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CROP PRODUCTION

Markov chains to determine the probability of climate change for planting selection in the city of Caxias do Sul

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ABSTRACT: *The Markov stochastic chain model and the analytical hierarchy process (AHP) were used as tools to support decision-making for the best crop-planting choice in the city of Caxias do Sul, Brazil. Temperature and precipitation information were collected from the Meteorological Database for Teaching and Research of the National Institute of Meteorology of Brazil for the period 1997–2017. The stochastic model was applied to obtain the probability of transition between a range of variations for temperature and precipitation. In the second phase of the study, an algebraic model was developed, making it possible to link the probability of the Markov chain transition matrix to the AHP judgment matrix. In the third phase, the AHP was applied as a tool to determine the most beneficial crop that could be planted for the studied city, considering the evaluated criteria: temperature, precipitation, and soil pH. The alternatives for crop planting were carrots, tomatoes, apples, and grapes. These were chosen because they are the most-planted crops in the city of Caxias do Sul. The ranking of the benefit–force results of applying the model for spring was carrots (0.297), apples (0.259), grapes (0.228), and tomatoes (0.215); for summer: grapes (0.261), tomatoes (0.261), apples (0.238), and carrots (0.230); for autumn: carrots (0.316), grapes (0.243), tomatoes (0.228), and apples (0.213); and for winter: carrots (0.327), tomatoes (0.235), apples (0.222), and grapes (0.216). Thus, it was concluded that farmers would have a better chance of success if they planted carrots during the spring, autumn, and winter, and grapes during the summer.*

Key words: *Hierarchical analytical process, operational research, decision-making process, crops, temperature, precipitation, soil pH.*

Aplicação de cadeias de markov na probabilidade de mudanças climáticas para seleção de plantio na cidade de Caxias do Sul

RESUMO: *O Modelo de Cadeia Estocástica de Markov e o Processo de Hierarquia Analítica (AHP) foram utilizados como ferramentas de apoio à tomada de decisão para a melhor escolha de plantio na cidade de Caxias do Sul, Brasil. As informações de temperatura e precipitação foram coletadas de 1997 a 2017 no Banco de Dados Meteorológicos para Ensino e Pesquisa do Instituto Nacional de Meteorologia do Brasil. O modelo estocástico foi aplicado para obtenção da probabilidade de transição entre faixas de variação para temperatura e precipitação. Na segunda fase do estudo, um modelo algébrico foi desenvolvido, possibilitando vincular a probabilidade da matriz de transição de cadeias de Markov na matriz de julgamento do AHP. Na terceira fase, o AHP foi aplicado como ferramenta de apoio à decisão do cultivo mais benéfico para a cidade estudada, considerando os critérios avaliados: temperatura, precipitação e pH do solo. As alternativas escolhidas para fazer o ranking foram: cenoura, tomate, maçã e uva, escolhidas por possuírem a maior quantidade de plantio na cidade de Caxias do Sul. O ranking do resultado de força de benefício da aplicação do modelo para a primavera foi: cenoura (0,297), maçã (0,259), uva (0,228) e tomate (0,215); para o verão: uva (0,271), tomate (0,261), maçã (0,238) e cenoura (0,230); para o outono: cenoura (0,316), uva (0,243), tomate (0,228) e maçã (0,213); para o inverno: cenoura (0,327), tomate (0,235), maçã (0,222) e uva (0,216). Assim, concluiu-se que o agricultor terá mais chances de sucesso se optar por plantar cenoura durante a primavera, outono e inverno, e uva durante o verão.*

Palavras-chave: *processo analítico hierárquico, pesquisa operacional, processo decisório, cultivos, temperatura, precipitação, pH do solo.*

INTRODUCTION

GONDIM et al. (2017) predicted that if the burning of fossil fuels progresses at the current rate, without any changes in climate policy, there is at least a 66% probability that global temperatures will increase by at least 2.5 C by 2100 compared to pre-industrial levels (1850 to 1900). The authors also reported that, in Brazil with the exception of the Pampas and the Atlantic Forest, the tendency is for temperatures to increase while rainfall decreases.

According to the Intergovernmental Panel on Climate Change (IPCC) (2014), a 1 °C rise in temperature may have a negative impact on the cultivation of rice, wheat, and corn in tropical areas. However, MENDONÇA (2006) stated that

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one of the positive effects of global warming will be the expansion of agricultural areas with tropical and subtropical characteristics.

The Markov chain was first proposed in a 1906 article written by Russian mathematician Andrei Andreyevich Markov, in which he described the stochastic process and provided the probability information in a transition from one state to another (MARKOV, 1906). In the stochastic process, the probability distribution of the future state is based only on its current state, and is independent of previous events in the time series (YEH & HSU, 2019).

The analytical hierarchy process (AHP), developed by Thomas L. Saaty in the 1970s, is used to help people make complex decisions (SAATY, 1980). According to FORMAN & GASS (2001), the AHP is a methodology for structuring, measuring, and synthesizing data. The process effectively unifies the quantitative and qualitative aspects of the given problem, expresses the considerations of the decision maker, and exposes the preferences hierarchically (IAÑES & CUNHA, 2006). By means of algebraic calculations, it is possible to list the best alternatives for a decision-making process, while verifying, throughout the calculation, if the judgments are consistent.

According to FLORAVANÇO & SANTOS (2013), the ideal precipitation, temperature, and soil pH for apple cultivation are 700 to 1700 mm, between 18 and 23 °C, and from 6 to 7, respectively. For grape cultivation, NACHTIGAL & MAZZAROLO (2008) suggested a precipitation of up to 570 mm, 20 to 30 °C temperature, and a pH of 6 to 7. EMBRAPA (1993) suggested for tomato planting, a temperature of 20 to 24 °C and a pH between 5.5 and 7. Moreover, SILVA et al. (2006) said that 400 to 600 mm of rainfall is ideal for tomatoes. VIEIRA et al. (1999) indicated that, for successful carrot planting, the ideal rainfall is between 350 and 500 mm, with a temperature of 15 to 21 °C. Moreover, MAROUELLI et al. (2007) suggested a pH of 6 to 6.5.

In this context, this study evaluated the probabilities of possible climate changes, starting from an initial climatic state in the city of Caxias do Sul, Brazil, using the stochastic Markov chain model, and, based on this, indicated the best planting option per season for the city studied, using a multicriteria method.

MATERIALS AND METHODS

Database

The information for the present research was obtained from the Meteorological Database for Teaching and Research (BDMEP) of the National Institute of Meteorology (INMET), Brazil. The collected information comprises data from 1997 to 2017, i.e., 20 years, with a monthly period.

Crops

The following crops were chosen according to information from the Brazilian Institute of Geography and Statistics (IBGE) (2016), for having the four largest productions in the city of Caxias do Sul in the year 2016. They include apples (113,000 tons), grapes (78,100 tons), tomatoes (36,800 tons), and carrots (14,400 tons).

The parameters that were used in the study were the average temperature (°C), precipitation (mm), and soil pH. The relationships of their variations over time with climate change were taken into account.

Markov chains

To create a stochastic Markov model, the following example was used as a basis for calculation. According to HILLIER &LIEBERMAN (2013), the daily time evolution was formulated as a stochastic process $\{X_t\}$ (t = 0, 1, 2,...) where

$$X_t = \begin{cases} 0 & \text{if day } t \text{ is dry} \\ 1 & \text{if it is raining on day } t \end{cases} \quad (1)$$

$$P\,\{X_{t+1} = 0 | X_t = 0\} = 0.8 \quad (2)$$

$$P\,\{X_{t+1} = 0 | X_t = 1\} = 0.6 \quad (3)$$

Equations 2 and 3 represent, respectively, an 80% probability of having dry weather, if the weather was dry the day before, and a 60% probability of having dry weather, if it rained the day before.

Because these probabilities do not change if information about the time prior to today (day *t*) is taken into account:

$$P\{X_{t+1} = 0 | X_0 = k_0, X_1 = k_1, \ldots, X_{t-1} = K_{t-1}, X_t = 0\} = P\{X_{t+1} = 0 | X_t = 0\} \quad (4)$$

$$P\{X_{t+1} = 0 | X_0 = k_0, X_1 = k_1, \ldots, X_{t-1} = K_{t-1}, X_t = 1\} = P\{X_{t+1} = 0 | X_t = 1\}, \quad (5)$$

for t = 0, 1,... and for every sequence $k_0, k_1, \ldots, k_{t-1}$, where k represents the period of a state. These equations must also be valid, if X_{t+1}= 0 is replaced by X_t. This occurs because states 0 and 1 are mutually exclusive and are the only possible states; hence, the sum of the probabilities of the two states must equal 1. Thus, the stochastic process has a Markovian property.

Therefore, the transition probabilities are as follows:

$$p_{00} = P\{X_{t+1} = 0|X_t = 0\} = 0.8 \quad (6)$$
$$p_{10} = P\{X_{t+1} = 0|X_t = 1\} = 0.6 \quad (7)$$

For all t = 1, 2,..., the stationary transition probabilities are given as follows:

$p_{00} + p_{01} = 1$; therefore, $p_{01} = 1 - 0.8 = 0.2$.

$p_{10} + p_{11} = 1$;therefore, $p_{11} = 1 - 0.6 = 0.4$.

Therefore, the transition matrix is

$$P = \begin{matrix} 0 \\ 1 \end{matrix}\begin{bmatrix} p_{00} & p_{01} \\ p_{10} & p_{11} \end{bmatrix} = \begin{matrix} 0 \\ 1 \end{matrix}\begin{bmatrix} 0.8 & 0.2 \\ 0.6 & 0.4 \end{bmatrix}.$$

For HILLIER & LIEBERMAN (2013) and CECHIN & CORSO (2019), these transition probabilities refer to the transition from a row state to a column state. These transition probabilities provide the state's probability of what the weather will be like tomorrow, given the state of the weather today.

To create the matrix of ranges for the Markov chain, the maximum and minimum values of each range were defined and separated by season, from 1997 to 2017; with these values, the matrix of sums was obtained: the sum of times that a process went from one state to another. Thus, it was possible to obtain the transition matrix: the probability of an event moving to another state or remaining in the same, in a future time step.

A Markov chain was performed for the criteria of temperature and precipitation; however, because a database of the soil pH was not available for previous years, it was not possible to perform the stochastic process. According to GENRO et al. (2012), most soils of Rio Grande do Sul have an acidic characteristic. Therefore, for each crop, the soil pH was considered to be 5.0 to 6.0 in the optimal scenario.

Research model

In this research, a model was developed that enabled the connection of Markov chains to the AHP decision-making model. The model was based on three decision criteria: temperature, rainfall index, and soil pH. Four crops were considered as alternatives for the decision model.

Using the conditions for planting the selected crops as a base, it was possible to relate the probabilities of the transition-matrix bands to these conditions. Thus, with the objective of indicating which ranges of temperature and rainfall index meet the desired values for these parameters, the transition probabilities that encompass the ranges are added. Within the developed model, these ranges are marked with a "1"; that is, the ideal ranges are those with the highest probability of occurring. Thus, the probability of a successful planting of a crop is considered by evaluating the temperature and precipitation.

In table 1, the research model for the temperature and rainfall-index criteria related to each type of crop can be observed. The columns of the lower and upper limits, indicated in table 1, correspond to the lowest and highest values of the data used for each range defined in the Markov chain application, respectively. The probability column, conversely, is the steady state probability—it is considered mainly for medium and long-term probabilities, and is also found for each season of the year.

Analytic hierarchy process (AHP)

According to FLORAVANÇO & SANTOS (2013), temperature is one of the most important climatic variables that influence the production, growth, and quality of apple trees. EMBRAPA (2004) also emphasized that, for the production of root crops, e.g., carrots, the temperature is the most important climatic factor, followed by the rainfall index. The authors indicated the soil pH as a variable for plantations, but do not indicate its relevance with regard to the other variables. The values used in the AHP method were obtained with the help of the degree of importance cited by the authors, which can be seen in figure 1, where a comparison of the ideal range of parameters requires for each crop is made between the crops.

The defined framework considers decision-making based on the benefit, without considering costs. Therefore, to determine the strength of the criteria (temperature, precipitation, and soil pH) and the chosen alternatives (apple, grape, tomato, and carrot cultivation), the mathematical model described here was followed.

First, the judgment matrix was performed for the criteria. The definitions of the degree of importance were set with the help of the aforementioned literature; thus, it was possible to generate the normalized matrix and the eigenvector, generated by the average of the lines of the matrix, and represent the strength that each criterion has in relation to the study. Subsequently, the eigenvalue was calculated, the judgment matrix was multiplied by the eigenvector, and the maximum eigenvalue was divided by the eigenvector. Finally, the consistency index and the consistency ratio were calculated to verify the consistency of the matrix. The calculation for temperature, in the spring season, is fully analyzed in figure 1.

Table 1 - Research model for the temperature and rainfall index criteria.

Season	Criterion	Track	Low Lim. (°C)	High Lim. (°C)	Prob. (%)	Apples	Grapes	Tomatoes	Carrots
Spring	Temperature	A	4.88	9.51	1.3	0	0	0	0
		B	9.52	14.16	14.2	0	0	0	0
		C	14.17	18.80	42.9	1	0	0	1
		D	18.81	23.45	37.2	1	1	1	1
		E	23.46	28.10	4.3	0	1	1	0
		--------------------------Total (%)------------------------				80.1	41.5	41.5	80.1
	Rainfall Index	A	186.60	294.93	8.6	0	1	0	0
		B	294.94	403.27	15.2	0	1	0	1
		C	403.28	511.61	38.6	0	1	1	1
		D	511.62	619.95	10.6	0	1	1	0
		E	619.96	728.30	27.0	1	0	0	0
		-------------------------Total (%)-------------------------				27.0	73.0	49.2	53.8
Summer	Temperature	A	12.96	16.33	4.2	0	0	0	1
		B	16.34	19.72	23.0	1	0	0	1
		C	19.73	23.10	51.6	1	1	1	1
		D	23.11	26.49	19.9	0	1	1	0
		E	26.50	29.88	1.3	0	1	0	0
		-------------------------Total (%)-------------------------				74.6	72.8	71.5	78.8
	Rainfall Index	A	46.00	175.65	10.5	0	1	0	0
		B	175.66	305.31	18.5	0	1	0	0
		C	305.32	434.97	16.0	0	1	1	1
		D	434.98	564.63	35.2	0	1	1	1
		E	564.64	694.30	19.8	0	1	1	0
		-------------------------Total (%)-------------------------				0	100	71.0	51.2
Autumn	Temperature	A	1.40	6.41	2.0	0	0	0	0
		B	6.42	11.42	15.3	0	0	0	0
		C	11.43	16.44	37.6	0	0	0	1
		D	16.45	21.46	38.4	1	1	1	1
		E	21.47	26.48	6.6	1	1	1	0
		-------------------------Total (%)-------------------------				45.0	45.0	45.0	76.0
	Rainfall Index	A	0.00	120.19	4.9	0	1	0	0
		B	120.20	240.39	11.1	0	1	0	0
		C	240.40	360.60	24.7	0	1	0	1
		D	360.60	480.80	34.6	0	1	1	1
		E	480.80	601.00	24.7	0	1	1	1
		-------------------------Total (%)-------------------------				0	100	59.3	84.0
Winter	Temperature	A	0.64	5.67	5.7	0	0	0	0
		B	5.68	10.70	21.5	0	0	0	0
		C	10.71	15.74	37.7	0	0	0	1
		D	15.75	20.78	29.1	1	1	1	1
		E	20.79	25.82	5.9	1	1	1	1
		-------------------------Total (%)-------------------------				35.0	35.0	35.0	72.7
	Rainfall Index	A	0.80	149.02	4.6	0	1	0	0
		B	149.02	297.23	18.2	0	1	0	0
		C	297.24	445.45	18.2	0	1	1	1
		D	445.46	593.67	36.1	0	1	1	1
		E	593.68	741.90	22.9	1	0	1	0
		-------------------------Total (%)-------------------------				22.9	77.1	77.2	54.3

Indicated the probability of success of each crop in the four seasons.

	Criteria	Temperature	Rainfall Index	Soil pH
Judgment-Criteria	Temperature	1	3	9
	Rainfall Index	1/3	1	5
	Soil pH	1/9	1/5	1
	Sum	1.44	4.20	15.00

	Criteria	Temperature	Rainfall Index	Soil pH	Eigenvector (W)	Eigenvalue (λ)	λ Max	λMax Media	CI	CR
Normalized-Criteria	Temperature	0.69	0.71	0.6	0.67	2.04	3.06			
	Rainfall Index	0.23	0.24	0.33	0.27	0.81	3.02	3.03	0.01	0,03
	Soil pH	0.08	0.05	0.07	0.06	0.19	3.00			

	Alternatives	Apples	Grapes	Tomatoes	Carrots
Inserting the values obtained in Markov in AHP	Markov	0.8	0.42	0.42	0.80
	Apples	1.00	0.80/0.42	0.80/0.42	0.80/0.80
	Grapes	0.42/0.80	1.00	0.42/0.42	0.42/0.80
	Tomatoes	1/(0.80/0.42)	1/(0.42/0.42)	1.00	0.42/0.80
	Carrots	1/(0.80/0.80)	1/(0.42/0.80)	1/(0.42/0.80)	1.00

	Alternatives	Apples	Grapes	Tomatoes	Carrots
Judgment-Temperature-Spring	Apples	1.00	1.93	1.93	1.00
	Grapes	0.52	1.00	1.00	0.52
	Tomatoes	0.52	1.00	1.00	0.52
	Carrots	1.00	1.93	1.93	1.00
	Sum	3.04	5.85	5.85	3.04

	Alternatives	Apples	Grapes	Tomatoes	Carrots	W	λ	λ Max	λMax Media	CI	CR
Normalized-Temperature-Spring	Apples	0.33	0.33	0.33	0.33	0.33	1.32	4.00			
	Grapes	0.17	0.17	0.17	0.17	0.17	0.68	4.00	4.00	0	0
	Tomatoes	0.17	0.17	0.17	0.17	0.17	0.68	4.00			
	Carrots	0.33	0.33	0.33	0.33	0.33	1.32	4.00			

	Alternatives x Criteria	Temperature	Rainfall Index	Soil pH
Benefits-Temperature-Spring	Apples	0.33	0.13	0.05
	Grapes	0.17	0.36	0.28
	Tomatoes	0.17	0.24	0.56
	Carrots	0.33	0.26	0.09

	Autovetor Global	
Global Eigenvector-Spring	Temperature	0.67
	Rainfall Index	0.27
	Soil pH	0.06

	Benefits	
Final Result AHP-Spring	Apples	0.26
	Grapes	0.23
	Tomatoes	0.21
	Carrots	0.29

Figure 1 - Algebraic model for criteria and for the spring temperature alternative. The figure demonstrated the calculation model used.

RESULTS AND DISCUSSION

Markov chains

Initially, the results of the temperature and precipitation transition matrices were analyzed, observing that there is a probability between 84% and 86% of a temperature increase. The temperature ranges with the highest probabilities for each season were spring (14 to 19 °C), summer (20 to 23 °C), autumn (16 to 21 °C), and winter (11 to 16 °C).

The precipitation indicates a 75% to 100% probability of an increase in the pluviometric index, with the greatest probabilities of the ranges as follows: spring (403 to 512 mm), summer (435 to 565 mm), autumn (361 to 481 mm), and winter (445 to 594 mm), based on the period studied.

Research model

Based on the ideal information for the selected crops, the ranges in table 1 where this information would fit were highlighted. For example, for the apple crop, the ideal temperature was determined as being 18 to 23 °C; thus, it fits in Range C, which goes from 14.17 to 18.80 °C and in Range D, which goes from 18.81 to 23.45 °C, in the spring. For these determined ranges, the number 1 was inserted, with the intention of adding the probability of each crop to be successful in each range, defined by the steady state. That is, the probability of a successful apple crop is 80.1%, once the probability of Range C (42.9%) and that of Range D (37.2%) were added. This procedure was done for the temperature and precipitation criteria, in the four seasons of the year.

Analytic hierarchy process (AHP)

The AHP was applied for each season of the year to obtain a quarterly result, in the same manner that data were collected for the application of Markov chains. Regarding the soil pH criterion, and taking into account the literature compilation of the pH of crops and the pH of a large part of the Caxias do Sul region, optimal and good scenarios were considered for tomato and grape crops, respectively, and average and bad scenarios for carrot and apple crops, respectively. The AHP of the soil pH was considered the same for the four seasons. To obtain the results of the final alternative rankings, illustrated in figure 2, one must multiply the eigenvectors of the alternatives and the criteria, as per the partial results presented in figure 1. Thus, the final priority matrix is obtained.

CONCLUSION

In view of the obtained information and the proposed algebraic models, the carrot crop is suggested as the most suitable, among those evaluated for the winter, autumn, and spring seasons of the year; however, for the summer, a greater production of grapes is suggested. The study was conducted taking into account only the benefit factor, without relating it to the costs of the crops. In addition, it is emphasized that the farmer should pay greater attention to the apple plantation, because it had a low rate of planting success compared to the others, when the aggregate benefit matrix was applied. These results are indicated only for the city where this research was conducted, Caxias do Sul (RS).

Because the general objective of this research was to evaluate the transition probabilities between variation ranges for the temperature and rainfall index, in addition to indicating the best cultivation option, meteorological data were collected, already known algebraic models were applied, and a research model that made it possible to apply the stochastic model of Markov chains to the AHP decision-making method was developed.

The Markov chains, AHP, and models developed in this research proved to be effective for the proposed objective, resulting in an indication of cultivation by season. Moreover, observations to make the city more beneficial, effective, and safe were presented. The study created precedents for a further study of the subject in question, linking the benefits with the costs to provide for an economic improvement for the agriculture in the region. Moreover, other crops already cultivated in the city and the feasibility of new crops should be evaluated.

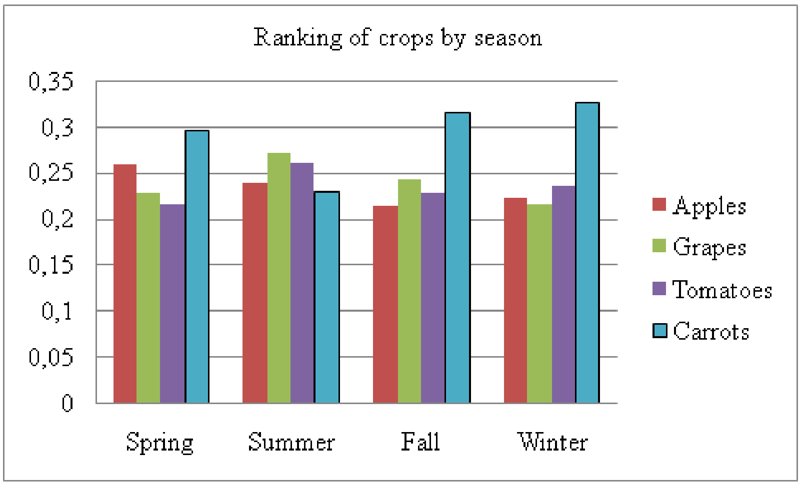

Figure 2 - Ranking of success of crops divided by the season of the year.

Rankings obtained by multiplying the eigenvectors of the AHP.

DECLARATION OF CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

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AUTHORS' CONTRIBUTIONS

Vanessa and Leandro contributed for the conception and writing of the manuscript. All authors critically revised the manuscript and approved of the final version.

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