Australian Journal of Crop Science AJCS

Aust J Crop Sci. 19(05):518-523 (2025) | https://doi.org/10.21475/ajcs.25.19.05.p235 ISSN:1835-2707

Evaluating oat yield and economic profitability in integrated crop-livestock systems with *Eucalyptus* trees and varying nitrogen levels

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Submitted:* *11/08/2024

Revised:* *05/10/2024

Accepted:* *28/01/2025

Abstract: Integrating trees into typical crop-livestock systems (ICLS) in South America, which are primarily characterized by the succession of annual pastures in winter and crops in summer, may enhance ecosystems functions. However, during the initial phase of tree introduction in ICLS, livestock may not be introduced due to the negative impact of animals on trees. Therefore, cash crop alternatives during winter are important in subtropical regions during this phase. Our study evaluates white oat (cv. Artemis) grain yield, its components (number of panicles, panicle length, number of spikelets per panicle, number of grains per panicle and 1000-grain weight), and economic profitability during two consecutive winters in systems along with (238 trees ha^{-1}) and without eucalyptus trees, using two N levels (20 vs. 60 kg N ha^{-1}). Oat was sown with 0.17 m line spacing, at seed rates of 70-100 kg ha^{-1} in winter 2020- 2021. The randomized complete block design included four treatments (2 systems × 2 N levels) and three replicates. We observed a negative impact of immature trees on panicle length (-6%), number of panicles per m^2 (-13%), and grain yield (-18%). An increase in N level did not guarantee an increase in oat grain yield or profit, regardless of the system. Economic losses were observed in all treatments (-107±16.3 U$ ha^{-1}), due to low yield and market prices. Our results suggest that oat production is unsuitable in association with eucalyptus at a density of 238 trees ha^{-1}, particularly in shallow soils where competition between trees and intercrops is more intense.

Keywords: Agroforestry; *Eucalyptus grandis*; Integrated crop-livestock systems; Sustainable agriculture; White oat.
Abbreviations: CL, crop-livestock; CLT, crop-livestock-trees; DBH, diameter at breast height; ICLS, integrated crop-livestock systems; GY, grain yield; NP, number of panicles per m^2; PL, panicle length; NSP, number of spikelets per panicle; NGP, number of grains per panicle; GW, 1000-grain weight.

Introduction

Integrated crop-livestock systems (ICLS) have been encouraged worldwide as they align with the principles of cleaner production by optimizing synergies and providing a more sustainable agro-ecosystem (Lemaire et al., 2023; Delandmeter et al., 2024). These systems stand out in the southern region of Brazil, where most areas cultivated with summer crops remain fallow during the winter (Moraes et al., 2014), possible due to a lack of economically viable crop alternatives (Balbinot Jr. et al., 2009). In a long-term ICLS experiment, Pontes et al. (2021) observed that despite the many benefits provided by cover crops, the absence of short-term returns led to economic losses, as revenue was only provided by summer crops. However, when the livestock component was integrated with a cool season pasture preceding summer cash crops, the systems began to show greater profit. Consequently, ICLS in South America is mainly characterized by the succession of annual pastures during winter and crops during summer in no-tillage systems, where the pasture component is used to produce meat, milk and wool (Moraes et al., 2018). Although crop-livestock systems can more consistently integrate crop and livestock components, in ICLS with trees, these components may not be associated with trees during certain periods of tree development. For instance, the crop component could be restricted to phases with a positive or neutral tree effect, and livestock may not be associated in the initial tree introduction phase due to the animal's impact on trees (unless the trees are protected against animals). Therefore, alternatives of cash crop during winter are important for ICLS with trees in this initial tree introduction phase. Agroforestry systems have been projected as a promising form of agro-ecological management, improving ecosystems functions (Veldkamp et al., 2023; Monteiro et al., 2024).

White oat (*Avena sativa*) is a low input cereal with various benefits for human health. It is also used as a high value animal feed and increasingly as a source of high-value compounds for industrial use (Marshall et al., 2013; Kurt, 2021). As a result,

Table 1. Mean minimum-maximum monthly temperature and total rainfall during the experimental period (2020 and 2021) and historical mean (HM, 26-year mean). Source: SIMEPAR.

Months	Temperature (ºC)			Total rainfall (mm)		
	2020	2021	HM	2020	2021	HM
January	20.5-21.7	17.9-26.4	17.4-27.3	105.0	180.6	162.3
February	20.2-21.5	15.3-27.4	17.2-27.6	145.4	48.4	156.0
March	19.6-21.0	16.8-27.5	16.7-27.2	24.2	195.2	124.8
April	17.1-18.6	12.8-24.2	14.5-25.2	51.2	9.6	85.0
May	13.3-14.9	9.6-21.9	10.8-20.9	67.8	87.6	91.0
June	14.8-15.9	9.1-19.1	9.9-20.2	144	74.6	106.5
July	13.3-14.7	5.3-18.9	9.1-20.2	40.0	36.4	91.3
August	13.9-15.3	10.9-22.0	10-21.9	138.4	44.0	79.3
September	18.5-20.0	12.8-26.0	12.1-23.4	35.0	58.2	122.6
October	18.8-20.2	13.4-22.3	14.1-25.0	89.4	230.2	167.0
November	18.9-20.3	14.5-27.1	15-26.1	116.8	38.0	119.4
December	20.0-21.3	15.3-28.1	16.5-27.2	139.6	107.8	149.8

Table 2. Means (± standard error) for panicle length (PL), number of spikelets per panicle (NSP), number of grains per panicle (NGP), number of panicles per m^2 (NP), 1000-grain weight (GW), grain yield (GY, *Avena sativa* cv. Artemis), revenue and total cost from white oat grain yield in two experimental years (2020 and 2021).

Variable	2020	2021	*F*	*P*
PL (cm)	14.5 ± 0.20	17.2 ± 0.36	95.8	0.0000
NSP	25.9 ± 0.89	25.8 ± 0.82	0.01	0.9247
NGP	46.3 ± 1.55	55.1 ± 1.91	12.4	0.0024
NP	278 ± 11.2	358 ± 11.4	35.2	0.0000
GW (g)	43.4 ± 0.73	38.1 ± 0.63	30.3	0.0000
GY (kg ha^{-1})	1712 ± 110.3	3057 ± 208.7	41.8	0.0000
Revenue (U$ ha^{-1})	215 ± 18.3	480 ± 40.2	97.3	0.0000
Total cost (U$ ha^{-1})	314 ± 10.9	601 ± 23.1	511.0	0.0000
Profit (U$ ha^{-1})	-98.4 ± 14.6	-116 ± 29.7	0.32	0.5758

Means ± standard error. *F* and *P* = *F*-ratio and probability for year effect.

there has been an increase in the use of oats and a broadening of oat-based products (Marshall et al., 2013). Thus, oat represent an important commercial crop in the Brazilian subtropical region. The objective of this study was to evaluate the oat grain yield and its economic profitability, during two consecutive winters in an ICLS with and without eucalyptus trees, immediately after planting the trees, with two levels of N as topdressing. Oat cultivation during winter was considered as an alternative to livestock in this season. Since N is a high-cost input, this factor can contribute to a better economic evaluation of the ICLS, in addition to its expected impact on oat grain yield.

Results

Tree measurements

The mean diameter at breast height (DBH) and tree height for eucalyptus in November 2020 were 2.2 ± 0.11 cm and 2.4 ± 0.07 m, respectively. By September 2021, the trees had reached a DBH of 9.9 ± 0.19 cm and 7.0 ± 0.12 m of height.

Grain yield and yield components

No significant differences were observed among years and treatments for the number of spikelets per panicle (25.9 ± 0.59). Addittionally, no significant differences between N levels (Table 3) and interactions between years and treatments were observed for the variables studied.

Significant differences were observed among years for oat grain yield (GY) and its components (PL, NGP, NP, GW), with generally greater values in 2021 compared to 2020, except for GW (Table 2). Furthermore, greater values for PL, NP, and GY were observed in the treeless system compared to the agroforestry system (Table 4).

Economic analysis

No significant differences were observed among years and treatments for profit, with an average of -107,4 ± 16.28 U$ ha^{-1}. No significant interactions between years and treatments were observed for the economic parameters. Significant differences between N levels were only observed for the total cost. Winter costs were significantly greater for the N60 treatment than for N20 (Table 3). Significant differences were observed among years for revenue and total cost, generally showing higher values in 2021 compared to 2020 (Table 2). Additionally, greater values for revenue and total cost were observed in the treeless system compared to the agroforestry system (Table 4). A more detailed description of production cost (i.e., total cost, input costs, agricultural operations, and other cost) per year and system is presented in Table 5. Higher costs were observed in treeless systems and in 2021.

Table 3. Means (± standard error) for panicle length (PL), number of spikelets per panicle (NSP), number of grains per panicle (NGP), number of panicles per m² (NP), 1000-grain weight (GW), grain yield (GY, *Avena sativa* cv. Artemis), revenue, total cost and profit from white oat grain yield in two nitrogen levels (20 *vs*. 60 kg N ha^{-1}, N20 and N60, respectively).

Variable	N20	N60	*F*	*P*
PL (cm)	15.8 ± 0.59	15.8 ± 0.39	0.45	0.5106
NSP	25.2 ± 0.98	26.6 ± 0.64	1.36	0.2587
NGP	48.4 ± 2.13	53.0 ± 2.01	3.47	0.0789
NP	311 ± 16.8	324 ± 16.0	0.89	0.3582
GW (g)	41.0 ± 1.11	40.5 ± 0.99	0.21	0.6500
GY (kg ha^{-1})	2346 ± 279.3	2424 ± 244.3	0.14	0.7103
Revenue (U$ ha^{-1})	342 ± 52.1	354 ± 49.2	0.40	0.5369
Total cost (U$ ha^{-1})	432 ± 43.3	483 ± 49.1	13.28	0.0019
Profit (U$ ha^{-1})	-88.6 ± 22.2	-126 ± 23.5	1.48	0.2390

Means ± standard error. *F* and *P* = *F*-ratio and probability for nitrogen effect.

Table 4. Means (± standard error) for panicle length (PL), number of spikelets per panicle (NSP), number of grains per panicle (NGP), number of panicles per m² (NP), grain yield (GY, *Avena sativa* cv. Artemis), revenue and total cost from white oat grain yield (2020/2021) in two systems, treeless and agroforestry.

Variable	Treeless	Agroforestry	*F*	*P*
PL (cm)	16.3 ± 0.52	15.3 ± 0.43	14.5	0.0013
NSP	26.8 ± 0.98	25.0 ± 0.59	2.29	0.1478
NGP	50.6 ± 1.95	50.8 ± 2.39	0.00	0.9462
NP	340 ± 14.7	295 ± 15.4	11.0	0.0039
GW (g)	40.0 ± 0.98	41.5 ± 1.07	2.63	0.1224
GY (kg ha^{-1})	2618 ± 285.7	2152 ± 215.6	5.02	0.0379
Revenue (U$ ha^{-1})	411 ± 55.4	285 ± 36.8	19.5	0.0003
Total cost (U$ ha^{-1})	500 ± 50.1	415 ± 39.4	40.7	0.0000
Profit (U$ ha^{-1})	-87.3 ± 27.8	-127 ± 16.3	0.01	0.9078

Means ± standard error. *F* and *P* = *F*-ratio and probability for system effect.

Discussion

In both systems, the grain yield for cv. IPR Artemis was below 3822 and 4123 kg ha^{-1}, as recorded as averages in Southern Brazil for the crop years 2020 (Lângaro et al., 2021) and 2021 (Carvalho et al., 2022), respectively. It's worth mentioning that large variations are observed according to the region. For instance, the grain yield of Artemis ranged from 720 to 6215 kg ha^{-1} in 2021 (Carvalho et al., 2022), likely due to different environmental conditions and the occurrence of lodging and diseases. The lower values for the first winter were probably due to strong competition with ryegrass from natural reseeding, as this species had been cultivated for many years in the experimental area. In the following year, despite good control of ryegrass, the low yield can be mainly attributed to the availability of rainfall, as 39% less rainfall than the historical average was observed during the winter (Table 1). Cereals such as oat are highly sensitive to weather conditions, with rainfall being one of the meteorological factors that most affects the expression of oat yield potential (Mantai et al., 2020), since it has a major influence on grain number (Ju et al., 2022).

In general, the treatments resulted in losses in oat grain production due to a combination of low yield and low market prices. An increase in N level did not guarantee an increase in oat grain yield and consequently in profit. This has a great impact on economic profit because an increase in N level significantly increased the total cost by an average of 11%. According to Ju et al. (2022), the yield response of oats to applied N depends on soil N status, seasonal rainfall, sowing date, seed rate and cultivar. For instance, in both years, the N applied as topdressing was performed in July, when rainfall was around 56 – 60% lower than the historical averages (Table 1). Instead, the lowest N levels (between 40 and 55 kg ha^{-1} of N, including base fertilizer plus topdressing), likely combined with nutrient cycling in these long-term no-till systems, may have provided a non-limiting N nutrition level.

Contrary to our expectations, a negative impact of immature trees has already been observed in this initial tree introduction phase, as significant differences among systems were observed in panicle length and in the number of panicles per m², which are key factors determining oat grain yield (Table 3). The fast eucalyptus growth, reaching 7 m in height by winter/2021, may have influenced these results. The reason may be that the competition with eucalyptus trees did not allow oats to better utilize available resources (e.g., light and water) to enhance yield component parameters. For instance, in shallow soils, as in the current experiment, the effect of lower rainfall availability may be more intense in systems with trees (Menezes et al., 2002), likely due to water competition between tree and oat. These findings contrast with Ford et al. (2017), who observed higher forage production in silvopastural systems compared to open pasture during periods of drought due to increased evapotranspiration rates in the latter system. We found no evidence of benefits from microclimate conditions in the agroforestry system during periods of drought or temperature variations. Furthermore, since we didn't find a significant interaction between years and systems, it seems that the effect of the trees was similar in both years, despite the large difference in height (2.4 m in 2020 and 7.0 m in 2021). It's important to note that pruning was carried out between the two years, so one hypothesis is that the increase in height in the second year of our study may have been offset by a decrease in tree size due to pruning.

Table 5. Means (n = 6) for production cost (± standard error) of oat in two systems (treeless vs. agroforestry) at Ponta Grossa-PR, Brazil, for the agricultural years 2020 to 2021 (in US$ ha^{-1}).

	Treeless system		Agroforestry	
	2020	2021	2020	2021
Total cost	340 ± 10.6	661 ± 25.2	288 ± 11.7	541 ± 16.7
Inputs	221 ± 9.8	471 ± 21.7	185 ± 7.9	371 ± 15.7
Agric. operations	75 ± 2.7	99 ± 1.2	66 ± 12.7	98 ± 1.1
Other costs	44 ± 1.6	86 ± 4.7	36 ± 0.8	72 ± 1.8

Additionally, the cultivation history of this long-term experiment may have influenced these results. In previous studies, significant differences in pasture productivity were observed (Pontes et al., 2017, 2020), leading to differences in residue addition on the soil surface (plant and animal). Greater residue deposition in CL compared to CLT systems over time could positively impact soil physical and chemical characteristics (Carpinelli et al., 2020).

In summary, since oats occupied 84% of the area, with the remaining 16% being taken up by trees, the actual oat yield achieved in 1 ha of this association of oats and trees would be 1248 kg in 2020 and 2367 kg in 2021. The rest of the 16% of the area would be wood-producing. The income from trees is crucial for farmers. However, despite the resource from the trees not being considered in the current study, they should serve as extra income rather than offsetting losses in CLT systems. As oat cultivation is an important commercial crop in the subtropical region and the aim is to encourage the use of woody ICLS, the study emphasizes the necessity for more meticulous management of the components of the system in a broader range of situations to attain sustainable oat yield levels.

Material and methods

Study area

A field experiment was conducted at Ponta Grossa, PR (25°07'22''S, 50°03'01''W) in Southern Brazil. The climate is humid subtropical or Cfb according to the Köppen classification. The historical averages, mean temperatures, and rainfall during the experimental period are listed in Table 1. The soil is a transition from Typic Distrudept to Rhodic Hapludox, with 19%, 3% and 78% clay, silt, and sand in the upper 20 cm, respectively. The average soil chemical attributes (0-20 cm) during the experimental period (December 2020) were: pH ($CaCl_2$) = 5.0, P (Mehlich-1) = 75 mg dm^{-3}; 0.31, 2.1 and 1.4 $cmol_c$ dm^{-3} of exchangeable K, Ca and Mg, respectively; base saturation of 39.7%; carbon (Walkley-Black) was 20 g dm^{-3}.

The experimental area of 13.2 ha was divided into 12 plots (i.e., experimental units) and, since 2010, integrated cattle grazing on cool-season pasture (ryegrass, *Lolium multiflorum* + black oat, *Avena strigosa*) and warm-season corn or soybean crops on the same area using no-till. In November 2019, *Eucalyptus grandis* clone GPC 23 was planted in 6 of 12 plots, at 3×14 m spacing, in the same rows previously cultivated with trees since 2006. Therefore, a second cycle with trees started in this long-term experiment. For more detail related to the first cycle of this long-term experiment, please see Pontes et al. (2021). A first pruning was carried out in February 2021.

White oat (cv. IPR Artemis) was sown for grain production, with 0.17 m line spacing, in the winter 2020 (12 June), at a seed rate of 70 kg ha^{-1} with 200 kg ha^{-1} of N-P_2O_5-K_2O (10-20-20), and in winter 2021 (10 June), at a seed rate of 100 kg ha^{-1} with 100 kg ha^{-1} of 10-30-10. For two years, white oat for grain production was sown during winter in order to replace the livestock phase of ICLS to avoid a great animal impact in the small trees. Superficial calcitic liming was performed in May 2021, between 1 – 3 t ha^{-1} per experimental unit according to previous soil analysis. Topdressing fertilizations to complement the nutrient supply were performed with 22.5 kg ha^{-1} of N in 2021, 20 kg ha^{-1} of K_2O in 2020 and 30, 40 or 50 kg ha^{-1} of K_2O in 2021, according to previous soil analysis per experimental unit. Further, weed/disease control were performed with phytosanitary treatments.

Treatments and experimental design

The experimental design was a randomized complete block with three replicates with treatments arranged in a 2 × 2 factorial. Two N levels (20 *vs*. 60 kg N ha^{-1}, approximately 40 days after sowing, in July of both years, using urea) were crossed with two ICLS: crop-livestock (CL) only and crop-livestock-trees (CLT). The N supply was selected to provide limiting (N20, expected production < 2 t/ha according to SBCS/NEPAR, 2017) and non-limiting (N60, expected production > 4t/ha, according to SBCS/NEPAR 2017) N nutrition. Despite a short period without livestock phase during winter and 10 years of treatment history, the systems will be referred to throughout this work as treeless system (i.e., open cropland, before CL when with beef cattle during winter) *vs*. the alley-cropping agroforestry system (before CLT).

Measurement of trees, oat yield and yield components

Tree height and diameter at breast height (DBH, 1.3 m) were measured in November 2020 (n = 118) and September 2021 (n = 110), 12 and 23 months after tree planting, respectively.

The number of panicles per m^2 (NP) was estimated by counting from five samples of 0.25 m^2 each per plot. Thirty plants in each plot were selected randomly to investigate the panicle length (PL, cm), number of spikelets per panicle (NSP) and number of grains per panicle (NGP) at harvest. The 1000-grain weight (GW) was determined by measuring the weight of 500 grains from each plot and multiplying by 2. Grain yield at harvest was evaluated on 20 October 2020 and 26 October 2021. Grain yield estimation (GY, kg ha^{-1}) was obtained by manually cutting in three lines of 6 m per plot. For grain yield and 1000-grain weight, the weight was corrected to 13% of the moisture content.

The GY in the tree system was extrapolated to hectares to facilitate a comparison with the results recorded under full exposure to the sun when oat productivity per se was analyzed. However, since oats occupied 84% of the area, with the remaining 16% being taken up by trees, the actual oat yield for the association of oats and trees was also calculated.

Economic analyses

The economic indicators used in this study were: revenue, total cost, and profit. To perform the economic analysis, we considered all inputs and agricultural operations used in each plot. For all economic indicators, we conducted a survey on the average cost for all agricultural operations and inputs related to oats (e.g., seeds, fertilizers) for each experimental year, based on information obtained from at least three cooperatives and companies in the study region.

In the cost analysis, we used operational costs related to production (i.e. variable costs), following the methodology of Fuentes-Llanillo et al. (2018) and Volsi et al. (2020). To establish the operational costs of seeding, spraying, and harvesting, including labor, we used the technical coefficients of the experimental station where the experiment was conducted. The technical coefficient represents the time spent carrying out each agricultural operation per hectare. The values for agricultural operations and inputs are presented per hectare. The costs in the agroforestry systems considered that 16% of the area was occupied by trees. Thus, this percentage was applied to cost reductions for some inputs (e.g., seeds and fertilizers) because sowing was not done in the tree line, as well as in the grain yield. The cost and revenues of the trees were not included since the current study considered a short period rather than the entire development cycle of the trees.

We used the relationship between revenue and cost, or net return, for each plot. Revenue was derived by multiplying production outputs (i.e., kg grains ha^{-1}) by the respective selling prices at harvest (i.e. October). The selling prices were obtained from the Paraná State Department of Agriculture and Supply (SEAB, 2023). We corrected all economic indicators to February 2023 values using the extended national consumer price index (IPCA), the official inflation index in Brazil. This procedure was performed to convert nominal values into real values to avoid the effects of inflation during the study period. The values were converted to US dollars based on the current exchange rate (i.e., February 2023, 1 BRL = 0.1920 USD).

Statistical analyses

Analyses of variance were performed for oat yield, yield components and economic parameters to test the effect of years (DF=1), block (DF=2), N levels (DF=1), ICLS (treeless system × agroforestry, DF=1) and interactions in Statgraphics Centurion XV (2006) using GLM. Treatments (ICLS and N levels) and years were considered as fixed terms, with blocks employed as the random effect. Interactions were checked for each variable and removed from the final model if they had a p value > 0.05. Revenue and cost were transformed in logarithms, according to Lütkepohl and Xu (2012). For panicle length, data were transformed using Box-Cox to normalize the residuals.

Conclusions

Treeless system performed better than agroforestry in terms of oat grain yield. An increase in the N level reduced profit, regardless of the system. In a subtropical region, oat grain production therefore carries higher risks associated with production and market. The association with eucalyptus, at a density of 238 trees ha^{-1}, may increase this risk due to a decrease in grain yield, particularly in shallow soils where competition between trees and intercrops is more intense. Therefore, our results suggest that oat production is an unsuitable alternative during winter for ICLS with trees in the initial tree introduction phase. Integrating livestock from the first winter by using physical barriers, such as fences around immature trees, could be a more profitable alternative, especially if combined with initiatives that add value to the products from ICLS with trees. Further research is needed to explore the interaction of factors related to variety, management and environment, which determine the development and growth of oats, across a broader range of situations, in order to enhance oat yield in ICLS.

Acknowledgments

The first author and the third authors are grateful to CNPq (304426/2022-9) and to 'Fundação Araucária' (MUL2022201000015) for the fellowship, respectively.

Statements of contribution

Laíse da S. Pontes designed the experiment, performed statistical analyzes of experimental data and wrote the first version of the article. Luiza Carneiro and Debora Rodrigues performed the experiment, Tiago S. Telles performed the economic analyses. All authors reviewed the manuscript and approved the final version.

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