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Application of the Concepts of Reliability, Resilience and Vulnerability to Bean Production in the Municipality of Garanhuns-PE

Maurício Costa Goldfarb[1], Dâmolces Aurélio Nascimento da Silva Alves[2], Irami Buarque do Amazonas[3], Willames de Albuquerque Soares[4]

1 - Adjunct Professor at the University of Pernambuco in Polytechnic School of Pernambuco, mauricio.goldfarb@upe.br;
2 - Adjunct Professor at the University of Pernambuco in Polytechnic School of Pernambuco, damocles.aurelio@upe.br;
3 - Adjunct Professor at the University of Pernambuco in Polytechnic School of Pernambuco, iba@poli.br;
4- Associate Professor at the University of Pernambuco and permanent member of the Postgraduate Program in Civil Engineering at the Polytechnic School of Pernambuco, was@poli.br.

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R E S U M O

Em regiões semiáridas, a oscilação da produção agrícola, especialmente de pequenos agricultores que utilizam pouca tecnologia em áreas não irrigadas, provoca enormes prejuízos sociais e econômicos. Essa é a realidade vivenciada pela grande maioria dos produtores de feijão no município de Garanhuns (PE). Nesse caso, para o direcionamento correto de políticas que objetivem a redução destes efeitos é imprescindível a utilização de indicadores eficientes que reflitam essa realidade da melhor forma possível. Neste trabalho, apresenta-se a análise da produção de feijão no município de Garanhuns, no período entre 1992 e 2021, utilizando os conceitos de confiabilidade, resiliência e vulnerabilidade, propostos inicialmente por Hashimoto *et al.* (1982), para avaliação de sistemas de abastecimento de água. As similaridades observadas entre estes sistemas, principalmente com relação a dependência das precipitações e a gravidade relacionada a falta da produção, tornam possível esta utilização. Os indicadores foram calculados para três cenários distintos, caracterizados por limites críticos decrescentes de 590, 447 e 300 toneladas. A confiabilidade nos três cenários foi de 70, 80 e 93%. A resiliência foi 56, 67 e 100%. A vulnerabilidade de aproximadamente 574, 640 e 807 toneladas. Observa-se, entre outros fatores, a necessidade de medidas para aumento da resiliência, extremamente baixa no primeiro cenário, e especialmente para redução da vulnerabilidade visto que no terceiro cenário o valor representa 87% de perda da produção esperada.
Palavras-chave: Agricultura, Semiárido, Confiabilidade, Resiliência e Vulnerabilidade.

Application of the Concepts of Reliability, Resilience and Vulnerability to Bean Production in the Municipality of Garanhuns (PE)

A B S T R A C T

In semi-arid regions, fluctuations in agricultural production, especially by small farmers who use little technology in non-irrigated areas, cause enormous social and economic losses. This is the reality experienced by the vast majority of bean producers in the municipality of Garanhuns (PE). In this case, for the correct direction of policies that aim to reduce these effects, it is essential to use efficient indicators that reflect this reality in the best possible way. In this work, an analysis of bean production in the municipality of Garanhuns is presented, in the period between 1992 and 2021, using the concepts of reliability, resilience and vulnerability, initially proposed by Hashimoto *et al.*. (1982), for evaluating water supply systems. The similarities observed between these systems, mainly in relation to the dependence on precipitation and the severity related to the lack of production, make this use possible. The indicators were calculated for three different scenarios, characterized by decreasing critical limits of 590, 447 and 300 tons. Reliability in the three scenarios was 70, 80 and 93%. Resilience was 56, 67 and 100%. The vulnerability of approximately 574, 640 and 807 tons. Among other factors, there is a need for measures to increase resilience, extremely low in the first scenario, and especially to reduce vulnerability since in the third scenario the value represents 87% loss of expected production.
Keywords: Agriculture, Semi-arid, Reliability, Resilience and Vulnerability.

Introduction

Agricultural production in the Brazilian semi-arid region, strongly characterized by small property and family farming, has intermittency as an inexorable and determining feature. Some years the harvest is plentiful, in others, not enough to recover the amounts invested or even justify the labor employed in the activity.

In this context, the climatic factor, with spatial and temporal irregularity of rainfall, has historically been blamed. As Santos de Araújo (2021) points out, in the Brazilian semi-arid region, records of droughts and related losses have occurred since the colonial period.

Analyzing the effects of drought on bean production in the rural region of Pernambuco, Silva *et al*. (2021), shows that this problem, in addition to being persistent, is even more serious when it comes to rainfed crops, which are typical of the region and completely depend on rainfall. Almeida (2021), also researching agriculture in a semi-arid region, characterizes the dry bean farming culture as being quite susceptible to climate variations.

Nowadays, the consequences of droughts are already extremely serious, however, if nothing is done, the forecasts are for it to get even worse in the medium and long term. Researchers such as Kundzewicz *et al*. (2007), Robertson *et al*. (2014) and Sung *et al*. (2018), among many others, show that global climate changes already observed in recent decades, as well as studies of predictive models, show a tendency to worsen the problem.

In the same sense, the report presented by the National Water Agency, in Portuguese, Agência Nacional de Águas (ANA, 2021), confirms the problem related to climate change in Brazil and, more specifically about the Brazilian Northeast, Ribeiro Filho *et al*. (2013), Assad (2013) and Souza Filho, Aquino and Martins (2014), observe the worsening of the drought phenomenon and its consequences for the populations of semi-arid regions.

Despite the importance of the climate issue, and more specifically the phenomenon of droughts and the tendency for this problem to worsen, several other variables, political, economic and even cultural, are also contributors to this reality. A significant component of contemporary agricultural development concerns the technological level used in the production process.

In Brazil, the South, Southeast and Center-West regions, mainly monoculture crops, related to export agribusiness, are those that use more technology in production compared to those developed in the North and Northeast regions. And this inequality in the use of technology in agriculture is not only observed between Brazilian regions.

Considering exclusively the Northeast region of Brazil, Costa Filho, Campos and Lemos (2023) observe considerable discrepancies. For these researchers, crops of products intended for commerce, such as sugar cane and cotton, use more technology than those related to traditional or subsistence agriculture, whose main purpose is internal consumption and family maintenance, as is the case in most often the case of corn and bean crops in the Brazilian Agreste.

In the same sense, and dealing specifically with the Brazilian semi-arid region, researchers such as Cavalcante Júnior *et al.* (2019), Santos de Andrade *et al*. (2020) and Borba *et al*. (2023) highlight the importance of the availability of technology to guarantee the stability of production, preventing it from being completely subject to variations in environmental conditions.

Researching bean production in a region that includes the municipality of Garanhuns, Leite (2019) confirms the predominance of small producers, showing that approximately 77% of cultivated areas are less than 6 hectares. Bringing up another specific question about bean production, this researcher also states that the physiological characteristics of the bean plant make it very susceptible to pests and diseases, and this factor, associated with climate issues and restricted access to technical assistance, makes productivity in this region is considerably lower than the national average values, in addition to contributing to the unpredictability of the harvest.

Whatever the reason, the uncertain nature of precipitation, typical of semi-arid regions, politics and the economy, which limit access to technology and technical assistance, or even the characteristic fragility of the bean plant against pests and diseases, the consequence of an unstable production is directly related to serious limitations on the producer's quality of life. As several researchers point out, such as Obermaier (2011) and Araújo (2013), the drop in agricultural productivity, especially for small producers, is often related to states of extreme poverty among the rural population.

For Gallopín (2006), uncertainty in semi-arid agricultural production can be thought of as an intrinsic characteristic of the system and, precisely because it is impossible to avoid, coexistence must be sought through the development of short and long-term strategies. According to this researcher, short-term activities are aimed at developing responsiveness, and long-term activities are aimed at developing adaptation capabilities. In other words, long-term measures must seek to improve coexistence with semi-aridity and short-term measures must ensure immediate assistance when production drops.

In the same sense, Manevska *et al*. (2023) notes the importance of policies to improve climate resilience through various measures, such as encouraging research in agriculture, the availability of technology and technical assistance to small producers, support for investment in agricultural infrastructure, and even regulation and certification of land use.

In order to adopt appropriate measures aimed at improving the quality of life of the rural population, it is essential to have the most detailed understanding possible of the temporal evolution of this production, as well as the losses related to its lack. In this sense, this work aimed to adapt and apply the concepts of reliability, resilience and vulnerability, initially proposed by Hashimoto *et al*. (1982) to evaluate water resources systems, bean production in the municipality of Garanhuns (PE).

In this sense, based on the calculation and analysis of these indicators for the 30-year period, from 1992 to 2021, we seek to understand the probability of bean production meeting a certain pre-established demand, that is, the non-occurrence of a failure (reliability), the ability to return the production system to a satisfactory state, once a failure has occurred (resilience), and finally, the extent of the losses related to a failure, if it were to occur (vulnerability).

Methodology

Study Area

Recognized as a hub for commerce and higher education in the 26 municipalities that make up the Agreste Meridional Pernambucano mesoregion, the municipality of Garanhuns is located 230km from the capital of the state of Pernambuco, Recife. Its average altitude of 842m in relation to sea level, and position, located on the windward side of the Borborema plateau, guarantee it a microclimate typical of high-altitude marshes, with fine and persistent rain, mainly between the months of May to August, alternated by a dry period, between October and December.

Its territorial extension of 458.5 Km^2 s completely inserted in the region defined by SUDENE (2019) as the Brazilian semi-arid region. Region where annual potential evapotranspiration exceeds historically observed precipitation values.

According to data from the latest census from the Brazilian Institute of Geography and Statistics, IBGE (2022), Garanhuns has a population of 142506 inhabitants and a demographic density of 310.8 inhabitants/Km^2.

Its economy has as its main driver the services sector, with emphasis on commerce, education, tourism, and public administration; followed respectively by the industrial and agricultural sectors.

The commerce is quite diversified, with the strong presence not only of open markets, but of many stores in the city center, possibly thanks to the absence of large shopping malls, as well as the offer of higher education, with three important public universities, UPE, UFAPE and FAGA, in addition to private institutions, are responsible for a considerable daily flow of visitors from nearby municipalities.

Tourism is strong and driven by the rich history of the municipality, by the strongly undulating and distinct topography, by the well-developed gardening of squares and public spaces that guarantee it the code name of the city of flowers, by the well-structured network of accommodation and gastronomy, and mainly by various art and cultural events that take place throughout the year, such as the Winter Festival, the Jazz Festival, among others.

The gross domestic product (GDP) per capita for the year 2022, just over 21.300 reais, can be considered low for the national reality, as it is a value very close to half of the Brazilian average in this same year. However, according to data presented by Silva and Ferreira (2022), Garanhuns has the highest GDP per capita in the Garanhuns microregion, which, in addition to Garanhuns, comprises the municipalities of Lajedo, Bom Conselho, Caetés, São João and Iati.

The Human Development Index of 0,66 is considered high for the regional reality, and relatively close to the Brazilian average. Regarding the HDI also in the interior region of Pernambuco, in this case in Vale do Pajeú, Nascimento (2023) observes a similar result, with relatively low income and education, contrasting with the high human development index, with values close to the national average, because of high life expectancy.

In the population of Garanhuns, high life expectancy is also the main component that guarantees an increase in the HDI as it is relatively higher than the education and income levels.

Figure 1, adapted from the location map presented by Ramos *et al*. (2019), prepared from the UTM projection system, Datum WGS 84, Zone 24S, from the IBGE cartographic base, presents the location of the state of Pernambuco in Brazil and the municipality of Garanhuns in the State.

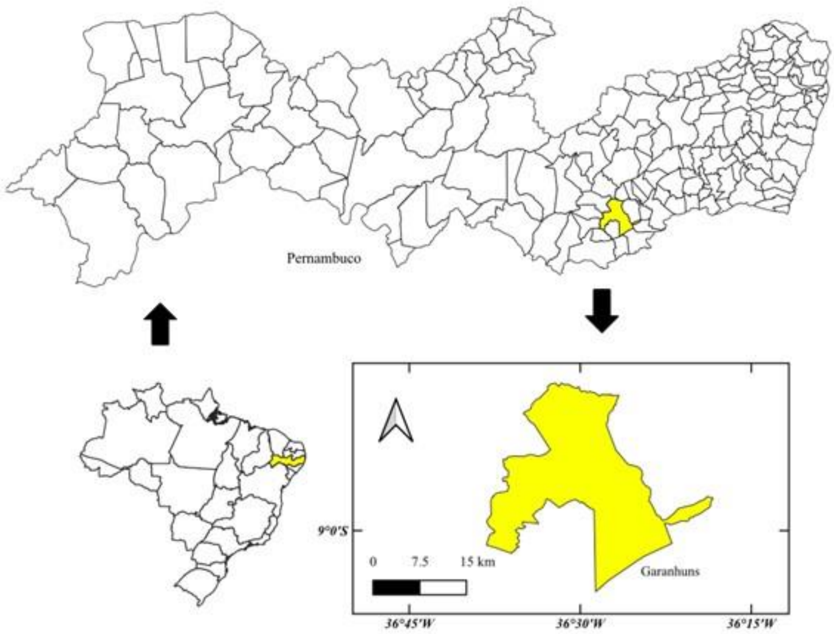

Figure 1. Location of the municipality of Garanhuns.

Reliability, Resilience and Vulnerability

The performance of a water resources system, strongly related to climate phenomena, is, according to Sneyers (1975) and Zongxue *et al*. (1998), commonly carried out based on the analysis of a historical series that represents the reading of production values obtained at pre-established time intervals. In these cases, the arithmetic mean and variance are the main statistical parameters recommended for analyzing system performance.

Figure 2 and Figure 3, presented below, prepared by Hashimoto *et al*. (1982), briefly explain the problem of using only the mean and variance as analysis parameters for series that describe the productivity of water resource systems.

Figure 2 presents a time series that never reaches the pre-established failure level. In other words, throughout the analyzed period, the system represented by the series is capable of meeting the requested demand.

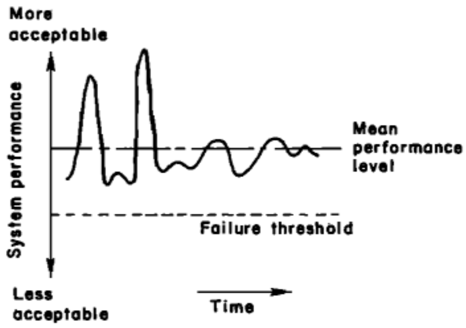

Figure 2. Historical series without occurrences of failures. Source: Hashimoto *et al.* (1982).

Figure 3 has the same failure level as Figure 2, that is, the same reference critical level. It also has the same mean and variance, as it was strategically generated by mirroring the values in Figure 2 around its average value. However, despite these conditions, Figure 3 presents failures at two distinct moments.

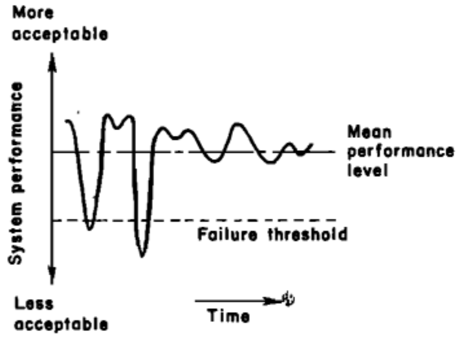

Figure 3. Historical series with occurrences of failures. Source: Hashimoto *et al.* (1982).

For Hashimoto *et al.* (1982), when an unsatisfactory result does not result in serious effects, in this case, the interruption of the water supply, the mean and variance may be sufficient analysis parameters. Otherwise more efficient indicators must be used.

Another problem with analysis based exclusively on the use of mean and variance is the inability, for example, to answer whether an increase in the mean associated with an increase in variance is or not a positive aspect of the system. To answer these questions, these researchers proposed analysis based on parameters called reliability, resilience and vulnerability.

The application of these parameters has been presented in the literature at different scale levels ranging from a reservoir, such as Hashimoto *et al.* (1982), Kjeldsen and Rosbjerg (2004), Asefa *et al.* (2014), Risso and Mendes (2022), even much larger ones, as is the case of Hazbavi *et al.* (2018). These researchers, Hazbavi *et al.* (2018), use the parameters of reliability, resilience and vulnerability to analyze the performance of river basins subject to periods of drought and conclude, among other things, that the joint analysis of these parameters can provide comprehensive information that is important for management plans, mainly in arid and semi-arid regions.

Calculation of indicators

To analyze the performance of a water system, after reading a certain state, the observed value can be classified as satisfactory or unsatisfactory. When the system has managed to meet a certain requested demand, since the previous reading, the response is satisfactory, otherwise, unsatisfactory.

In the application presented in this work, it is important to make an analogy between the water system and the agricultural production of a region. Agricultural productivity is also a value that may or may not be sufficient to meet the producer's needs or expectations.

For the following calculations, when the value is sufficient we say that it is a success value, otherwise, that the production was a failure, or that it did not reach a previously established critical value.

To define the parameters, the data set of a time series, $[X_t = X_1, X_2, X_3, \ldots]$, is called X, which can be divided into two other disjoint subsets: success (S) and failure (F).

The first parameter presented in Hashimoto *et al.* (1982) is reliability, defined as the probability of no performance failure occurring in the analyzed period.

$$\alpha = P[X_t \in S] \tag{01}$$

In other words, reliability α is simply the probability of the set of success. Obviously, allowing similar analysis, the probability of failure will be the probability of the set complementary to the success.

The second parameter, Resilience, represents the system's ability to recover once a failure has occurred. Thinking about an agricultural system, a failure, represented by the collapse of a harvest, can compromise the availability of seeds and financial resources for a new planting, requiring the system to take the necessary time to recover.

If T_F is the period of time required for the system to emerge from a failure, resilience will be exactly the inverse of this time.

In terms of probability, resilience ɣ can be given by the ratio between the probability of X_t belonging to the success set such that X_{t-1} belongs to the failure set and the probability of X_t belonging to the failure set:

$$ɣ = \frac{P[X_t \epsilon S e X_{t-1} \epsilon F]}{P[X_t \epsilon F]} \tag{02}$$

For a mathematical definition of resilience Hashimoto uses the terms Z_t, a function of the current performance state,

$$Z_t = \begin{cases} 1, se X_t \epsilon S \\ 0, se X_t \epsilon F \end{cases} \quad (03)$$

and the term W_t, a function of both the current performance state and the immediate future performance state:

$$W_t = \begin{cases} 1, if\ X_t \epsilon S\ and\ X_{t+1} \epsilon F \\ 0,\ in\ any\ other\ case \end{cases} \quad (04)$$

From the calculation of the terms Z_t and W_t the resilience of the system can be obtained through the following equation:

$$ɣ = \frac{1}{n}\sum_{t=1}^{n}(W_t). [\frac{1}{n}\sum_{t=1}^{n}(1 - Z_t)]^{-1} \quad (05)$$

Using the concept of resilience it is also possible to calculate the return period to a satisfactory situation:

$$T_F = ɣ^{-1} \quad (06)$$

The third performance parameter, vulnerability ν, unlike the previous two, is not a probabilistic value. The vulnerability seeks to describe the magnitude of the failure, if it were to occur. To develop a vulnerability quantifier, each element X_j, such that X_j is a failure event, is related to the term s_j that represents the size or magnitude of the failure X_j.

$$\nu = \sum_{j \epsilon F} s_j\, e_j \quad (07)$$

Where e_j is the probability of occurrence of x_j, n the failure set F. And, s_j is calculated by the difference between the expected or average production value and the production value in the specific year, whenever production is less than the critical value, and equal to zero whenever production is greater than the critical value, according to equation 08.

$$s_j = \begin{cases} 0, & if\ X_t \in S \\ X_m - X_t, & if\ X_t \epsilon\ F \end{cases} \quad (08)$$

The analysis of the three parameters allows the assessment of the risk of failure (reliability), the ability to restore satisfactory conditions (resilience), and the size of the loss associated with a failure if it were to occur (vulnerability).

Results and discussion

The study period covered the 30-year interval, from 1992 to 2021, of bean production in the municipality of Garanhuns. The values presented comprise the sum of the production of several varieties cultivated in the municipality, highlighting the common bean (*Phaseolus vulgaris L.*) and the cowpea or macassar (*Vigna unguiculata*). The values in Table 1, presented below, were obtained from Municipal Food Production (PAM) publications, developed by IBGE (2022), and present the total production of beans in the municipality of Garanhuns expressed in tons.

Table 1 – Bean production, in tons, in the municipality of Garanhuns: 1992 – 2021.

Year	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Production (ton)	370	155	1439	1331	1576	2160	483	400	1368	710
Year	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Production (ton)	810	447	936	1017	1073	1005	1349	1100	590	1280
Year	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Production (ton)	418	960	900	563	89	968	300	1590	1100	1281

Source: Municipal Agricultural Production - IBGE (2022)

In Table 1, the total amplitude given by the difference between the year of highest productivity, in 1997 with 2160 tons, and the lowest, in 2016 with 89 tons, calculated at 2071 tons, quantifies the large fluctuation in production.

The relation between the fluctuation in agricultural productivity and the climate issue in the semi-arid region, widely discussed in the specific literature, can be proven by comparing productivity data and precipitation time series, such as that presented in Costa *et al.* (2013)

However, low production often occurs not necessarily in a drier year, but following a dry period. Table 1 also shows the year with the lowest productivity, in 2016 with 89 tons, which does not occur in a year with the strongest drought, but which follows the period of severe drought, between 2012 and 2015, described by Silva *et al.* (2021), including specifically on bean production in the semi-arid region of rural Pernambuco.

The justification lies in the consequence of the drop in previous production, which limits the availability of seeds, the necessary capital and even the motivation to remain in agricultural activity and, in more extreme cases, even the necessary conditions to remain in the field.

Widely described in the literature, such as Magalhães and Glantz (1992) and in Filho, Moraes and Bennati (2016), the drop in production has been the main driver of the exodus of populations from the countryside to the cities. This observation shows not only the importance of analyzing the parameter called resilience, but unlike what is thought in common sense about agriculture in a semi-arid region, it attributes to water the status of a necessary condition, but not sufficient to guarantee agricultural productivity in the region after a production breakdown event.

Still with reference to the production data presented in table 1, as well as bean consumption values, the values of the critical production levels, necessary to calculate the three parameters, are determined.

Regarding the consumption of beans by the Brazilian population, Wander and Chaves (2011), working with data from 1998 to 2010, present a per capita value of 17kg per year.

Considering the population presented in BDE (2010), of 129.408 (year of census carried out closest to the center of the study period), we arrive at an approximate value of 2200 tons; value higher than the maximum annual productivity of the analyzed period.

Analyzing data from 2019, Coêlho and Ximenes (2020) confirm this observation, when they show that the state of Pernambuco imports the vast majority of beans consumed. Therefore, local consumption would not be a viable parameter for estimating critical production, because if it were, all years would be considered lower than the critical value.

The critical reference values used in the calculations were the productions of three years of low productivity: critical value 1, 2010 production with an approximate value of 590 tons; critical value 2, production in 2003, with an approximate value of 447 tons; and critical value 3, with 2018 production, with an approximate value of 300 tons.

Figure 4, presented below, shows the evolution of bean production in the analyzed period and the three critical values used as reference.

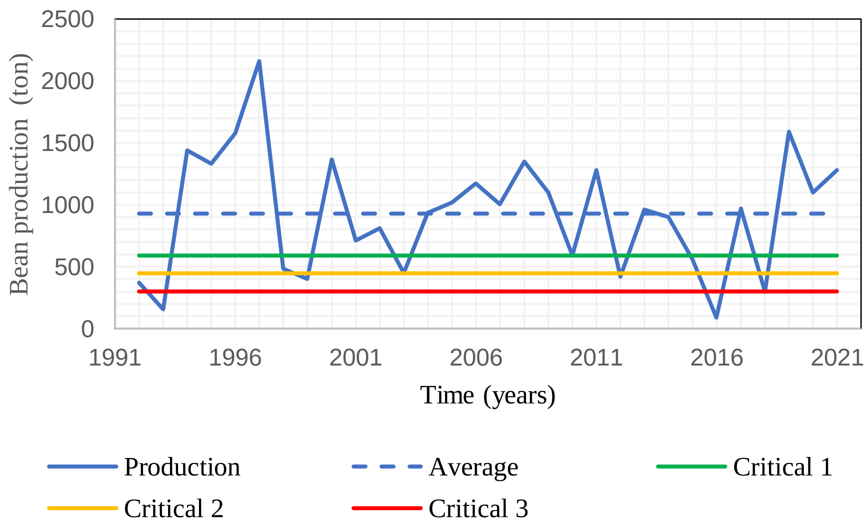

Figure 4**.** Bean production in the municipality of Garanhuns over a period of thirty years: 1992 – 2021. Source: Authors.

In Figure 4, considering critical level 1, we can observe six regions in which production values are lower than the pre-established critical limits, three of them, with two consecutive years, 1992 to 1993, 1998 to 1999 and 2015 to 2016. For the level critical 2, we can observe five critical regions and only one of these with two consecutive years, 1992 to 1993. At level 3 we have two critical regions and no occurrence of years with critical productions in consecutive years.

Table 2 presents the results of the equation parameters, necessary to determine reliability, resilience and vulnerability, for the first critical level established.

To determine the s_j values presented in lines 6, 12 and 18, the average annual productivity value in the study period was previously calculated at 928.9 tons.

Table 2 – Calculation of parameters for the first critical level.

Year	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**
Production (ton)	370	155	1439	1331	1576	2160	483	400	1368	710
Critical V. 1 (ton)	590	590	590	590	590	590	590	590	590	590
Zt	0	0	1	1	1	1	0	0	1	1
Wt	0	0	0	0	0	1	0	0	0	0
Sj (ton)	559	774	0	0	0	0	446	529	0	0
Year	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Production (ton)	810	447	936	1017	1073	1005	1349	1100	590	1280
Critical V. 1 (ton)	590	590	590	590	590	590	590	590	590	590
Zt	1	0	1	1	1	1	1	1	1	1
Wt	1	0	0	0	0	0	0	0	0	1
Sj (ton)	0,0	482	0	0	0	0	0	0	0	0
Year	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Production (ton)	418	960	900	563	89	968	300	1590	1100	1281
Critical V. 1 (ton)	590	590	590	590	590	590	590	590	590	590
Zt	0	1	1	0	0	1	0	1	1	1
Wt	0	0	1	0	0	1	0	0	0	0
Sj (ton)	511	0	0	366	840	0	629	0	0	0

Applying the results from Table 2 to equations 1, 5 and 7, we respectively obtain the parameter values for the first critical level. Under these conditions, reliability was calculated at 70.0%, a value that can be considered low when taking into account the importance of production for economic and even food security for the producer's family. Resilience was calculated at 55.6%, a value that can also be considered low and which reflects that in just over half of the times production values below the critical limit occurred, there was recovery in the following harvest. At the first critical level, vulnerability was calculated at 573.9 tons.

Table 3 presents the results of the equation parameters, necessary to determine reliability, resilience and vulnerability, for the second critical level established.

Using the values in Table 3, the indicators for the second critical level are calculated: reliability of 80.0%, resilience of 66.7% and vulnerability of 640.2 tons. Comparing to the values of the first critical level, an increase of approximately 10 percentage points can be observed in both reliability and resilience. Vulnerability, in turn, has a slightly higher percentage increase, 11.7%.

Table 4 presents the results of the equation parameters, necessary to determine reliability, resilience and vulnerability, for the third critical level, which is 300 tons per year.

With the results in table 4, the parameter values for the third critical level: reliability equal to 93.3%, resilience equal to 100%, and vulnerability of 806.9 tons.

Table 3 – Calculation of parameters for the second critical level.

Year	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Production (ton)	370	155	1439	1331	1576	2160	483	400	1368	710
Critical V. 2 (ton)	447	447	447	447	447	447	447	447	447	447
Zt	0	0	1	1	1	1	1	0	1	1
Wt	0	0	0	0	0	0	1	0	0	0
Sj (ton)	559	774	0	0	0	0	0	529	0	0
Ano	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Production (ton)	810	447	936	1017	1073	1005	1349	1100	590	1280
Critical V. 2 (ton)	447	447	447	447	447	447	447	447	447	447
Zt	1	1	1	1	1	1	1	1	1	1
Wt	0	0	0	0	0	0	0	0	0	1
Sj (ton)	0	482	0	0	0	0	0	0	0	0
Ano	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Production (ton)	418	960	900	563	89	968	300	1590	1100	1281
Critical V. 2 (ton)	447	447	447	447	447	447	447	447	447	447
Zt	0	1	1	1	0	1	0	1	1	1
Wt	0	0	0	0	0	1	0	0	0	0
Sj (ton)	511	0	0	0	840	0	629	0	0	0

In relation to critical level 2, an increase in reliability is observed, and especially in resilience, which reaches a maximum value of 100%. In this case, the positive aspect of the elevation of these two parameters is associated with the very low critical level. The 100% resilience value indicates that throughout the analyzed period there were no two consecutive years with a production value below 300 tons. However, an undesirable change was also observed, which was the increase in vulnerability in relation to critical level 2.

Table 4 – Calculation of parameters for the third critical level.

Year	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Production (ton)	370	155	1439	1331	1576	2160	483	400	1368	710
Critical V. 3 (ton)	300	300	300	300	300	300	300	300	300	300
Zt	1	0	1	1	1	1	1	1	1	1
Wt	1	0	0	0	0	0	0	0	0	0
Sj (ton)	0	774	0	0	0	0	0	0	0	0
Year	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Production (ton)	810	447	936	1017	1073	1005	1349	1100	590	1280
Critical V. 3 (ton)	300	300	300	300	300	300	300	300	300	300
Zt	1	1	1	1	1	1	1	1	1	1
Wt	0	0	0	0	0	0	0	0	0	0
Sj (ton)	0	0	0	0	0	0	0	0	0	0
Year	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**
Production (ton)	418	960	900	563	89	968	300	1590	1100	1281
Critical V. 3 (ton)	300	300	300	300	300	300	300	300	300	300
Zt	1	1	1	1	0	1	1	1	1	1
Wt	0	0	0	1	0	0	0	0	0	0
Sj (ton)	0	0	0	0	840	0	0	0	0	0

Table 5 presents the reliability, resilience and vulnerability values for the three scenarios analyzed, described by their respective critical levels.

Table 5 – Reliability, resilience and vulnerability for the three critical levels.

Scenarios	Critical V. (ton)	Reliability (%)	Resilience (%)	Vulnerability (%)
First	590	70.0	55.6	573.9
Second	447	80.0	66.7	640.2
Third	300	93.3	100	806.9

Made from the values in table 5, the graphs in Figures 4 and 5 show the evolution of the indicators with the progressive reduction of the three critical levels, from the first to the third scenario, obtained from years of low production time series.

Figure 4 presents Reliability and resilience, probabilistic parameters of the system for the three scenarios.

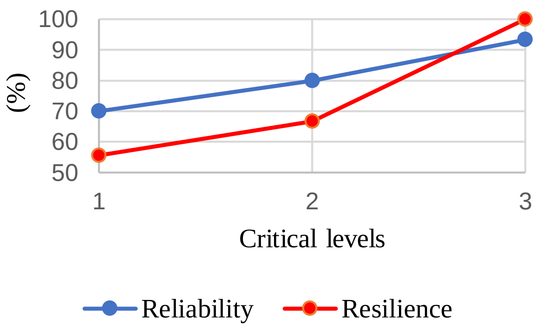

Figure 5. Reliability and Resilience in the three scenarios.

In Figure 5, we can observe an increase in reliability of approximately 33.3%, and in resilience of approximately 79.9%, with the passage of critical levels from 1 to 3. This result, also observed by Risso and Mendes (2022), was already expected since when we reduce the value of the critical level it becomes less likely to be reached, causing an increase in reliability, and on the other hand, with a greater probability of being surpassed once it has occurred, causing a corresponding increase in resilience.

Figure 5, presented below, shows the evolution of vulnerability in the three scenarios studied. The need for this parameter not to be included in Figure 4, along with reliability and resilience, occurs due to the fact that vulnerability, unlike the previous ones, is not, in principle, a probabilistic indicator.

However, although vulnerability is an absolute value, as shown after Figure 5, it is possible to calculate a relative value of vulnerability in relation to the expected average production value.

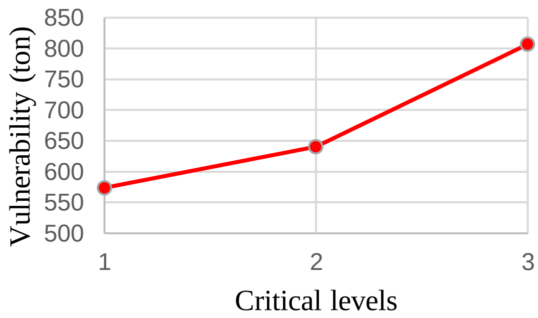

Figure 6. Vulnerability in all three scenarios.

The growth in vulnerability, shown in Figure 6, which occurs at the same time as the increase in guarantee and also in resilience, observed in Figure 5, a result also observed in Hashimoto *et al.* (*op cit*) and Risso and Mendes (2022), can be understood as a consequence of the reduction in the limit values of critical productions that occurs between the three stages analyzed.

Considering the average expected value of 928.9 tons, the vulnerability related to the first critical value (573.9 ton) corresponds to 61.2% of this value, which can already be considered a very high vulnerability. For the second critical value (640.2 ton), the vulnerability will correspond to 68.9%, and, finally, for the third critical value (806.9 ton), the vulnerability, that is, the magnitude of the loss in production reaches at 86.9% of the expected average value.

Therefore, in the three scenarios analyzed, the vulnerabilities, especially when compared to the expected average values, were always very high, showing that once a failure occurs, the losses incurred for producers are extremely serious.

Conclusion

Just as in the analysis of water supply systems, when any failure in the water supply can result in serious consequences for the lives of users, in agricultural systems, especially in family agricultural systems, losses can include the loss of livelihoods, food insecurity and often forced displacement to urban centers.

In delicate analyses, which include the production of a water system or a crop, as observed by Hazbavi *et al.* (2018), it is really important to use indicators that are as efficient as possible, which serve as parameters for the development of new techniques for evaluating and managing natural resources.

for evaluating water systems, can be used to allow a substantiated analysis of the productivity of agricultural systems. The similarity between the two sets of temporal data, which describe the production of a reservoir or a crop, occurs not only due to the climatic dependence related to precipitation, but also to other elements of the hydrological cycle such as infiltration, surface runoff and evapotranspiration, as well as the responses, positive or negative, of human actions in these production systems.

Regarding the establishment of critical values for calculating the parameters, an adaptation is necessary in relation to the application of the indicators in a water system and in agricultural production. While in the water system a state of failure can be characterized simply by a flow of demand exceeding supply, for an agricultural system production must meet not only the family's direct consumption, but several other issues that include the maintenance of the activity itself. In this sense, the definition of criteria for determining critical values based on the production history itself still needs to be worked on in future research.

Regarding the evolution of the indicators in the three scenarios analyzed, a result similar to those presented in Hashimoto *et al.* (1982), Sung *et al.* (2018) and Risso e Mendes (2022) were observed, with regard to the considerable increase in reliability, resilience but also vulnerability, as a result of the reduction in the critical limits considered in each scenario.

Considering the importance of production for the producer's quality of life, reliability values were low in all scenarios. In the first scenario, for example, reliability of 70% indicates that there is a 30% probability of production failure, that is, an extremely high risk of production loss.

Although resilience reaches 100% in the third scenario, due to the critical reference value of 300 tons being very low, this indicator can also be considered low in the first two scenarios. Especially in the first scenario, the value of 56% reveals a very low capacity of the system to respond positively after the occurrence of a critical event.

Still in relation to the values observed in the resilience calculations, it is possible to state that the satisfactory production of a given year depends not only on the climatic conditions, but also on the production of the previous year. This fact demonstrates the importance of strengthening policies such as the crop insurance proposal to improve resilience in order to guarantee the minimum resources that enable the following year's production.

The vulnerability values calculated in this work were extremely high in all scenarios evaluated, reaching a total of approximately 87% of the expected production. As this value refers to average production values of a group of small producers, it is possible to state that in critical years, a large number of these farmers experience total losses of their production.

The values of the reliability, resilience and vulnerability indicators, calculated for the present day, based on the historical series of the past thirty years, already reveal a very worrying scenario. However, the worsening of climatic conditions, as observed by researchers such as Nascimento (2023), Assad (2013), Souza Filho (2016), among others mentioned in the introduction to this work, exposes rural populations in semi-arid regions to increasing risks of more intense loss of livelihoods. In other words, not only the present scenario, but mainly what research forecasts already indicate, show the importance of developing and expanding policies aimed at improving the lives of populations in the semi-arid region.

The actions necessary to increase reliability and resilience, while reducing vulnerability, must occur on a global and regional scale. Global actions, well exemplified by the objectives of the United Nations 2023 agenda, presented at the UN (2023), observe the need to combat climate change and its impacts, including the availability of a budget for investment in climate management and adaptation, mainly in populations with greater socioeconomic fragility, as is the case of most family producers in the Brazilian semi-arid region. On a regional scale, it is necessary to strengthen actions, such as the one presented in IPA (2022), for the distribution of seeds of plant varieties that are more resistant to droughts, which has been taking place in the municipality of Garanhuns.

These actions must include the adoption of policies that encourage the processes of organization and participation of the local population with the aim of environmental and social sustainability. These policies, according to researchers such as Almeida et al. (2024) and Jesus et al. (2024), when based on the principles of agroecology, they are especially important for the development of family farming in the semi-arid region.

In general, it is essential that public authorities provide access to technology and technical assistance to small producers and, just as importantly, guarantee the availability of resources not only to finance production, but also, and mainly, as crop insurance to guarantee a minimum income in years of production decline, essential to maintaining the producer's quality of life.

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