WRIM
ISSN 2316-6886

Water Resources and Irrigation Management
v.9, n.1-3, Jan-Dec., 2020.

ORIGINAL PAPER

Water and energy efficiency in bean crop under center pivot irrigation

Cristian Epifânio de Toledo[1]*; Thályta Lharissa Gonçalves Rodrigues Silva[2]; Emanuelly de Moura Silva Almeida[2]; Alexandre Vicente Lopes Neto[2]; Filipe Augusto Rodrigues Santos[2]

[1]Departamento de Agronomia, Universidade Estadual de Goiás; [2]Universidade Estadual de Goiás. *Corresponding author: cristian.toledo@ueg.br

Abstract: Sprinkler irrigation systems, mainly of the center pivot type, provide high productivity and profitability, but require the adoption of management practices that allow greater efficiency in the use of water and energy resources. The objective of the present study was to analyze the efficiency in the use of water and energy resources of the irrigation management in the cultivation of common bean crop under center pivot irrigation systems in the Northeast of Minas Gerais. The efficiency of the use of water and energy resources was verified by comparing the irrigations practiced and the irrigations simulated according to a spreadsheet of 7 rural properties, with irrigated bean cultivation by center pivot with more than 10 years of use and without the adoption of management of irrigation. For this, irrigations carried out by the farmers were monitored and the hydraulic characteristics of the pivots, soil physical-water properties and climatic and crop data (ETc) were surveyed. Comparison of performed and recommended irrigations, showed that 6 of the 7 pivots irrigated excessively, but with an efficient use of water and energy resources, between 78 and 99%. A pivot performed a deficient management, being considered inefficient, since they did not provide the minimum conditions required by the culture. The irrigation systems evaluated have a tendency to perform an excessive irrigation, despite the efficiency in the use of water and energy resources in general considered good.

Keywords: management, irrigation, Christiansen Uniformity Coefficient - CUC.

Eficiência hídrica e energética em cultivo de feijão sob irrigação por pivô central

Resumo: Os sistemas de aspersão, principalmente, do tipo pivô central, proporcionam alta produtividade e rentabilidade, porém requerem a adoção de práticas de manejo que permitem maior eficiência no uso dos recursos hídricos e energético. Objetivo do presente estudo foi analisar a eficiência no uso dos recursos hídricos e energéticos do manejo da irrigação no cultivo de feijão em sistemas de irrigação por pivô central no nordeste de Minas Gerais. A eficiência do uso dos recursos hídricos e energético foi verificada comparando as irrigações praticadas e as irrigações simuladas conforme uma planilha eletrônica de 7 propriedade rurais, com cultivo de feijão irrigado por pivô central com mais de 10 anos de uso e sem a adoção de manejo de irrigação. Para isso, as irrigações realizadas pelos agricultores foram monitoradas e levantadas as características hidráulicas dos pivôs, as propriedades físicas-hídricas do solo e dados climáticos e da cultura (ETc). A comparação das irrigações realizadas e recomendada, demonstraram que 6 dos 7 pivôs realizaram uma irrigação excessiva, porém com eficiência no uso dos recursos hídricos e energética ficando entre 78 e 99%. Um pivô realizou um manejo deficitário, sendo considerado sem eficiência, já que não proporcionaram as condições mínimas exigidas pela cultura. Os sistemas de irrigação avaliados possuem uma tendência de realizarem uma irrigação excessiva, apesar da eficiência no uso dos recursos hídricos e energéticos no geral de considerado boa.

Palavras-chave: manejo, irrigação, Coeficiente de Uniformidade de Christiansen - CUC.

Introduction

Irrigated agriculture occupies about 18% of the total cultivated area on the planet, but this area contributes 42% of the total world production. However, this type of agriculture is considered the largest water user, consuming about 70% of the total water collected, – but these amounts can reach as much as 95 percent in some developing countries, increasing pressure to reduce water consumption without reducing food and fiber production [18, 11, 23, 13].

Another widely used input, especially in sprinkler irrigation, is energy, whether electric or combustion [12, 21]. According to Alves et al. [3] analyzing the economic viability of center pivot irrigation in soybean, corn and tomato crops, found that on average 7.2% of the production cost of these crops are related to energy to perform irrigation, in systems with optimized sizing.

Among the irrigation systems, the center pivot is the most widespread mechanical system in the world and in Brazil its use has been highlighted due to the significant growth in recent decades [14, 26]. Guimarães and Landau [14] conducted a survey of the center pivots in Brazil, found that in 2013, the country had nearly 18,000 center pivots, making up an area of approximately 1.2 million hectares, 32% larger than the 2006 Agricultural Census.

This growth in center pivot use has also increased the demand for water and energy resources, creating major future challenges. Since the availability of water and energy for irrigation should be reduced due to the increased demand for other priority sectors, which can lead to serious conflicts [24, 29].

More than ever, mainly center pivot sprinkler systems require the adoption of practices that allow high productivity and profitability, but with greater efficiency in the use of water and energy resources. But even considering the modernization of irrigation systems, the lack of a maintenance program for this equipment and inadequate irrigation management creates problems in the use of energy and water resources [15, 19, 28].

Thus, the objective of the present study was to analyze the efficiency in the use of water and energy resources of the irrigation management in the cultivation of common bean (*Phaseolus vulgaris* L.) crop under central center pivot irrigation systems in the Northeast of Minas Gerais.

Material and Methods

The work was carried out in 7 rural properties with agriculture irrigated by center pivot irrigation system, located in the municipalities of Paracatu, Unaí and João Pinheiro, located in the northeast of the state of Minas Gerais, Brazil (Table 1). The participant irrigating properties were chosen based on three factors: center pivot irrigated area with more than 15 years of use; lack of irrigation management; and Carioca bean (*Phaseolus vulgaris* L.) cultivation between March and August 2018.

In the evaluation of the equipment, surveys of the following characteristics were performed, according NBR 14244 to ABNT,

Table 1: Characterization of the selected center pivots to evaluate the efficiency in the use of water and energy resources in northern Minas Gerais

County	Property/Pivot	Brand	Year of installation
Paracatu	1	Valley	2002
Paracatu	2	Valley	2005
Paracatu	3	Valley	2004
Unaí	4	Asbrasil	1994
Unaí	5	Asbrasil	1992
Unaí	6	Asbrasil	1990
João Pinheiro	7	Valley	2000

Table 2: Characteristics of carioca beans (*Phaseolus vulgaris* L.) grown in the pivots

Pivot	Cultivars	Cycle	Root depth (cm)	Depletion factor (f)[1]	Kc[2]		
					1	2	3
1	Pérola	85-95	30	0.60	0.40	1.15	0.30
2	Madrepérola	75-85	30	0.60	0.40	1.15	0.30
3	Pérola	85-95	30	0.60	0.40	1.15	0.30
4	Pérola	85-95	30	0.60	0.40	1.15	0.30
5	Pérola	85-95	30	0.60	0.40	1.15	0.30
6	Madrepérola	75-85	30	0.60	0.40	1.15	0.30
7	Pérola	85-95	30	0.60	0.40	1.15	0.30

[1] Soil water depletion factor for no stress; and [2] Crop coefficient according to Doorenbos and Pruitt [8], where 1: early stage, 2: reproductive, and 3: harvest.

Toledo, Souza, and Albuquerque [28] and Coelho et al. [7]: irrigated radius (m), last tower radius (m), area (ha), system flow ($m^3\,h^{-1}$), displacement speed ($m\,h^{-1}$), percentage timer setting of 100% - revolution time (h), irrigation applied (irrigation water depth - mm), Irrigation application efficiency (irrigation project / irrigation applied - %), Christiansen Uniformity Coefficient (CUC) (%) and motor pump set power (hp). In addition to the hydraulic characteristics of the equipment, information was obtained on the soil attributes required in the calculation of available soil water such as soil density ($g\,cm^{-3}$), soil water retention curve and particle size distribution. For this, undisturbed and disturbed soil samples were taken at three predetermined points along the lateral pivot lateral line (beginning, middle and end), trying to obtain an average value for the cultivated area and in the layers 0 - 20 and 20 - 40 cm. The hydro-physical properties analysis was performed in the laboratory of the Department of Soils, Universidade Federal de Viçosa - UFV. The efficiency of the use of water resources and electricity was evaluated based on the irrigation management adopted daily by the owner at the center pivots, during the whole bean crop cycle, without interference with the irrigation moment and the amount of water to be applied. The irrigations performed were recorded registering the dates, the period (time) and the speed of displacement of the system used. The climatic data of each property were monitored by automatic climatological stations, providing information such as rainfall and crop evapotranspiration (ETc), estimated based on the Penman-Monteith method and bean crop coefficients [2]. The irrigation management performed at each center pivot was compared with a rational or recommended irrigation management generated in an "Irrigafácil" of Embrapa Milho e Sorgo (Brazil), which considers crop characteristics (Table 2), soil conditions (Table 3) and the weather. The spreadsheet, when entering the appropriate soil, crop and climate data, indicates when and how much to irrigate through a soil water balance. However, it has a flexibility in decision making so that the user has the freedom of when and how much to irrigate within their operational capacity. Thus, the management considered recommended will be the management indicated by the spreadsheet.

Results and Discussion

In Table 4 the general characteristics of the center pivots obtained in the field are presented. The irrigated radius ranged from 358 to 578 m, resulting in an area variation of 40.2 to 104.9 ha. The project flow was 284.8 to 516.6 m³ h-1 and the average displacement velocity was 274 m h-1, and its range was 251 m h-1 from pivot 7 to 285 m h-1 of pivot 2, generating a revolution time (RT), the percentage timer setting of 100%, of 11.8 and 12.6 hours, respectively.

The irrigation applied (IA) in the uniformity test ranged from 4.56 to 6.56 mm, always below the project irrigation. However, the irrigation application efficiency (IAe) was between 89 and 94%, generally considered normal. The application efficiency in a normal center pivot system should be around 90%, assuming a 10% loss of the applied water due to wind drag and evaporation [4].

Regarding the Christiansen Uniformity Coefficient (CUC), the values found ranged from 76 to 92%, considered based on the Christiansen Classification as good in the general scope [22, 28, 7]. CUCs classified as good (80 - 90%) and excellent (¿ 90%) indicate that the equipment has good maintenance of its components, being essential in cultivation of high commercial value [4].

In several studies CUC has been shown to be relevant in evaluating crop yields, where the higher the CUC value, the higher the CUC, the higher uniformity of application in the area, and the closer to optimum water distribution. Every irrigation system distribute water unevenly, in other words, parts of the irrigated area receive more or less water than the average irrigation depth. Thus, in a system with higher CUC, the water application in the area will be smaller than in a system with lower CUC, to obtain maximum culture yield.

For example, Stone, Silveira, and Moreira [25] comment that to obtain a productivity of 12 tons ha-1 corn under 95% CUC conditions, an irrigation depth of approximately 500 mm was required and under low uniformity conditions, 55% CUC, the irrigation depth was greater than 1,100 mm. Mantovani et al. [17], observed that system's with CUC values above 90% promoted maximum grain yield (2946 $\mathrm{kg\,ha^{-1}}$) and with 65% CUC occurred lowest productivity of 1975 $\mathrm{kg\,ha^{-1}}$. As to the depth applied, the 90% CUC provided water savings of 32.8%.

The electric motor power installed in the pivot systems of the analyzed center pivots ranged from 100 to 300 hp. This variation is normal, since the pump-motor assembly of the pumping system is calculated based on the demanded flow, the head of each project and the size of the installed piping. The Minas Gerais Energy Company - CEMIG, found that for each hectare irrigated by center pivot, an average of 2.35 hp is required [6]. This value is close to those observed in this study, which ranged from 2.1 to 3.2 hp $\mathrm{ha^{-1}}$. Toledo et al. [27] analyzing the possibility of optimizing the design of two center pivot irrigation systems, found a much lower potential/area ratio of 1.2 and 1.6 hp $\mathrm{ha^{-1}}$.

Analyzing the irrigated bean crop in the center pivots, it can be observed that the cycle of each cultivar was as expected, leaving the normal cycle cultivars with average of 91 days and the early cycle cultivars of 80 days

Table 3: Particle size analysis and average hydro-physical characteristics of the soils found in the pivots assessed

Pivot	Soil layer (cm)	Sand	Silt	Clay	Soil texture (average)	FC[1]	WP[1]	Ds[2]	TAW[3]
		—%	—			g g^{-1}		g cm^{-3}	mm
1	0-20	47	11	42	Sandy clay	0.311	0.206	1.26	26.46
	20-40	46	11	43		0.318	0.215	1.20	24.72
2	0-20	26	14	60	Clay	0.392	0.246	1.21	35.33
	20-40	24	12	64		0.387	0.251	1.21	32.91
3	0-20	9	26	65	Clay	0.395	0.235	1.22	39.04
	20-40	8	10	82		0.388	0.221	1.22	40.74
4	0-20	76	6	18	Sandy loam	0.182	0.092	1.35	24.30
	20-40	74	6	20		0.175	0.091	1.32	22.17
5	0-20	25	8	67	Clay	0.368	0.227	1.25	35.25
	20-40	24	8	68		0.382	0.219	1.22	39.77
6	0-20	27	17	56	Clay	0.331	0.221	1.23	27.06
	20-40	26	18	56		0.334	0.217	1.20	28.08
7	0-20	9	23	68	Clay	0.411	0.210	1.23	49.44
	20-40	8	6	86		0.409	0.209	1.24	49.60

[1] Soil moisture at field capacity (FC) and withering point soil moisture (WP); [2] Soil density (Ds); and [3] Total available water (TAW), according to Allen et al. [2].

(Table 5). Precipitation during bean cultivation was insignificant compared to crop evapotranspiration (ETc). The daily ETc values in the 7 pivots ranged from 1.75 to 5.54 mm, and the mean evapotranspiration at the end of the cycle was between 3.6 to 4.2 mm, with the largest evapotranspiration amplitude occurring at pivot 3. (3.79 mm) and the smallest on pivot 1 (1.62 mm).

Analyzing the irrigation management performed in each center pivot, it can be observed that the performed irrigation application (IAP) was 272 to 406.0 mm, values close to the minimum precipitation of 100 mm $month^{-1}$ recommended for beans [9]. Thus, the performed irrigated water volume (IWVP) in the pivots ranged from 0.11 to 0.38 hm^3, requiring from 365.85 to 773.39 hours of operation of the pumping system (OTP). In the recommended irrigation management, the irrigation application (IAR) was between 266.1 and 347.6 mm, which results in a water volume (IWVR) of 0.13 to 0.36 hm^3 and an operating time (OTR) varying. from 458.38 to 763.30 hours.

Analyzing the irrigations (Figure 1) it is observed that all pivots analyzed had a very different irrigation management than recommended based on the soil water balance. In pivots 1, 2, 3, 5, 6 and 7 the irrigation management adopted maintained throughout the bean cycle high soil moisture, providing an average water reserve of 87, 88, 74, 80, 87 and 79% of the available soil water to plants, respectively. Compared to the recommended irrigation management for the same center pivots, the average water reserve would be 71, 69, 68, 70, 70 and 71% of the available soil water, respectively, indicating that excessive irrigation occurred.

Irrigation management for pivots 1, 2, 3, 5, 6 and 7 could have been done with a smaller amount of irrigation or used smaller applications at some moments, providing a water reserve within the ideal moisture range for the beans, would not cause damage to crop productivity. Another problem of maintaining soil with high humidity for

Table 4: Hydraulic characteristics and application uniformity of the on-site center pivots

Pivot	Area (ha)	Flow ($m^3\,h^{-1}$)	RT (h)	IP (mm)	IA (mm)	IAe (%)	CUC (%)	Pot. (hp)
1	46.8	284.8	9.2	5.60	5.0	89	86	150
2	102.7	530.0	12.6	6.50	6.0	93	76	300
3	73.6	436.6	10.8	6.41	6.0	94	85	200
4	40.2	300.8	8.2	6.13	5.6	92	92	100
5	104.9	478.6	12.8	5.84	5.3	91	91	300
6	83.6	516.6	11.7	7.23	6.5	91	90	200
7	70.0	292.9	11.8	4.94	4.5	92	88	150

* Resolution time (RT); Irrigation project (IP); Irrigation aplication (IA); Irrigation application efficiency (IAe); Christiansen uniformity coefficient (CUC); and Required power on the electric motor (Pot.)

Table 5: Data of irrigation management performed and simulation of recommended irrigation management in carioca bean cultivation in center pivots in northern Minas Gerais

Pivot	Cycle (day)	Prec (mm)	ETc (mm)	IA_P (mm)	IA_R (mm)	IWV_P (hm^3)	IWV_R (hm^3)	OT_P (hour)	OT_R (hour)
1	89	2.4	360.8	406.0	370.7	0.19	0.16	667.0	554.58
2	83	2.2	302.1	299.0	266.1	0.31	0.27	579.6	514.85
3	91	1.8	340.4	302.4	292.3	0.22	0.22	509.7	495.35
4	93	6.8	352.8	272.6	318.5	0.11	0.13	365.8	427.40
5	92	7.4	390.5	350.3	347.6	0.37	0.36	773.4	763.30
6	78	8.2	314.6	360.0	281.8	0.30	0.24	585.0	458.36
7	92	6.2	340.0	315.6	312.3	0.22	0.22	758.6	755.97

* Precipitation (Prec), Crop evapotranspiration (ETc), according to Penman-Monteith; Irrigation application (IA), Performed or Recommended; Irrigated water volume (IWV), Performed or Recommended; and Operating time (OT) Performed or Recommended.

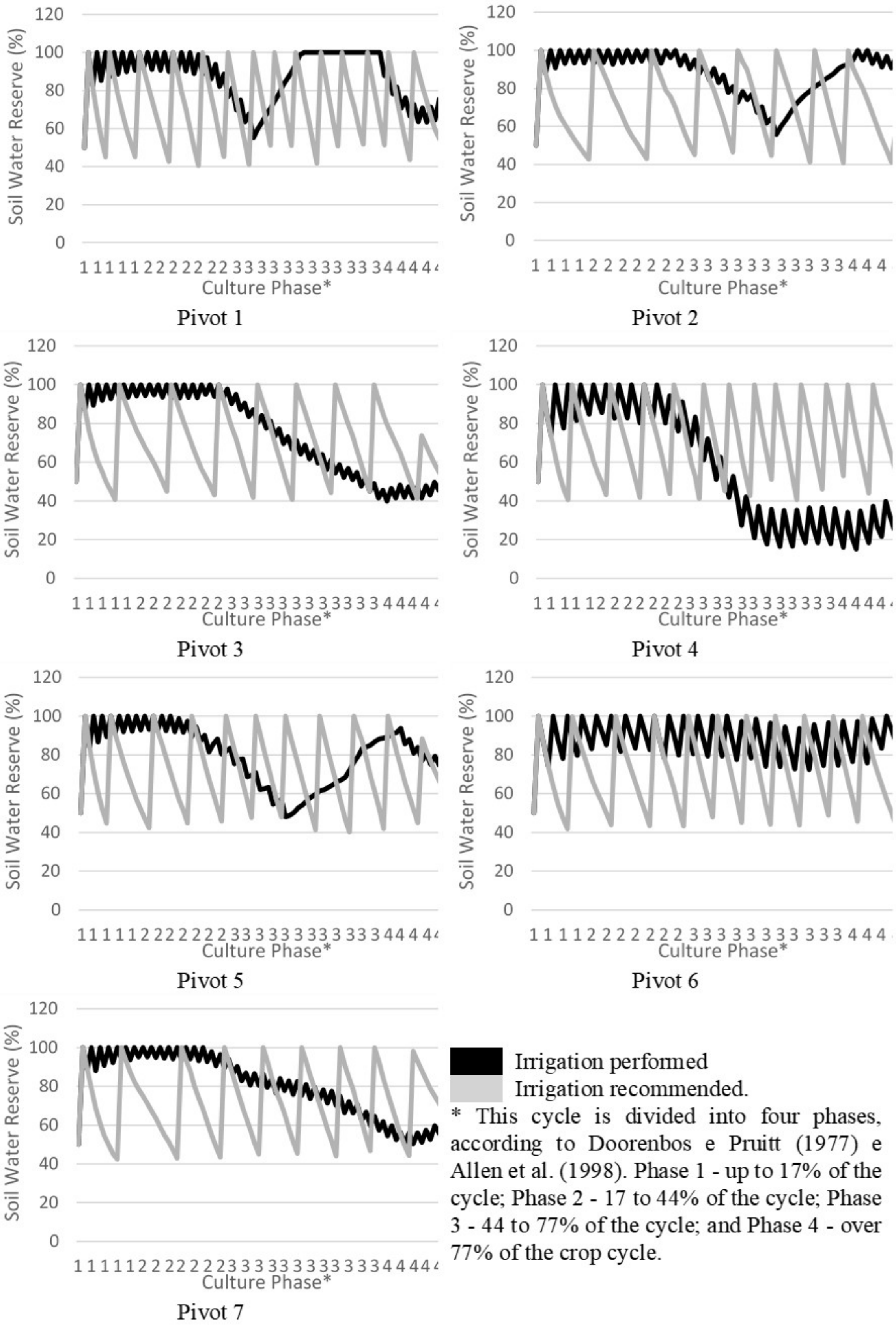

Figure 1: Variation in soil water reserve, referring to available soil water for plants, according to irrigation management performed and recommended in bean center pivots in Minas Gerais.

long periods, as occurred in pivot 1 that was 20 days with moisture at field capacity, is the greater loss of water through evaporation and/or percolation. In addition to favoring the emergence of fungal diseases, such as white mold, root or lap rot, bean molasses, fusarium wilt, among others.

In the case of pivot 4, the irrigation management employed resulted in a lower average soil water reserve than the recommended management (56 and 70% of the available soil water to plants, respectively), indicating poor irrigation. The management performed was satisfactory until half of the cultivation. However, in the following half, a period that comprised the phenological stages of flowering, grain filling and harvesting, a severe water deficit occurred. With water reserves ranging from 16 to 37% of the available soil water, soil moisture was close to PM during critical phenological stages for high productivity, as Aguiar et al. [1], Moraes et al. [20], and Endres et al. [10].

The water deficit verified in pivot 4 significantly compromised the productivity of beans cultivated in the same area, which was estimated at 628 $kg\,ha^{-1}$. Bezerra et al. [5] demonstrated that the occurrence of a water deficit in one of the phenological stages, be it vegetative, flowering or grain filling, provided a yield reduction of 20.1, 20.7 and 26.1%, respectively, in relation to the control without water deficit. When the water deficit occurs during the phenological stages of flowering and grain filling, the reduction reaches 31%.

Comparing the performed irrigation application (IAP) and the recommended (IAR) (Figure 2A), it is verified the systems that perform an efficient or deficient management, being the poor management with the possibility of being deficient or excessive. In pivot 4, as previously indicated, a 45.9 mm deficit irrigation management was performed, which corresponds to a deficit of 14.4% of the recommended irrigation application (IAR).

In the other center pivots the opposite occurred, excessive irrigation management was performed. The adopted irrigation management of pivots 1, 2, 3, 5, 6 and 7 applied an excessive depth of 69.4; 32.9; 10.1; 2.7; 78.2; and 3.3 mm, respectively. Requiring an extra water volume of 0.032; 0.034; 0.007; 0.003; 0.065; and 0.002 hm^3 and a system operating time of 112.4; 64.7; 14.3; 10.1; 126.6; and 2.6 hours more (Figure 2B), respectively.

Lima, Ferreira, and Christofidis [16], mentions that a rational irrigation management consists in applying the necessary amount of water to the plants at the right time. However, the farmer usually irrigates excessively, due to not adopting a method of irrigation control and fearing that if not irrigated, the crop will suffer a water stress, which may compromise the production. On the other hand, over-irrigation results in a large waste of water and energy used for unnecessary pumping.

Studies conducted by CEMIG showed that if irrigation were used rationally, about 20% of water and 30% of energy consumed would be saved; 20% of the energy saved due to unnecessary water application and 10% due to the scaling and optimization of irrigation equipment [16].

As for the efficiency of water application and the operation of irrigation management (Figure 2C), the results show that in pivots 3, 5 and 7, even performing excessive management, the irrigation management adopted was close to the recommended management, providing optimum water and energy efficiency. (¿ 90%). As for pivots 1, 2 and 6 the irrigation management performed was further from the recommended management, obtaining good (80 to 90%) and regular (70 to 80%) water and energy efficiency. As the applied irrigation depth at pivot 4 as the applied blade was lower than recommended, the adopted management was considered inefficient (¡70% efficiency).

According to Lima, Ferreira, and

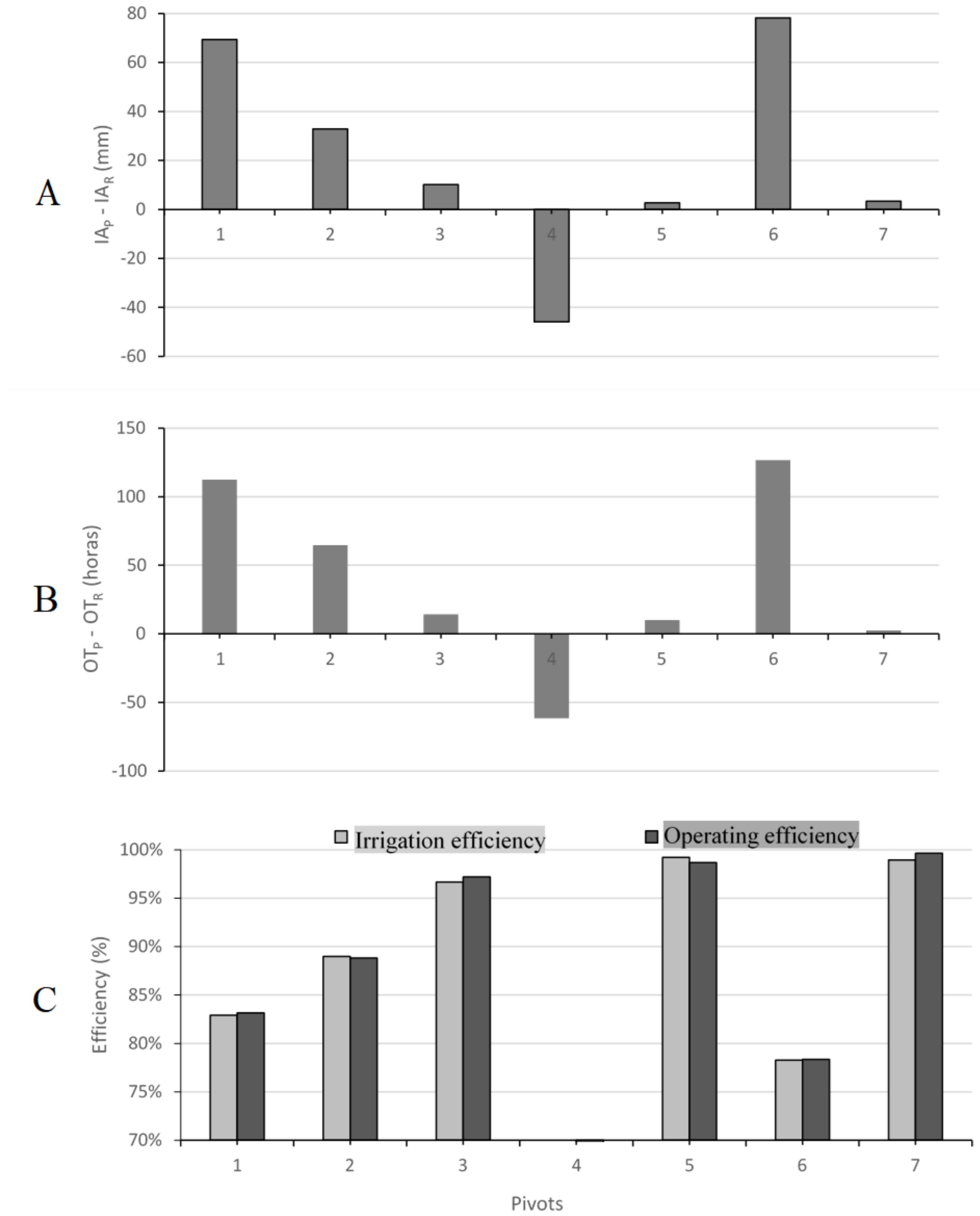

Figure 2: Difference between the performed irrigation application (IAP) and recommended (IAR) - A; between performed operating time (OTP) and recommended (OTR) - B; and efficiency in the use of water and energy resources from irrigation management carried out and recommended – C.

Christofidis [16], worldwide, the irrigation efficiency (ratio between the amount of water required by the crop – ETc and the total amount applied by the system) is still very low, around 37%. Simply improving the efficiency of irrigation water use by 1%, in tropical and arid countries, would save 200,000 liters of water per farmer per hectare/year. Thus, the adoption of practices that increase the efficiency of water and electricity use are fundamental to reduce the waste of these resources from the current production patterns of irrigated agriculture.

Conclusions

Center pivot irrigation systems with bean cultivation in the north of Minas Gerais without adopting an irrigation management with technical bases, tend to perform an excessive irrigation, applying a water depth higher than that required by the crop (ETc), keeping soil moisture close to Field Capacity.

The center pivots evaluated obtained a classification of the efficiency in the use of water and energy resources as good, which was surprising, since the irrigation management of the least did not use any kind of technical-scientific knowledge.

References

[1] R. S. Aguiar, V. Moda-Cirino, R. T. Faria, and L. H. I. Vidal. "Avaliação de linhagens promissoras de feijoeiro (Phaseolus vulgaris L.) tolerantes ao déficit hídrico". In: *Semina: Ciências Agrárias* 29.1 (2008), p. 1. DOI: 10.5433/1679-0359.2008v29n1p1.

[2] R. Allen, L. S. Pereira, D. Raes, and M. Smith. *Crop evapotranspiration - Guidelines for computing crop water requirements.* Rome: FAO Irrigation and Drainage, 1998, p. 15.

[3] J. Alves, D. L. A. Sales, R. M. Pereira, W. D. M. Rodriguez, D. Casaroli, and A. W. P. Evangelista. "Viabilidade econômica da irrigação por pivô central nas culturas de soja, milho e tomate". In: *Pesquisa Agropecuária Pernambucana* 22 (2017). DOI: 10.12661/pap.2017.011.

[4] S. Bernardo, E. C. Mantovani, D. D. Silva, and A. A. Soares. *Manual de irrigação.* 9th ed. Viçosa: UFV, 2019, p. 625.

[5] F. M. L. Bezerra, M. A. E. Araripe, E. M. Teófilo, L. G. Cordeiro, and J. J. A. Santos. "Feijão caupi e déficit hídrico em suas fases fenológicas". In: *Revista Ciência Agronômica* 34.1 (2003).

[6] CEMIG. *Estudo de otimização energética - setor irrigação por pivô central - relatório final.* Belo Horizonte: Companhia Energética de Minas Gerais, Universidade Federal de Viçosa, 1993, p. 24.

[7] A. P. Coelho, J. R. Zanini, V. A. Filla, A. B. Dalri, and L. F. Palaretti. "Uniformity of water application to central pivot and to super 10 sprayer". In: *Applied Research & Agrotechnology* 11.2 (2018).

[8] J. Doorenbos and W. O. Pruitt. *Guidelines for predicting crop water requirements.* Irrigation and Drainage Paper 24. Rome: FAO, 1977, p. 179.

[9] D. Dourado Neto and A. L. Fancelli. *Produção de feijão.* Guaíba: Editora Agropecuária, 2000.

[10] L. Endres, J. L. Souza, L. Teodoro, P. M. G. Marroquim, C. M. Santos, and J. E. D. Brito. "Gas exchange alteration caused by water deficit during the bean reproductive stage". In: *Revista Brasileira de Engenharia Agrícola e Ambiental* 14.1 (2010), pp. 11–16. DOI: 10.1590/s1415-43662010000100002.

[11] FAO. *Water at a glance: the relationship between water, agriculture, food security and poverty.* Rome, 2017, p. 15.

[12] J. A. Frizzone. "Planejamento da irrigação com uso de técnicas de otimização". In: *Revista Brasileira de Agricultura Irrigada* 1.1 (2007), pp. 24–49. DOI: 10 . 7127 / rbai . v1n100107.

[13] Q. Geng, Q. Ren, R. H. Nolan, P. Wu, and Q. Yu. "Assessing China's agricultural water use efficiency in a green-blue water perspective: A study based on data envelopment analysis". In: *Ecological Indicators* 96 (2019), pp. 329–335. DOI: 10.1016/j.ecolind. 2018.09.011.

[14] D. P. Guimarães and E. C. Landau. *Levantamento da agricultura irrigada por pivôs centrais no Brasil em 2013.* Sete Lagoas: Embrapa Milho e Sorgo, 2014, p. 40.

[15] A. L. Justi, M. A. Vilas Boas, and S. C. Sampaio. "Índice de capacidade do processo na avaliação da irrigação por aspersão". In: *Engenharia Agrícola* 30.2 (2010), pp. 264–270. DOI: 10 . 1590/s0100-69162010000200008.

[16] J. E. F. W. Lima, R. S. A. Ferreira, and D. Christofidis. "O uso da irrigação no Brasil". In: M. A. V. Freitas. *O Estado das Águas no Brasil.* MME, MMA/SRH, OMM, 1999, pp. 73–101.

[17] E. C. Mantovani, D. R. P. Montes, G. H. S. Vieira, M. M. Ramos, and A. A. Soares. "Estimativa de produtividade da cultura do feijão irrigado em Cristalina-GO, para diferentes lâminas de irrigação como função da uniformidade de aplicação". In: *Engenharia Agrícola* 32.1 (2012), pp. 110–120. DOI: 10 . 1590 / s0100 - 69162012000100012.

[18] M. M. Mekonnen and A. Y. Hoekstra. "Water footprint benchmarks for crop production: A first global assessment". In: *Ecological Indicators* 46 (2014), pp. 214–223. DOI: 10.1016/j. ecolind.2014.06.013.

[19] M. J. Moraes, D. Oliveira Filho, E. C. Mantovani, P. M. B. Monteiro, A. L. C. Mendes, and J. H. A. C. Damião. "Automação em sistema de irrigação tipo pivô central para economia de energia elétrica". In: *Engenharia Agrícola* 34.6 (2014), pp. 1075–1088. DOI: 10.1590/s0100-69162014000600005.

[20] W. B. Moraes, S. Martins Filho, G. O. Garcia, S. P. Caetano, and W. B. Moraes. "Avaliação de linhagens promissoras de feijoeiro tolerantes à seca". In: *Revista Brasileira de Ciências Agrárias* 3.2 (2008), pp. 121–125. DOI: 10 . 5039 / agraria . v3i2a149.

[21] A. Nasseri. "Energy use and economic analysis for wheat production by conservation tillage along with sprinkler irrigation". In: *Science of The Total Environment* 648 (2019), pp. 450–459. DOI: 10.1016/j.scitotenv.2018.08.170.

[22] M. A. O. Paulino, F. P. Figueiredo, R. C. Fernandes, J. T. L. S. Maia, D. O. Guilherme, and F. S. Barbosa. "Avaliação da uniformidade e eficiência de aplicação de água em sistemas de irrigação por aspersão convencional". In: *Revista Brasileira de Agricultura Irrigada* 3.2 (2009), pp. 48–54. DOI: 10 . 7127 / rbai . v3n200011.

[23] K. C. O. Saath and A. L. Fachinello. "Crescimento da demanda mundial de alimentos e restrições do fator terra no Brasil". In: *Revista de Economia e Sociologia Rural* 56.2 (2018), pp. 195–212. DOI: 10 . 1590 / 1234 - 56781806 - 94790560201.

[24] C. Santos, Ignacio J. Lorite, M. Tasumi, R. G. Allen, and E. Fereres. "Performance assessment of an irrigation scheme using indicators de-

termined with remote sensing techniques”. In: *Irrigation Science* 28.6 (2010), pp. 461–477. DOI: 10.1007/s00271-010-0207-7.

[25] L. F. Stone, P. M. Silveira, and J. A. A. Moreira. *Eficiência de irrigação: conceitos e avaliação*. Santo Antônio de Goiás: Embrapa Arroz e Feijão, 2007, p. 83.

[26] C. E. Toledo and E. E. Moraes. “Levantamento e atualização dos sistemas de irrigação por pivô central instalados nos municípios de Paraúna e Palmeiras de Goiás”. In: *Revista Engenharia na Agricultura* 26.3 (2018), pp. 277–283. DOI: 10.13083/reveng.v26i3.919.

[27] C. E. Toledo, L. R. Pires Neto, T. L. G. R. Silva, and J. C. M. Nogueira. “Viabilidade econômica-financeira da otimização de sistemas de irrigação tipo pivô central”. In: *Revista Brasileira de Agricultura Irrigada* 13.1 (2019). DOI: 10.7127/RBAI.V13N1001055.

[28] C. E. Toledo, C. M. P. Souza, and P. E. P. Albuquerque. “Eficiência da aplicação da água por pivô central em diferentes regiões de Minas Gerais”. In: *IRRIGA* 22.4 (2017), pp. 821–831. DOI: 10.15809/irriga.2017v22n4p821-831.

[29] G.H.S. Vieira, E.C. Mantovani, A.A. Soares, D.R.P. Montes, and F.F. Cunha. “Custo da Irrigação do Cafeeiro em Diferentes Tipos de Equipamento e Tamanhos de Área”. In: *Revista Engenharia na Agricultura* 19.1 (2011), pp. 53–61. DOI: 10.13083/1414-3984.v19n01a06.