Medicon Agriculture & Environmental Sciences
Volume 2 Issue 3 March 2022
Research Article

Evaluation of Sustainability of Cropping Sequences on Production Systems: Agricultural Intensification Indices

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Received: February 24, 2022

DOI: 10.55162/MCAES.02.020

Abstract

In recent decades, agriculture has undergone intensification and diversification processes to improve productivity, the economic income and to face the climate variability. However, concerns about environmental problems associated with agricultural practices are increasing. In this way, effects such as soil erosion, changes in soil carbon stock, fertility losses, eutrophication and aquatic-biotic integrity degradation have been reported. Although several methodological frameworks have been developed to assess the environmental performance of farms and to support the decision-making process, these frameworks normally rely on indicators that measure a particular characteristic of an agricultural system. The aim of this work was to propose an integrated index considering (a) sequence diversification, the area occupied by crops in winter and summer, and the participation percentage of each crop and (b) two weighting factors to reflect the differential contributions of cropping sequences to environmental performance. The study was carried out between 2008 and 2020 in a commercial farm in northwest Uruguay with cropping sequences that included rice, soybean, corn, sorghum and pastures. Our results show that the proposed index is suitable for assessing the intensification degree and allowing the selection of agricultural sequences that present the highest environmental performance. The optimal spatial scale for applying the index is on farms no larger than 1000 hectares; this threshold includes approximately 90% of Uruguayan farms. Due to the similar physical characteristics, weather conditions and management practices in farms in southern Brazil and central-eastern Argentina, the index is suitable for applications in these regions as well.

Keywords: Weighted intensification index; Sustainable agriculture; Agricultural intensification; Crop diversification

Abbreviations

MGAP: Ministry of Livestock, Agriculture and Fisheries (spanish acronym)
ISI : Intensification Sequence Index
AII : Agricultural Intensification Index
WII : Weighted Intensity Index
CDI : Crop Diversification Index
WQI : Water Quality Index

Introduction

Since the middle of the 20th century, the global agricultural area has increased by approximately 50% and crop yields have increased more than 200%, mainly due to the growing demand for food supply, biofuels and animal grain-based feed production [12, 14-16]. In addition to intensive practices, agricultural production systems have diversified cropping sequences as an adaptation framework to

Citation: Noelia Rivas-Rivera., et al. “Evaluation of Sustainability of Cropping Sequences on Production Systems: Agricultural Intensification Indices”. Medicon Agriculture & Environmental Sciences 2.3 (2022): 32-41.

face climate variability and enhance income stability [17, 20]. However, these transformations can also affect the natural resources (such as soil and freshwater) or ecosystem services that are required to support agricultural production systems [2, 18, 23]. For example, these transformations can be associated with soil erosion, fertility losses, water quality degradation, reductions in biodiversity [3, 5, 7, 24, 25], and lessened stream or aquifer recharge, among other effects. In this sense, the increased application of fertilizers is one of the most important causes of the eutrophication of surface water courses [6, 22, 27].

In Uruguay since the year 2000, the traditional agricultural system, which was based mainly on winter crops and summer pastures, began to convert to continuous agriculture with an important dominance of summer cereal crops [1]. According to the Ministry of Livestock, Agriculture and Fisheries (MGAP, spanish acronym), the ratio between the numbers of hectares cultivated in winter and summer decreased from approximately 2 before the year 2000 to a value of 0.5 at present. This shift in land use is closely related to the increase in global demand for soybean, which led to soybean becoming the main cereal crop in the country, occupying 916,800 hectares [8-10]. Furthermore, in recent years, the National Plan for Adaptation to Variability and Climate Change for the Agricultural Sector has promoted the diversification of cropping sequences to reduce the adverse impacts of climate change on agriculture [19].

To enhance conditions with the goal of achieving sustainable agricultural development, it is necessary to develop tools to assess the impacts of intensification and diversification processes that consider economic, social and environmental dimensions. In this sense, several indices have been proposed to evaluate these processes, and the most commonly used indices in the Pampas region are the intensification sequence index (ISI), which is based on the relationship between the number of crops per agricultural sequence and the duration of each sequence (crops per year), therefore, lower values indicate less intensive management practices [4, 13, 21, 26]. On the other hand, the Uruguayan agricultural authority (Ministry of Livestock, Agriculture and Fisheries - MGAP) applies the agricultural intensification index (AII) based on the relation between the numbers of hectares with winter and summer crops and the total cropped area [10]. The value is close to 1 when the system corresponds only to summer or winter crops and increases if the same area is used for continuous agriculture. Finally, Mukherjee [20], by applying Simpson's diversity and evenness approach, developed the crop diversification index, which varies between 0 (low diversification) and 1 (greatest possible diversification). Although these indices are useful for evaluating agricultural practices, they only consider a few cropping sequence parameters.

The main goal of this work was to propose an integrated and weighted index that allows the sustainability of cropping sequences to be evaluated by considering diversification (the number of crops per unit of time), intensification (the areas cultivated in winter and summer) and evenness (the area occupied by each crop in the sequence).

Materials and Methods

Study area

The study was carried out in the Del Tala stream basin, which is located on the northwest coast of Uruguay. The basin has an area of 159.29 km2 (Fig 1), with 3,500 hectares destined for the agricultural production system which includes mainly summer crops (rice, soybean, sorghum and corn) and pastures. In Table 1, the distribution of crops into management units (MUs) can be observed. These units were delimited according to the irrigation system, similar existing management practices, and coverage areas between 800 and 1,100 hectares.

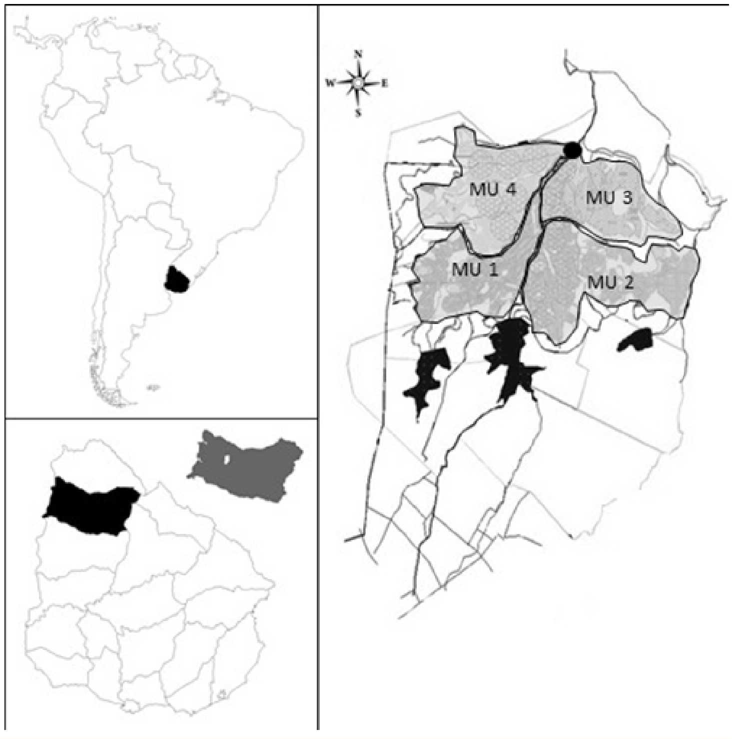


Figure 1: Study area. MU: Management units.

		Harvest											
		08-09	***09-10***	***10-11***	***11-12***	***12-13***	***13-14***	***14-15***	***15-16***	***16-17***	***17-18***	***18-19***	***19-20***
MU 1 722 ha	***Summer***												
	Rice	311	76				672				520		
	Soybean		213	250	380	500		280	411	370		522	260
	Corn												
	Pasture		233	92		150	50	50	211	252	202	200	250
	Sorghum	355	200	380	342			200		100			212
	Fallow	56				72		192	100				
	Winter												
	Pasture		233	92		150	50	50	211	252	202	200	250
	Cover crop		213	250	380			280	411			392	260
	Fallow	722	276	380	342	572	672	392	100	470	520	130	212

MU 2 1073 ha	***Summer***												
	Rice	279	413	527	121	190		659				780	163
	Soybean		550	360	567	600	670	194	735	600	700		330
	Corn								60	100		200	80
	Pasture	710	110		165	165	165			373	373		150
	Sorghum	84		186	220		220	220				93	350
	Fallow					118	18		278				
	Winter												
	Pasture	710	110		165	165	165			373	373		150
	Cover crop		360	360	567	600		194	735	600			330
	Fallow	363	603	713	341	308	908	879	338	100	700	1073	593
MU 3 832 ha	***Summer***												
	Rice			403	718	336			562				577
	Soybean		327			300	290	432		300	300	598	55
	Corn	340				160	160	80		200	200		100
	Pasture	380	380	100						162	162	174	
	Sorghum	112	125	329	114		240	50		170	170	60	
	Fallow					36	142	270	270				100
	Winter												
	Pasture	380	380	100						162	162	174	
	Cover crop					300	290			300	300		55
	Fallow	452	452	732	832	532	542	832	832	370	370	658	777
MU 4 840 ha	***Summer***												
	Rice					420	181			781		130	
	Soybean		800	580	450	200	350	593	593		782	460	360
	Corn					100	100	100				100	120
	Pasture			60	190	120	109	47					
	Sorghum	840	40	200	200		100	100	156		58	150	160
	Fallow								91	59			200
	Winter												
	Pasture			60	190	120	109	47					
	Cover crop		800	580	200	200	350	593			652	460	
	Fallow	840	40	200	450	520	381	200	840	840	188	380	840

MU: Management units.

Table 1: Crop distribution expressed in hectares.

Index Calculation

The analysis was performed between 2008 and 2020 and considered 4-year sequences (Table 2) according to the requirements established in the Plans for Land Use and Responsible Management (National Law No. 15.239).

	Start harvest	Final harvest
Sequence 1	2008/09	2011/12
Sequence 2	2012/13	2015/16
Sequence 3	2016/17	2019/20

Table 2: Cropping sequences.

The number of crops, the area occupied by each crop, the length of the sequence, and the hectares cultivated in winter and summer were considered in the calculation of the index. The main contribution of this index it to include in the calculation the degree of participation of each crop in the sequence trough the evenness factor, which establishes that greater equity in the distribution of crops improves both environmental and economic performance and therefore decreases the final value of the index. The participation of each crop was calculated as a percentage of the total cropped area by agricultural year. It should be noted that only crops with market value were considered in the calculation; that is, cover crops that played a role in soil protection are not considered. The other factor considering in the calculation of the index is the land use pressure represented by the number of hectares that are cultivated in both winter and summer. In this case, the criterion used for the calculation was that a lower pressure, that is, a smaller area affected by use in winter and summer, results in a lower intensification index. In the same way as the evenness factor, the pressure of use is expressed as a percentage of the area. So that, to calculate the index, a weighted system was developed for these two cropping sequence characteristics (Table 3). The weighted intensity index (WII) was obtained by multiplying the quotient between the number of crops and the length of the sequence by the weighted evenness and intensification factors. A higher value of the index will be given by a surface with a high pressure of use and a low evenness in the crop distributions.

Weighted value	*Land use pressure*	*Crop distribiution*
0.5	<25% cropped summer and winter area	>75% evenness
1.0	25%-50% cropped summer and winter area	50%-75% evenness
1.5	50%-75% cropped summer and winter area	25%-50% evenness
2.0	>75% cropped summer and winter area	<25% evenness

Table 3: Weighted system.

Index applicability

As will be discussed further, the developed index is based on the existence of indices that independently contemplate certain components. Therefore, to compare the efficiencies of these indices in their ability to discriminate among different sequences with different degrees of intensification, the agricultural intensity index (AII) [10] and the crop diversification index (CDI) [20] were also calculated (Eqs. 1 and 2, respectively):

$$AII = \frac{s+w}{A} \text{ (Eq. 1)}$$

$$CDI = 1 - \sum\left(\frac{pi}{\sum pi}\right)^2 \text{ (Eq. 2)}$$

Where s is the area cultivated in summer, w is the area cultivated in winter, A is the total arable area in the AII, and pi is the area under crop i in the CDI.

The applicability degree of the index was evaluated with regard to its spatial resolution (scaling). To do this, the indices obtained were compared at management unit scale and the total area of the basin destined for agricultural production scale.

Finally, to assess its usefulness as a decision-making tool, the index results calculated based on a given agricultural year were compared with the water quality index (WQI) measured post-harvest during the corresponding year, as proposed by Eguren et al [11].

Results and Discussion

It should provide complete findings of the research using texts, Graphs, Charts and tables etc.

Weighted intensification index (WII).

Table 4 shows the characteristics of the analyzed sequences, as well as the results of the index at the management unit scale.

		MU 1		***MU 2***		***MU 3***		***MU 4***	
Sequence 1	Number of crops	13	1,6	16	3,0	14	7,0	11	2,8
	% cropped summer and winter area	11		23		26		7	
	% of evenness	62		25		7		0	
	P 1	0,5		0,5		1		0,5	
	P 2	1		1,5		2		2	
Sequence 2	Number of crops	13	3,3	13	3,3	10	1,9	18	4,5
	% cropped summer and winter area	18		9		0		8	
	% of evenness	8		0		30		11	
	P 1	0,5		0,5		0,5		0,5	
	P 2	2		2		1,5		2	
Sequence 3	Number of crops	14	5,3	16	4,0	17	3,2	10	2,5
	% cropped summer and winter area	31		21		15		0	
	% of evenness	29		6		35		0	
	P 1	1		0,5		0,5		0,5	
	P 2	1,5		2		1,5		2	

MU: Management units. P1: weighting factor related to land use pressure. P2: weighting factor related to evenness.

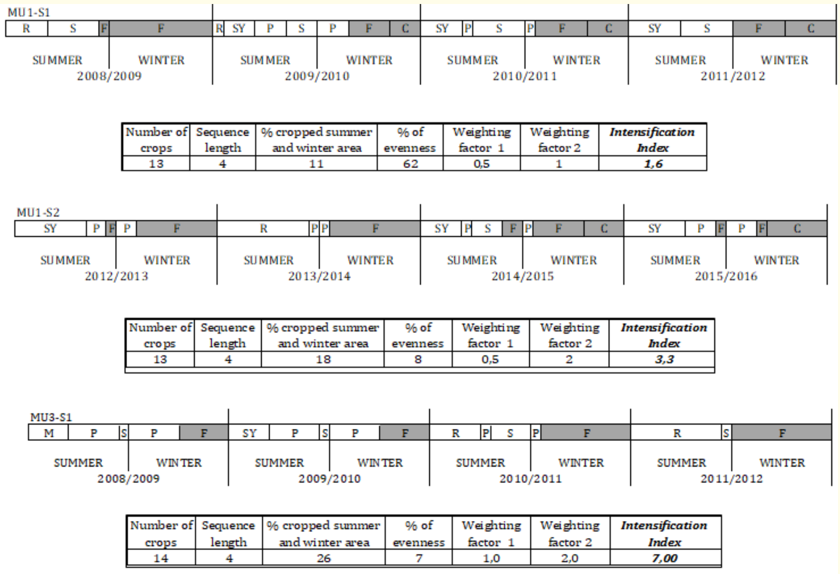
Table 4: Weighted intensification index.

Our results indicate that different sequences can present similar degrees of enhancement in the same management unit (SQ1 and 2 in MU2 or SQ1 and 3 in MU4). This allows, in the face of environmental or economic restrictions (for example, due to market prices, input costs, or the availability of water for irrigation), the selection of the most feasible sequence.

To evaluate the performance of the index, three representative sequences were selected to include the range of obtained values (Table 4 and Fig 1).

As can be observed in Fig 2, the cover crops and fallow have spatial representation since they contribute to the total area of the management unit in the calculation of the index. However, they are not considered in the total crop number or in the evenness calculation. For example, MU1-S1 presents a greater presence of cover crops and fallow in the sequence, resulting in a low land use intensity (2 years without winter crops).

The index proposed not only reflects the weight of each variable individually but also the interactions among them, and this is clearly visualized by analyzing MU3-S1. This sequence showed the highest intensification index, reflecting both a low evenness value and the highest obtained winter crop occupation percentage.



Number of crops	Sequence length	% cropped summer and winter area	% of evenness	Weighting factor 1	Weighting factor 2	***Intensification Index***
13	4	11	62	0,5	1	***1,6***

Number of crops	Sequence length	% cropped summer and winter area	% of evenness	Weighting factor 1	Weighting factor 2	***Intensification Index***
13	4	18	8	0,5	2	***3,3***

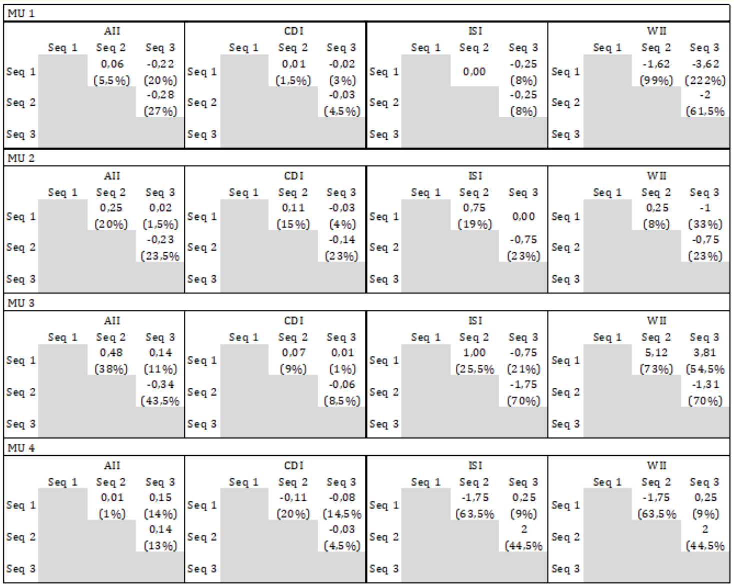
Number of crops	Sequence length	% cropped summer and winter area	% of evenness	Weighting factor 1	Weighting factor 2	***Intensification Index***
14	4	26	7	1,0	2,0	***7,00***

R: rice, SY: soybean, M: maize, P: pastures, S: sorghum, F: fallow, C: winter cover crop. The size of each bars is proportional to the participation percentage of each crop in the total area. The cover crops and fallow are located in areas shaded with gray.

Figure 2: Cropping sequences with different intensification index values.

Index applicability

In Fig 3, the percentages of variation between each sequence and for each analyzed intensification index (AII, CDI, ISI, and WII) are presented.



MU 1

	AII			CDI			ISI			WII		
	Seq 1	Seq 2	Seq 3	Seq 1	Seq 2	Seq 3	Seq 1	Seq 2	Seq 3	Seq 1	Seq 2	Seq 3
Seq 1		0,06 (5,5%)	-0,22 (20%)		0,01 (1,5%)	-0,02 (3%)		0,00	-0,25 (8%)		-1,62 (99%)	-3,62 (222%)
Seq 2			-0,28 (27%)			-0,03 (4,5%)			-0,25 (8%)			-2 (61,5%
Seq 3												

MU 2

	AII			CDI			ISI			WII		
	Seq 1	Seq 2	Seq 3	Seq 1	Seq 2	Seq 3	Seq 1	Seq 2	Seq 3	Seq 1	Seq 2	Seq 3
Seq 1		0,25 (20%)	0,02 (1,5%)		0,11 (15%)	-0,03 (4%)		0,75 (19%)	0,00		0,25 (8%)	-1 (33%)
Seq 2			-0,23 (23,5%			-0,14 (23%)			-0,75 (23%)			-0,75 (23%)
Seq 3												

MU 3

	AII			CDI			ISI			WII		
	Seq 1	Seq 2	Seq 3	Seq 1	Seq 2	Seq 3	Seq 1	Seq 2	Seq 3	Seq 1	Seq 2	Seq 3
Seq 1		0,48 (38%)	0,14 (11%)		0,07 (9%)	0,01 (1%)		1,00 (25,5%	-0,75 (21%)		5,12 (73%)	3,81 (54,5%
Seq 2			-0,34 (43,5%			-0,06 (8,5%)			-1,75 (70%)			-1,31 (70%)
Seq 3												

MU 4

	AII			CDI			ISI			WII		
	Seq 1	Seq 2	Seq 3	Seq 1	Seq 2	Seq 3	Seq 1	Seq 2	Seq 3	Seq 1	Seq 2	Seq 3
Seq 1		0,01 (1%)	0,15 (14%)		-0,11 (20%)	-0,08 (14,5%		-1,75 (63,5%	0,25 (9%)		-1,75 (63,5%	0,25 (9%)
Seq 2			0,14 (13%)			-0,03 (4,5%)			2 (44,5%			2 (44,5%
Seq 3												

The value of the difference is presented with its meaning and the variation percentage in parentheses.

Figure 3: Variation between sequences for each calculated index.

The results show that the proposed weighting system, which assumes the benefit of evenness and potential effects due to continuous agriculture, allows more differentiation between sequences than the other indices do [4, 10, 13, 20]. This enables the index to be a good decision-making tool for comparing different cropping sequences and selecting those with lower impacts or greater natural resource use efficiency.

With regard to the spatial resolution, the performance of the proposed index has been observed to be lower when the area under analysis increases. In this way, the unit with the smallest area (MU1, 722 ha) presents the highest variation percentages, while the largest unit (MU2, 1073 ha) shows a lower percentage of differentiation. The indices were calculated at the basin scale (3467 ha), and the results were compared (Table 5).

	AII	***CDI***	***ISI***	***WII***
Sequence 1	1,17	0,75	5,00	5,00
Sequence 2	0,96 (18%)*	0,67 (10%)*	5,75 (15%)*	4,31 (14%)*
Sequence 3	1,14 (2,5%)** (19%)***	0,73 (2,5%)** (9%)***	6,00 (20%)** (4%)***	4,50 (10%)** (4,5%)***

The values of the percentage of variation are shown in parentheses. *Sequence 1 vs Sequence2, ** Sequence1 vs Sequence3, *** Sequence2 vs Sequence3.

Table 5: Comparison of the intensification index values.

Although a reduction in the percentage of variation is observed, the capacity of the proposed index to differentiate the intensification degree among sequences is maintained. Furthermore, the index shows greater efficiency when it is applied on agricultural areas that are no larger than 1000 ha, have diversified sequences in terms of the number of crops and have continuous agriculture in all or part of the area.

Finally, as expected, increases in the intensification and evenness could produce a decrease in the water quality of a basin. An inverse relationship between the weighted intensity index (WII) and the water quality index (WQI) [11] was observed, mostly after the 2016-17 harvest (Fig. 4).

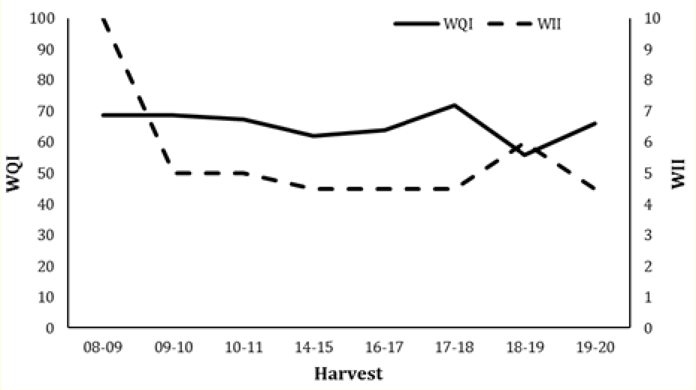


Figure 4: Relationship between the weighted intensity index (WII) and the water quality index (WQI).

Conclusion

According to the results obtained herein, it can be concluded that the weighted intensity index developed in this study is a useful decision-making tool that allows the cropping sequences that are the most sustainable to be selected. Although this index has been shown to be efficient in evaluating agricultural sequence performances at different spatial scales, the optimal range of its use is in

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management units no larger than 1000 hectares. In Uruguay, according to DIEA-MGAP [10], 90% of cereal producers and 95% of rice producers have farms smaller than 1000 hectares, and those who manage farms with larger surfaces usually divide the surfaces into agronomic management units, as observed in the case study. At the regional level, southern Brazil and central-eastern Argentina present similar cropping sequences, management practices and biophysical characteristics, so it is expected that this tool may also be applicable in their production systems.

Acknowledgements

We express our thanks to Santiago Bandeira and Bernardo Böcking for providing us access to information on the agronomic management of the basin.

This study was funded by the National Agricultural Research Institute Project SA01.4, the Development Basic Sciences Foundation, and the National Research and Innovation Agency through the Sectorial Fund INNOVAGRO Project FSA_PP_2018_1_147701.

The authors have no relevant financial or non-financial interests to disclose.

This work is included in the PhD studies in Biological Sciences (Basic Sciences Development Program – PEDECIBA) of the MSc. Noelia Rivas-Rivera

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