account the rotation sorghum-beans (Figure 2). These results show that the current ST is not sustainable and is more vulnerable to erosion and runoff, so it is necessary to incorporate technological changes if we hope to achieve sustainable agriculture in the region studied.

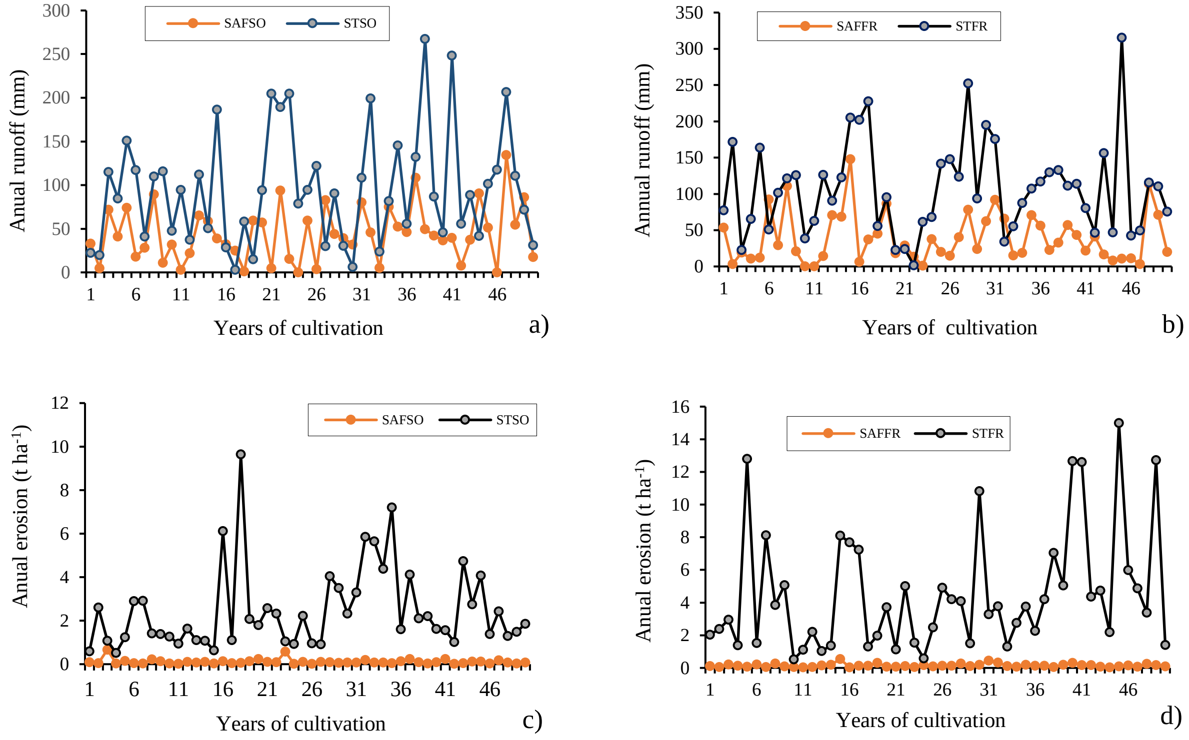

Figure 2. Long-term simulation of runoff (a, b) and erosion (c, d) for the agroforestry system *vs* traditional. Sandovales, Aguascalientes.

Fractal analysis of the rain, runoff, erosion and yield time series of sorghum and beans in two agrosystems

Table 1 shows the values of the Hurst exponent (H) and the fractal dimension (D) calculated for each of the series of values of the response variables: annual precipitation, biomass and grain yield, runoff and erosion, corresponding to the Figures 1 and 2. In the case of rainfall for a horizon of 100 years, it favors the stabilization tendency of the annual variability of its behavior, since it presents a clear fractal pattern with the persistence of D= 1.299 and H= 0.701. With values of D close to 1, the process becomes more and more reliable, since it exposes greater persistence. That is, the tendency of the series of precipitation is strengthened as time passes. Like the rain, the bean yield series for the SAF (Figure 1b) according to the exponent H (0.651) can be established that the series is persistent therefore, the variable is sensitive to its history. The persistence process increases as the value approaches 1. However, the yield series of sorghum and beans for SAF_{SO} and ST_{SO-FR}, are antipersistent (0< H< 0.5); that is, the series tend to oscillate more erratically (Table 1).

The results coincide with previous studies by Oñate, (1997); Amaro *et al*. (2004); Pérez *et al*. (2009). If 0<H<0.5 means that the time series is antipersistent. An antipersistent system covers less distance than a random one, in the case of an erratic particle. The values of H and D reported in Table 1, allow to determine that the runoff series (Q) for SAF_{SO-FR} are antipersistent; this means that, if in a small range of time Q it increases, the probability is high that in the following range of time Q it will decrease. With a mean value of D= 1753, which indicates that the series of Q tend to oscillate more erratically. However, the Q series for ST$_{SO\text{-}FR}$, show long-term persistence. This means that this series is strengthened as time passes.

Table 1. Fractal dimension of the series of rainfall, runoff, erosion and performance values of sorghum and beans, estimated with the wavelets (D$_W$) method, under different management.

Management system	Parameters	H$^£$	D$_W$
	Rain	0.701	1.299
SAF$_{SO}$	Q	0.138	1.862
ST$_{SO}$	Q	0.564	1.436
SAF$_{FR}$	Q	0.344	1.644
ST$_{FR}$	Q	0.6	1.4
SAF$_{SO}$	E	0.733	1.267
ST$_{SO}$	E	0.206	1.794
SAF$_{FR}$	E	0.638	1.362
ST$_{FR}$	E	0.729	1.271
SAF$_{SO}$	$\bar{Y}$	0.152	1.848
ST$_{SO}$	$\bar{Y}$	0.228	1.772
SAF$_{FR}$	$\bar{Y}$	0.651	1.349
ST$_{FR}$	$\bar{Y}$	0.379	1.621

Q= runoff; E= soil erosion; $\bar{Y}$= performance of sorghum and beans; $^£$= exponent of Hurst.

Finally, when considering the values of H and D for the erosion series (E), in Table 1 it is observed that for SAF with rotating sorghum and beans, it shows a high persistence. That is to say, the tendency of each series is strengthened as time passes. However, the erosion values of SAF in both crops are below the allowable ones. Thus, SAF increases its resilience against possible extreme weather events such as high intensity storms.

The results confirm that the annual precipitation at the Sandovales site, Aguascalientes, can be characterized through its fractal dimension, reaching values of D close to 1 and a high H exponent (0.701), which corroborate a high level of persistence. On the other hand, the results that show the majority of the series of values of the response variables in the management systems evaluated (SAF$_{SO\text{-}FR}$ *vs* ST$_{SO\text{-}FR}$) under rainfed conditions corroborate that these phenomena can be characterized through their fractal dimension. In practical terms, the analysis contributes to the estimation of hydrological phenomena associated with the variability of precipitation and the design of ‘systems’ aimed at modifying production techniques in order to sustainably and ‘resiliently’ increase productivity and overall profitability of the traditional productive systems.

Through fractal analysis, the temporal variability of a time series and its persistence can be determined. Likewise, the existence of a change in the pattern of precipitation and the different phenomena associated with it can be determined according to historical evidence.

Perspectives of sustainability and resilience of the productivity of the SAF with unirrigated dry-land sorghum-beans

In the Table 2 shows the values of the three evaluation criteria for sustainability and resilience of sorghum and beans for the two agrosystems compared. According to the value of the IVP, the ST with sorghum is not productive (the IEP goes below the minimum value of 0.4) practically from the first years of continuous cultivation (IVP= 0.02). On the other hand, ST with beans presents an IVP of 0.8 (IEP greater than the value of 0.6) which indicates a productive life of practically 80 years and finally, the SAF with rotating sorghum-beans has an IEP value of 1, which indicates that, in the 100-year evaluation period, the SAF is sustainable and resilient. From the results, it is inferred that, under this criterion, the rotation of sorghum-bean is kept closer to its optimum conditions, due to agricultural practices and soil conservation and water harvesting that integrates the SAF.

Table 2. Parameters used to evaluate the sustainability perspectives of the agroforestry system with rotating sorghum-bean and monoculture, in Sandovales, Aguascalientes.

Parameters	ST		SAF	
	So$_T$	Fr$_T$	So$_R$	Fr$_R$
IVP	0.02	0.8	1	1
IPP	0.002	-0.0002	0	0
RE	0.539	0.105	2.145	0.685
Evaluative criterion	Not sustainable	Sustainable	Sustainable	Sustainable

IVP= productive life index; IPP= productive loss index and RE= equilibrium yield; So$_T$= traditional sorghum; Fr$_T$= bean traditional; So$_R$= sorghum in rotation and Fr$_R$= bean in rotation.

In relation to the IPP, Table 2 shows that ST with sorghum has the highest slope of the IEP curve of the two agrosystems considered, this is an indicator that this production system has a yield loss of 0.54. t of dry matter in 100 years of continuous cultivation that equals a loss of 100% of productivity. On the other hand, the ST with beans presents a relatively low IPP, with this system, the beans lose 0.1 t of grain in 100 years, which is equivalent to a loss of productivity of 20%. Finally, the SAF presented a very low IPP, the sorghum-bean rotation loses a negligible amount of its productivity. Therefore, the results obtained for the SAF with this crop rotation exhibit a greater stability in yields and lower productivity reduction in drought conditions, unlike monocultures.

Finally, when considering the RE criterion, in Table 2 it is observed that for ST with sorghum, the scope of variation of the IEP gave a standard deviation of 0.53, the ST with bean of 0.1, SAF with sorghum of 2.14 and with beans of 0.68, respectively. In this case a hypothesis test of non-significant equality of variance, which meant that the scope of variation was the same in both production systems for the two crops.

Based on the results observed in this evaluation it is clear that, of the two production systems analyzed, SAF is the one that presents the best perspectives to resist or recover from extreme climates (droughts or intense rains). Simultaneously, it allows to achieve a sustained and resilient yield of sorghum and beans under crop rotation, while the ST, currently used, it is necessary to replace it to avoid further deterioration of the future productivity of the system in the study area, especially the ST with monoculture.

Conclusions

The current erosion for the semi-arid region is a serious problem under the traditional production system used by subsistence producers, because they are highly vulnerable to the impacts of climate change and favor erosion processes and accelerate the loss of crop productivity. The rotation of sorghum-beans presented greater sustainability and resilience in the SAF, reducing the negative effects of climatic variation on crop yield. The use of dynamic simulation models constitutes a modern methodological tool, useful in the quantification of erosion and the planning of resource conservation, as well as in the selection of the best production system. The annual precipitation in the semiarid Highlands region of Aguascalientes and the different phenomena associated with it such as E, Q and $\bar{Y}$ can be characterized through the fractal dimension, reaching values of D close to 1, which corroborate a high level of persistence. The indexes IVP, IPP and RE, used to evaluate the perspectives of sustainability and resilience of sorghum and beans, were able to determine the sustainable performance of annual crops in the long term, for the temperate, semi-arid region of the Aguascalientes highlands.

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