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Interference and level of economic damage of soybean voluntary plants infesting bean

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Abstract: Background: The interference caused by volunteer soybean plants from grains lost before or during harvest can cause economic losses to bean producers due to the competition they cause, especially for succeeding crops. Objective: Therefore, the objective of this work was to determine the competitive ability and economic damage level (EDL) of bean cultivars in the presence of different densities of soybean volunteer plants. Methods: The experiments were installed in completely randomized design, and replicated for two consecutive years, 2020/21 and 2021/22. Treatments consisted of the carioca bean cultivars BRS Tangará, IAC 1850, and BRS Estilo and the black type IPR Uirapuru, IPR Urutau, and BRS Esteio, and 12 volunteer soybean densities established for each cultivar, ranging from 0 to a maximum of 66 plants m^{-2}. Plant density, soil cover, leaf area, and shoot dry matter of volunteer soybean plants were determined 40 days after emergence. For bean, productivity, control cost, selling price, and control efficacy were determined. Results: Bean cultivars IPR Tangará, BRS Estilo, IPR Uirapuru and BRS Esteio showed greater competitive ability in the presence of soybean. The highest EDL values ranged from 1.00 to 2.89 plants m^{-2} for BRS Estilo, IPR Uirapuru, IPR Urutau and BRS Esteio cultivars when competing with soybean. Conclusions: Bean cultivars have different competitive abilities, and EDL is directly influenced by these different genetic traits.

Keywords: *Phaseolus vulgaris*; *Glycine max;* Harvest losses

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1. Introduction

The cultivation of beans (*Phaseolus vulgaris*) is one of the protein foods that form the basis of the Brazilians diet. This crop is also a source of income for rural producers, especially in family areas. Brazil produces about 2.98 million tons of beans per year (Companhia Nacional de Abastecimento, 2023). In Brazil, up to three harvests of beans can be grown, referred to as sowing: the rainy season (August to October - first harvest), the dry season (February to April - second harvest), and the fall-winter (May to June - third harvest).

In the southern region of Brazil, field beans are increasingly being grown as a second crop after soybeans. Thus, the management and cultivation practices for the successively grown crops are directly related. Grain losses in the soybean crop have led to an increase in the frequency of volunteer infestation in the succeeding bean crop. It is estimated that the average grain loss in mechanical harvesting of soybeans harvest is about 81 kg ha^{-1} (Schanoski et al., 2011). These losses may be related to the use of unsafe machinery, poor adjustment, inadequate speed, steep terrain slopes, harvesting in high humidity, lack of operator knowledge, and adverse weather conditions, among other factors (Faggion et al., 2017). When these volunteer soybean plants infest crops, they can compete for space, water, nutrients, and light, and are also hosts for various pests and diseases (Costa et al., 2020), resulting in high losses for producers.

Inspection of volunteer soybean plants is required in several states for a continuous period of 90 days. This period is referred to as "sanitary void" and one of its objectives is to reduce the source of the inoculum of the fungus *Phakopsora pachyrhizi*, which is responsible for Asian rust (Empresa Brasileira de Pesquisa Agropecuária, 2023). However, after beans are sown, this control is neglected, especially in southern Brazil, resulting in high losses for growers and difficulties in controlling voluntary soybeans, mainly with the use of herbicides that act selectively on the bean plant (Costa et al., 2020).

High densities of plants competing with crops make it easier for growers to decide to take control measures (Agostinetto et al., 2010; Tavares et al., 2019). However, when volunteer plants occur at lower densities, the adoption of control measures becomes difficult as growers need to quantify the economic benefits in relation to the costs of control (Kalsin and Vidal, 2013; Tavares et al., 2019; Oveisi et al., 2021). Therefore, it is necessary to implement management strategies that integrate technical knowledge and economic analysis combined with knowledge of crop-weed competition (Westwood et al., 2018). The Economic Damage Level (EDL) can be used to support this decision-making.

The EDL specifies that the use of herbicides or other control methods is only justified if the damage caused by weeds exceeds the cost of the intervention used (Agostinetto et al., 2010; Tavares et al., 2019). The EDL can be influenced by several factors, such as weed species present in the crop, density and timing of occurrence relative to the crop, percentage loss and potential productivity of the crop with and without weeds, value of harvested product, cost, effectiveness of control, and impact of remaining weeds on the crop (Agostinetto et al., 2010; Galon et al., 2016; Tavares et al., 2019).

Among the management practices, the use of bean cultivars with greater competitiveness stands out as an interesting alternative strategy for cultural control, which can have a direct impact on crop yield and EDL. Some studies have reported differences in the competitive ability of bean cultivars when infested with weeds, such as alexandergrass (*Urochloa plantaginea*; Kalsing, Vidal, 2013) and/or beggarticks (*Bidens pilosa*; Galon et al., 2016). Bean cultivars have different behaviors and this fact is related to their intrinsic characteristics, such as growth habit, development cycle, number of branches, height, and plant architecture, among others, which influence the crops competitive ability (Barroso et al., 2010; Parreira et al., 2014) and, consequently, the EDL (Galon et al., 2016).

Therefore, this work hypothesizes that bean cultivars may exhibit differences in competitive ability and consequently differences in EDL caused by competition with soybean volunteer plants. With this in mind, the objective of this work was to determine the competitive ability and EDL of the carioca bean cultivars IPR Tangará, EIAC 1850, and BRS Estilo, and the black cultivars IPR Uirapuru, IPR Urutau, and BRS Esteio in the presence of different densities of voluntary soybeans.

2. Material and methods

2.1 Study area characterization

Two field experiments were conducted in the experimental area of the Federal University of Fronteira Sul (UFFS), *campus* Erechim/RS (27.725269º S, 52.294485º W and 650 m altitude), from November to March 2020/21 (Experiment I) and from November to March 2021/22 (Experiment II). The soil in the experimental area is classified as Humic Alumino Ferric Latosol (Santos et al., 2018). The experiments were carried out on an area of 3,000 m^2 divided into two plots of 1,500 m^2 each. In year 1 (2020/21) experiment I was sown on the 1,500 m^2 plot and in year II (2021/22) the second experiment was sown on the remaining 1,500 m^2 plot so that the two experiments were not sown in the same place in both growing seasons. This was done to avoid problems with the occurrence of pests and also in terms of soil fertility if the two experiments were carried out on the same site, which characterizes the monoculture system.

To perform the chemical analysis, soil samples were collected from the layer of 0 to 10, on the 3.000 m^2 on which experiments I and II were carried out, which had the following characteristics: pH_{water} = 5.1; organic matter = 3.0%; clay > 60%; P = 5.2 mg dm^{-3}, K = 118.0 mg dm^{-3}, Ca^{+2} = 5.5 cmolc dm^{-3}; Mg^{+2} = 3.0 cmolc dm^{-3}; Al^{+3} = 0.3 cmolc dm^{-3}; H + Al = 7.7 cmolc dm^{-3}; $CEC_{effetive}$ = 16.6 cmolc dm^{-3}. Fertility correction was performed according to technical recommendations for bean crop for grain production (SBCS, 2016). Basic chemical fertilization was 350 kg ha^{-1} with the formula 05-30-15 and N-P-K. The other managements measures followed the technical recommendations for the cultivation of beans.

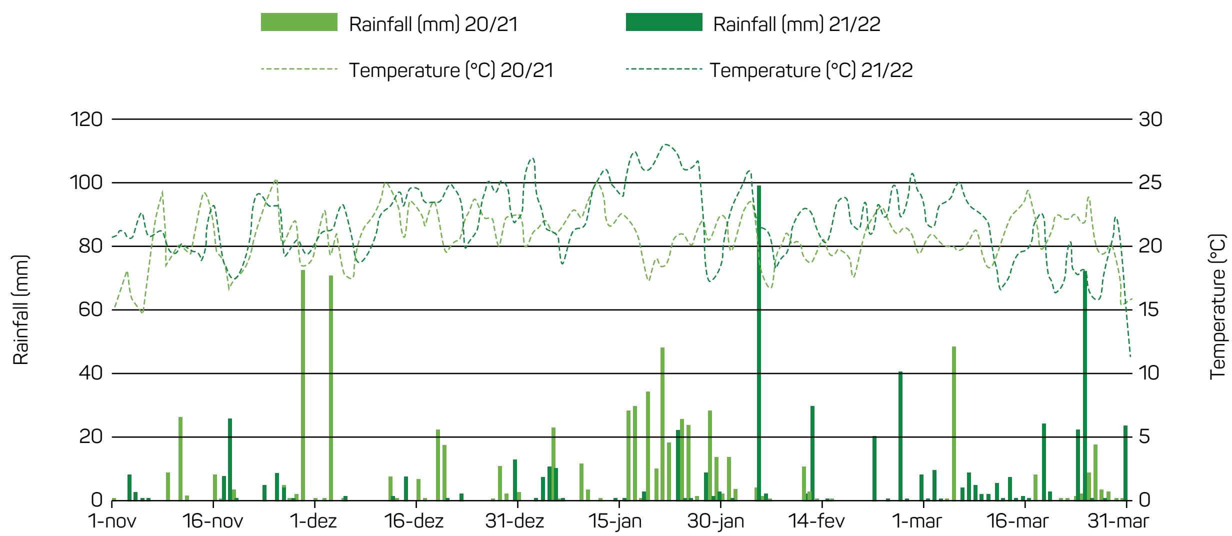
The environmental conditions at the time the experiments were conducted are shown in Figure 1. The climate of the region is classified as Cfa (humid temperate with hot summer) according to the Köppen-Geiger classification, with rainfall well distributed throughout the year (Peel et al., 2007).

2.2 Experimental design

The experiments were carried out in a completely randomized design, with four replications and replicated in two agricultural years. The treatments consisted of six bean cultivars and 12 voluntary soybean densities. In this study, the different densities of volunteer soybeans served as replicates and provided the variance necessary to perform the statistical analysis using the nonlinear model of rectangular hyperbole proposed by Cousens (1985). The same methodology was used in the work of Agostinetto et al. (2010), Galon et al. (2016), and Tavares et al. (2019).

2.3 Treatments used

The bean cultivars used were the carioca cultivars IPR Tangará (C1), IAC 1850 (C2), and BRS Estilo (C3), and the black cultivars IPR Uirapuru (C4), IPR Urutau (C5), and BRS Esteio (C6). These bean cultivars were selected because they are the most commonly grown in the region for the production of carioca and black bean seeds; their characteristics are shown in Table 1. Bean cultivars were grown in two crop seasons (2020/21 and 2021/22) in coexistence with different voluntary soybean densities: C1 *versus* 0, 10, 14, 15, 16, 16, 18, 20, 23, 25, 33 and 42 plants m^{-2}; C2 *versus* 0, 11, 13, 14, 15, 16, 17, 17, 18, 22, 23 and 30 plants m^{-2}; C3 *versus* 0, 14, 16, 16, 17, 18, 21, 22, 30, 35, 37 and 66 plants m^{-2}; C4 *versus* 0, 7, 12, 14, 14, 17, 20, 21, 26, 30, 30 and 40 plants m^{-2}; C5 *versus* 0, 8, 10, 12, 14, 16, 17, 19, 21, 22, 28 and 24 plants m^{-2}; C6 *versus* 0, 10, 11, 16, 16, 17, 18, 21, 22, 22, 24 and 30 plants m^{-2}. The density of volunteer soybeans varied due to the fact that sowing with hand rattles has an uneven depth from one pit to another because the soil is sometimes compacted, contains more straw, and



Source: INMET (2023)

Figure 1 - Average temperature (°C), precipitation (mm) and relative humidity (%) during the experimental period from November to March of the 2020/21 and 2021/22 crop seasons. UFFS/Erechim/RS

other factors such as soil moisture and temperature may have influenced the determination of an exact number of plants per plot (experimental unit). When working with regressions, whether linear or non-linear, the points tested in the experiment serve as the foundation for modeling a suitable regression. This regression equation numerically describes the relationship between the "X" and "Y" axes. Once the regression is properly modeled, researchers can calculate expected values of "Y" for any given value of "X." Therefore, weed density does not have to be identical for different genotypes. Some studies have used a similar methodology to the present work to describe competition between weeds and crops (Adati et al., 2006; Gazziero et al., 2019).

2.4 Experimental assessment

The experiments were conducted on 11/13/2020 and 11/29/2021 in a no-tillage system with straw. The soil mulch was formed from black oat and vetch, with a production of 5 t ha^{-1} dry matter. Desiccation was carried out with the herbicide glyphosate (1440 g ha^{-1}), 15 days before the sowing of the beans. The experimental units had an area of 15 m^2 and consisted of six bean rows spaced 0.5 m apart and 5 m long. In both experiments, the effective area was equal to the four central rows, minus one row on each side and 1 m at each end (2 m x 3 m). Mechanized sowing was carried out in both experiments with a precision band seeder/fertilizer, so that the plant population had a density of 12 plants m^{-2} or 240,000 ha^{-1}.

Voluntary soybean (*Glycine max*) PD for the two experiments was determined by manual ratchet seeding in each plot using the soybean cultivar Nidera 5909 RG. The density of volunteer soybean seeding was set to simulate different harvest losses, from low to high losses of grains in the field, and to calculate the amount of seed needed in each experimental unit depending on the proposed treatment, from 0 to 66 plants m^{-2} for both experiments. In the second experiment, conducted in the 2021/22 season, volunteer soybean plants in each experimental unit were counted, and if PD was found to be higher than the treatment proposed in the previous experiment (2020/21 season), the excess plants were thinned to have the same population in the two experiments conducted in different crop seasons. The other weeds not studied were controlled in both experiments with the application of fomesafen + fluazifop-p-butyl (200 + 200 g ha^{-1}) + adhesive spreader (0.2% v/v) to avoid competition with the crop.

Table 1 - Genetic characteristics, group, cycle, growth habit, and type of common bean cultivars used in the experiments in 2020/21 and 2021/22 crop seasons. UFFS, *campus* Erechim/RS, 2023

Company	Pedigree	Group	Cycle	Growth habit	Type
EMBRAPA	BRS Esteio	Black	Normal	Indeterminate	II
IAPAR	IPR Urutau	Black	Medium	Indeterminate	II
IAPAR	IPR Uirapuru	Black	Medium	Indeterminate	II
EMBRAPA	BRS Estilo	Carioca	Medium	Indeterminate	II
IAPAR	IPR Tangará	Carioca	Medium	Determinate	II
IAC	IAC 1850	Carioca	Medium	Indeterminate	II

Embrapa: Empresa Brasileira de Pesquisa Agropecuária; IAPAR: Instituto de Desenvolvimento Rural do Paraná; IAC: Instituto Agronômico

2.5 Studied variables

Quantification of plant density (PD), soil cover (SC), leaf area (LA), and shoot dry matter (DM) of soybean volunteer plants was conducted in both experiments 40 days after emergence (DAE), when the bean plant was at phenological stage V3 to V4 and the competitor plant was at V4 to V5.

To determine the explanatory variable PD, two random samples were taken per plot in a square of 0.5 m on each side. The SC by volunteer soybean was visually scored individually by two evaluators using a percentage scale where zero corresponds to no cover and 100% corresponds to complete SC. Quantification of LA competing plants was performed using a portable LA electronic integrator (model CI-203, CID Bio-Science), with all plants measured at 0.25 m^{-2} per plot. The DM of volunteer soybean plants (g m^{-2}) was determined by collecting plants in an area of 0.25 m^2 (0.5 x 0.5 m) per plot and drying them in an oven with forced air circulation at a temperature of 60±5°C until they reached a constant matter.

2.6 Calculation of grain productivity losses and the level of economic damage

Grain yield was quantified in both experiments by harvesting the plants on a usable area of 6 m^2 (2 x 3 m) per plot. Harvesting occurred when the average moisture content of the grains reached about 15%. After weighing, the moisture content was determined, correcting the masses to a moisture content of 13% and expressing the values in kg ha^{-1}.

The percentage losses of grain yield of beans, in relation to the free experimental units of the competing plants, were calculated according to Equation 1, considering the average of the data obtained in the two experiments:

$$\text{Loss (\%)} = \left(\frac{Ra - Rb}{Ra}\right) \times 100 \qquad \text{Equation 1,}$$

Where: *Ra* and *Rb*: crop productivity without and with presence of the competing voluntary soybean plant, respectively.

Prior to data analysis, the values SC (%), LA (cm^2), or DM (g m^{-2}) were multiplied by 100, eliminating the use of the correction factor in the model (Agostinetto et al., 2010).

The relationships between the percentage productivity losses of bean as a function of the explanatory variables were calculated separately for each cultivar, using the nonlinear regression model proposed by Cousens (1985) from the rectangular hyperbole given in Equation 2, adopting the average value obtained from the two experiments:

$$Pl = \frac{(i \times X)}{(1 + (i/a) \times X)} \qquad \text{Equation 2}$$

Where: Pl = Productivity loss (%); X = PD, LA, SC or DM of volunteer soybeans; *i* and *a* = = productivity loss (%) per unit of volunteer soybean plants when the value of the variables approaches zero and when it tends to infinity, respectively. The model was fiited to the data using the Proc Nlin procedure of the SAS program (SAS, 1989). For the calculation procedure, the Gauss-Newton method was used, which estimates, through successive iterations, the values of the parameters for which the sum of the squares of the deviations of the observations relative to the fitted values is minimal (Agostinetto et al., 2010). The value of the F statistic ($p \leq 0.05$) was used as the criterion for analyzing the data in the model. The acceptance criterion for fitting the data to the model was based on the significance of *F*, the highest value of the coefficient of determination (R^2), and the lowest value of the mean square of the residual (MSR).

The estimates of parameter *i* from Equation 2 (Cousens, 1985) and Equation 3 adapted from Lindquist and Kropff (1996) were used to calculate the amount of EDL, using the mean values of the two experiments.

$$EDL = \frac{(Cc)}{(R \times P \times (i/100) \times (H/100))} \qquad \text{Equation 3}$$

Where: EDL = economic damage level (plants m^{-2}); Cc = cost of control (commercial mixture of ethoxysulfuron herbicide (24 g ha^{-1}) + methylated soybean oil (0.2% v/v) and tractor application, in dollars ha^{-1}); R = bean grain yield (kg ha^{-1}); P = bean price (dollars kg^{-1} grains); *i* = productivity loss (%) of bean per unit of competing plants as population approaches zero; and H = herbicide efficacy (%).

Three values were estimated for the variables Cc, R, P, and H (Equation 3) that occurred in the last 10 years. Thus, for control cost (Cc), the average price (US$ 22.00) was considered, with maximum and minimum costs changed by 25% from the average cost. The bean grain yield (R) was based on the lowest (891 kg ha^{-1}), medium (962 kg ha^{-1}), and highest (1,057 kg ha^{-1}) obtained in Brazil in the last 10 years (Companhia Nacional de Abastecimento, 2023). The product price (P) was estimated with the lowest price paid for the carioca type (US$ 29.46) and the black type (US$ 22.55), the middle price paid for the carioca type (US$ 52.05) and the black type (US$ 25.96), and the higher price paid for the carioca type (US$ 76.89) and the black type (US$ 49.88) of the bean per 60 kg bag in the last 10 years. The dollar exchange rate at the time of data collection was R$ 5.06 for every US$ 1.00 (Banco Central do Brasil, 2023). Herbicide efficacy (H) values were set in the range of 80%, 90%, and 100%, with 80% representing the minimum control considered effective for the weed (Velini, 1995). For EDL simulations, intermediate values were used for variables that were not calculated.

3. Results and discussion

3.1 Fitting the data to the rectangular hyperbole model

The explanatory variables for volunteer soybeans PD, LA, SC, and DM, which were evaluated for productivity loss in bean cultivars showed significant statistical *F* values (Table 2). The rectangular hyperbolic model fit the data appropriately, with an average R^2 value above 0.57 and a low MSR. Galon et al. (2016), evaluating the competition of beggarticks with six black bean cultivars, found mean R^2 values greater than 0.61 for the same variables, which was similar to the results observed in the present study.

3.2 Competitive ability of common bean cultivars

Differences in productivity losses due to soybean volunteer infestation density were evident among the black bean cultivars (Table 2). Considering the average values of parameter *i* for the variables PD, SC, LA, and DM, the bean IPR Tangará, BRS Estilo, IPR Uirapuru, and BRS Esteio were characterized as the most competitive cultivars, with the lowest productivity losses compared to the other cultivars. Studies show that competitive ability of bean cultivars varies in the presence of weeds (Kalsing, Vidal, 2013; Parreira et al., 2014; Galon et al., 2016; Oveisi et al., 2021).

The difference in competitiveness between bean cultivars may be related to higher canopy (LA), leaf architecture, plant height, and/or higher relative growth rate and efficient use of environmental resources by the crop (Amini et al., 2014; Parreira et al., 2014; Oveisi et al., 2021). The use of more competitive cultivars is an important tool for integrated weed management. Characterizing of the competitive ability of crop cultivars in the presence of weeds can lead to economic and environmental benefits as fewer herbicides can be applied (Bajwa et al., 2017; Oveisi et al., 2021).

Values estimated using the hyperbolic equation show that the average density of 20 volunteer soybean plants m^{-2} resulted in yield losses ranging from 24 to 46% (Table 2). Studies evaluating the impact of different densities of maize

Table 2 - Bean productivity loss as a function of cultivars, plant density (m^{-2}), soil cover (%), leaf area ($cm^2\ m^{-2}$), and shoot dry matter ($g\ m^{-2}$) of competing volunteer soybean plants, considering the average values of the two crop seasons in which the experiments were conducted (2020/21 and 2021/22)

Explanatory variables	Parameters[1]		R^2	MSR	*F*
	i	*a*			
Density of volunteer soybean plants (plants m^{-2})					
IPR Tangará	2.07	100	0.80	98.34	91.34*
IAC 1850	4.11	100	0.75	25.44	729.50*
BRS Estilo	1.65	100	0.57	49.78	249.40*
IPR Uirapuru	2.12	100	0.77	119.77	105.35*
IPR Urutau	2.92	100	0.70	148.80	76.10*
BRS Esteio	2.28	100	0.73	22.40	430.16*
Soil cover of volunteer soybean plants (%)					
IPR Tangará	0.04	100	0.81	66.30	157.12*
IAC 1850	0.06	100	0.71	67.51	356.31*
BRS Estilo	0.04	100	0.81	18.43	504.14*
IPR Uirapuru	0.04	100	0.79	84.23	168.53*
IPR Urutau	0.05	100	0.87	34.35	669.60*
BRS Esteio	0.05	100	0.75	23.71	584.33*
Leaf area of volunteer soybean plants ($cm^2\ m^{-2}$)					
IPR Tangará	0.0002	100	0.59	105.13	86.11*
IAC 1850	0.0003	100	0.62	18.30	816.06*
BRS Estilo	0.0002	100	0.72	52.04	372.27*
IPR Uirapuru	0.0002	100	0.72	84.22	113.55*
IPR Urutau	0.0002	100	0.84	104.53	108.60*
BRS Esteio	0.0003	100	0.73	24.23	441.31*
Shoot dry matter of volunteer soybean plants ($g\ m^{-2}$)					
IPR Tangará	0.02	100	0.84	111.52	110.19*
IAC 1850	0.03	100	0.65	25.72	571.63*
BRS Estilo	0.02	100	0.84	36.29	240.13*
IPR Uirapuru	0.03	100	0.59	39.23	237.44*
IPR Urutau	0.03	100	0.71	138.96	79.13*
BRS Esteio	0.03	100	0.83	41.05	321.09*

[1] *i* and *a* productivity losses (%) per unit of volunteer soybean when the value of the variable approaches zero or tends to infinity, determined by the rectangular hyperbole model $Y = (i.X)/(1+(i/a).X$ (Cousens 1985); respectively. *Significant at $p \leq 0.05$. R^2: Coefficient of determination. MSR: Mean square of the residue. The parameters *i* and *a*, R^2, MSR, and *F* are values obtained by averaging the values of the two crop seasons (2020/21 and 2021/22) in which beans were grown

volunteer plants on bean plants show productivity losses ranging from 6.5 to 90% (Sbatella et al., 2016; Piasecki, Rizzardi, 2018). Considering the average loss of soybean grains (81 kg ha^{-1}) and estimating the average weight of 1,000 grains at 200 g (Câmara, 2015), this corresponds to a loss of 406,000 grains per hectare. At a 50% germination rate, there are 203,000 soybean plants per hectare, or 20.30 plants m^{-2} highlighting the high potential for productivity loss in bean production if voluntary soybean control is improperly implemented.

When comparing bean cultivars for the variable PD (Table 2), yield losses ranging from 1.65% (BRS Estilo) to 4.11% (IAC 1850) were found based on unity loss (*i*). As previously reported, the differentiation in competitiveness of bean cultivars in the presence of volunteer soybean is largely due to the genetic and phenotypic traits they exhibit. Selection of more competitive genotypes is a potential strategy for integrated weed management that helps reduce herbicide use and provides greater economic and environmental benefits to the producer (Jha et al., 2017; Oveisi et al., 2021).

A productivity loss of 27% was observed for the cultivar IAC 1850, when comparing the average results of parameter *i*, obtained by the rectangular hyperbole equation, with the other cultivars for the variable SC (Table 2). The cultivars IPR Tangará, BRS Estilo, IPR Uirapuru, IPR Urutau, and BRS Esteio had the lowest productivity losses, respectively: 0.04; 0.04; 0.04; 0.05 and 0.05%, with respect to IAC 1850. Therefore, it can be concluded that the degree of competition of volunteer soybeans with respect to the bean crop is influenced by SC, i.e., the more SC the weed has, the more competitive it is with respect to the crop. In this study, it can be seen that volunteer soybean as a weed has a high ability to attack bean plants, because with the increase of PD and the percentage of SC of the competitor, there is a high loss of productivity of the crop. The results of this study are consistent with those of Galon et al. (2016), who also observed that beggartick caused high losses in bean yield as it developed and grew.

The results for cultivar productivity losses in terms of percentage of LA and DM are similar to those observed in terms of PD and SC, as the cultivar IAC 1850 was the least competitive and had the highest productivity losses (Table 2). The increase in LA, SC, and DM of volunteer soybeans is directly related to PD, which explains the similarity of productivity losses between the variables evaluated, considering the *i* parameters of each of the variables studied. Among the factors associated with the strong impact of volunteer plants on crops of economic interest is the competition they exert for environmental resources such as water, light, and nutrients. According to Piasecki and Rizzardi (2018), the infestation of bean with volunteer maize can lead to productivity losses of more than 70%. These authors linked the high productivity losses to the high competitive capacity exhibited by the volunteer plants when infesting the bean crop.

The *i* parameter can be used to compare the competitive ability between species (Agostinetto et al., 2010). In this sense, different values were observed for the bean cultivars IPR Tangará, IAC 1850, BRS Estilo, IPR Uirapuru, IPR Urutau, and BRS Esteio in the explanatory variables tested and in the presence of voluntary soybean densities (Table 2). Comparing the cultivars considering the parameter *i*, in the average of the four explanatory variables (PD, SC, LA, or DM), it appears that the order of placement was generally in terms of competitiveness: BRS Estilo > IPR Tangará > IPR Uirapuru > BRS Esteio > IPR Urutau > IAC 1850. Differences in behavior between genetic material may be related to a number of factors, such as cycle, plant architecture, LA index, root system volume, use of resources available in the environment, or phenotypic plasticity of the crop in the presence of volunteer soybean (Galon et al., 2016; Bajwa et al., 2017; Piasecki, Rizzardi, 2018; Oveisi et al., 2021).

The cultivars showed different yield potentials, with yields of: 2.65; 3.12; 2.79; 2.55; 2.68, and 2.80 t ha^{-1} for the treatment in which the bean was grown without the presence of volunteer soybean for IPR Tangará, IAC 1850, BRS Estilo, IPR Uirapuru, IPR Urutau, and BRS Esteio, respectively (Table 2). The cultivar IAC 1850 showed the lowest competitiveness in the presence of voluntary soybean cultivation, compared to all other cultivars, in the average of parameter *i* evaluated in the variables PD, LA, SC, and DM. However, IAC 1850 was the material that showed 16% higher productivity in the absence of competition. Thus, this study shows that less productive material is better able to compete with volunteer soybeans. This fact can be attributed to the allocation of photoassimilates that are produced during the development of other plant organs/structures and do not have a direct effect on increasing plant productivity. Studies have shown that the allocation of photoassimilates is not only a fundamental aspect in the competition between plant species, but also an important factor affecting their competitiveness when they live in communities (Fernandes et al., 2015; Oveisi et al., 2021).

Regarding the competitive differences between cultivars in the presence of volunteer soybean, considering the carioca or black bean types, practically no differences are observed (Table 2). The average value of parameter *i* for the variables PD, SC, LA, and DM was 0.67 for the carioca bean cultivars (IPR Tangará, EIAC 1850, and BRS Estilo) and 0.63 for the black type cultivars (IPR Uirapuru, IPR Urutau, and BRS Esteio). This indicates that they are very similar in the presence of the competitor. However, when analyzing the effect of competition on the carioca type cultivars, it is found that they have a 4% higher productivity compared to the black type, considering the average effect of all voluntary soybean densities. This fact is important for the producer, because if he has a crop affected by volunteer soybeans and wants to sow second crop beans, he can give preference to Carioca type cultivars.

In the rectangular hyperbole model, the parameter *a* indicates the yield loss when the density of volunteer soybeans is maximum, i.e., it is possible to compare the maximum yield loss of cultivars of a given crop (Tavares et al., 2019). In the present study, all estimates of the parameter *a* with the volunteer soybean variables PD, SC, LA, and DM were overestimated by the rectangular hyperbole model. For this reason, the values were restricted to 100% (Table 2). The results may be due to the fact that the voluntary soybean densities were not high enough to estimate the maximum productivity loss in beans. Similar results were also obtained by Kalsing and Vidal (2013) when studying the effects of alexandergrass on common bean cultivars and by Tavares et al. (2019) when testing wheat cultivars in competition with ryegrass.

According to Cousens (1991), a reliable estimate of the parameter *a* requires that the experiments have a higher PD than is usually found in crops. Therefore, as observed in other works, the restriction to the maximum productivity loss was adopted, since there is no biological explanation for losses greater than 100% (Tavares et al., 2019).

Among the variables analyzed, the best fits of the model corresponded to SC > LA > DM > PD (Table 2). The highest mean values of R^2 and F and the lowest mean values of MSR were considered. Thus, the data show that SC can be used in place of other variables to estimate productivity losses. It was found that the variable PD can be replaced by another one depending on the bean cultivars to make decisions about voluntary soybean control. Research has reported that PD can be replaced by other variables such as DM, LA, or SC when evaluating competition of bean cultivars in coexistence with alexandergrass (Kalsing, Vidal, 2013) and beggarticks (Galon et al., 2016) or wheat with ryegrass infestation (Tavares et al., 2019).

3.3 Determination of the EDL of voluntary soybean densities

The simulation of EDL values was performed using the variable PD of the volunteer soybean. This variable was chosen because it is the most commonly used due to its ease of acquisition and also the most common in experiments with this objective (Agostinetto et al., 2010; Galon et al., 2016; Tavares et al., 2019).

Success in implementing management systems for volunteer soybean infestations can be determined by determining the density that exceeds the EDL. The lowest EDL caused by the density of volunteer soybean infestations for the six bean cultivars as a function of productivity, bag price, control cost, and herbicide efficacy was observed for IAC 1850 with an average value of 0.62 plants m^{-2} (Figures 2, 3, 4, and 5).

Considering the same criteria, the EDL was obtained with 1.55; 1.54; 2.25; 1.63, and 1.92 plants m^{-2} of volunteer soybean for the cultivars IPR Tangará, BRS Estilo, IPR Uirapuru, IPR Urutau, and BRS Esteio, respectively. It was found that the cultivars IPR Uirapuru, IPR Urutau, and BRS Esteio had the highest EDL values in all the simulations performed, ranging from 0.87 to 2.89 plants m^{-2}. The lowest EDL values were obtained with the cultivars IPR Tangará, IAC 1850, and BRS Estilo with 0.40 to 2.61 plants m^{-2}. It is noteworthy that the black bean cultivars (IPR Uirapuru, IPR Urutau, and BRS Esteio) had higher EDL values compared to the carioca cultivars (IPR Tangará, IAC 1850, and BRS Estilo), mainly due to the different genetic characteristics of the bean cultivars. Kalsing and Vidal (2013) also reported that when comparing the carioca bean cultivars (UTF-06) with the black cultivar (IPR Graúna), there were differences in the critical damage levels caused by alexandergrass infestation in the crop.

Yield, control costs, price paid per bean bag, and herbicide efficacy influenced EDL of volunteer soybean in the crop. When cultivars reduced productivity by 166 kg ha^{-1}, the density of volunteer soybeans required to achieve EDL increased by 19% in the IPR Tangará, IAC 1850, BRS Estilo, IPR Uirapuru, IPR Urutau, and BRS Esteio materials (Figure 2). Thus, it can be observed that the increase in the expected productivity of the crop is directly influenced by the competition with weeds. This fact was also observed by Galon et al. (2016) in the evaluation of bean cultivars affected by beggarticks.

By reducing the price of a bag of grain by US$ 47.43 from US$ 76.89 to US$ 29.46 for the carioca cultivars and by US$ 27.33 from 49.88 to US$ $ 22.55 for the black cultivars, it was necessary to increase voluntary soybean densities to achieve EDLs of 61% and 21% for the carioca and black bean cultivars, respectively (Figure 3). The US$ 11.00 increase in control costs increased the voluntary soybean density required to achieve the EDL by more than 67% (Figure 4). The results obtained confirm the findings of Galon et al. (2016), who reported that reducing the amount paid per bag of bean grains increased the density of beggarticks required to achieve the EDL of the weed on the crop.

Reducing the control efficiency from 100 to 80% increased the density of volunteer soybean required to reach EDL by about 25% for all cultivars (Figure 5). Galon et al. (2016) found that beggarticks density increased by more than 8% to reach EDL when this weed species infested multiple bean cultivars, which is partially similar to the results of the present study.

The variations between the highest and lowest values of the variables related to the bean crop resulted in a reduction in EDL of about 16% when productivity was taken into account, 160% in the price of the carioca type bean and 120% in the price of the black type bean, 67% in the cost of control, and 12% in the efficacy of the herbicide (Figures 2, 3, 4 and 5). These results are similar to those obtained by Agostinetto et al. (2010), Galon et al. (2016) and Tavares et al. (2019) when working with weed-infested rice, beans, and wheat, respectively.

The black cultivars showed the best results when calculating EDL considering productivity. This means that the evaluated cultivars of this bean type can coexist with a higher number of volunteer soybean compared to the

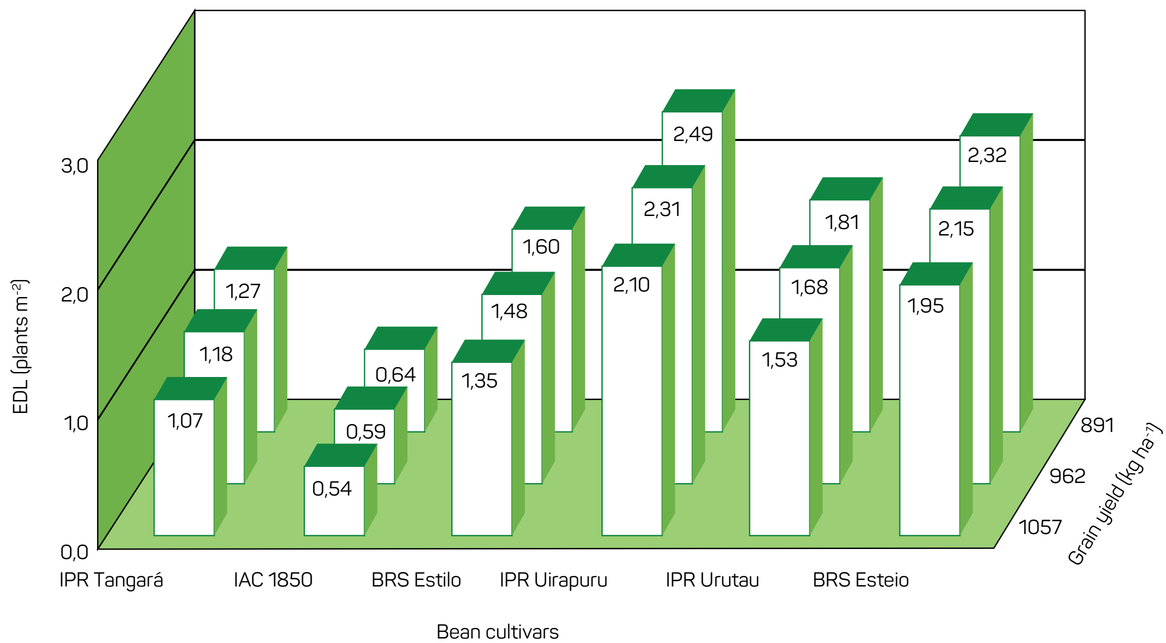


Figure 2 - Economic damage level (EDL) determined by averaging the values of the two crop seasons (2020/21 and 2021/22) as a function of volunteer soybean density, different cultivars, and grain yield of bean cultivars. UFFS, Erechim *campus*, Erechim/RS, 2023

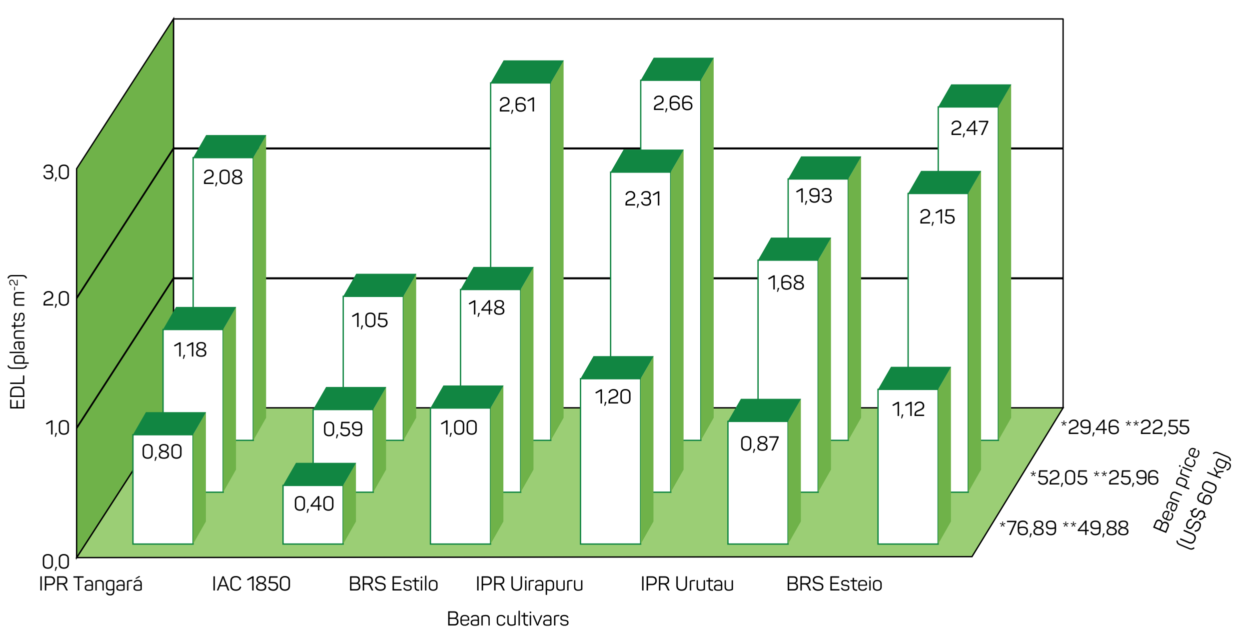


Figure 3 - Economic damage level (EDL) averaged over the two crop seasons (2020/21 and 2021/22) as a function of volunteer soybean density, different cultivars, and price paid for the bean crop. * and **: Price paid for bean cultivars of the carioca type (IPR Tangará, IAC 1850, and BRS Estilo) and the black type (IPR Uirapuru, IPR Urutau, and BRS Esteio), respectively. UFFS, Erechim *campus*, Erechim/RS, 2023

carioca cultivars (Figure 2). It was found that the greater the production potential of the crop, the lower the PD required to exceed the EDL values.

When comparing the productivity of the cultivars, a difference in EDL of up to 19% was found when considering the smallest (891 kg ha^{-1}) and the largest (1,057 kg ha^{-1}) (Figure 2). Thus, the greater the production potential of bean cultivars, the lower the density of volunteer soybean plants, which corresponds to the EDL. In this situation, it is important to take weed control measures, even if they occur at low densities. Galon et al. (2016) reported that the EDL of beggarticks infesting bean cultivars increases when the price of the crop decreases and the cost of control increases. On the

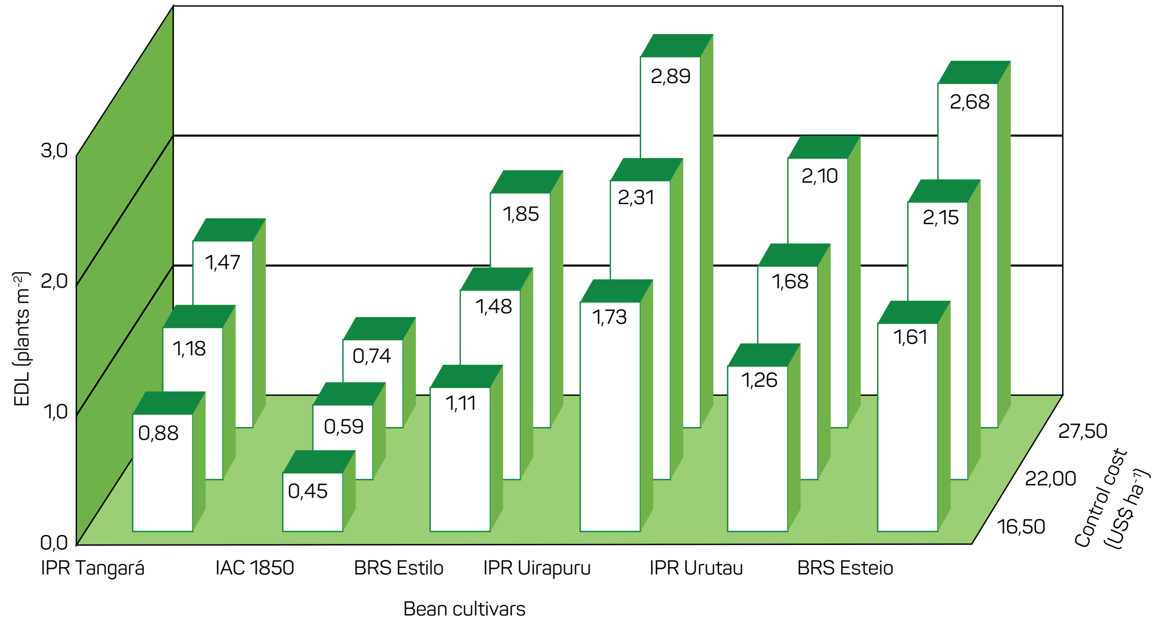


Figure 4 - Economic damage level (EDL) averaged over the two crop seasons (2020/21 and 2021/22) as a function of volunteer soybean density, different cultivars, and control costs. UFFS, Erechim *campus*, Erechim/RS, 2023

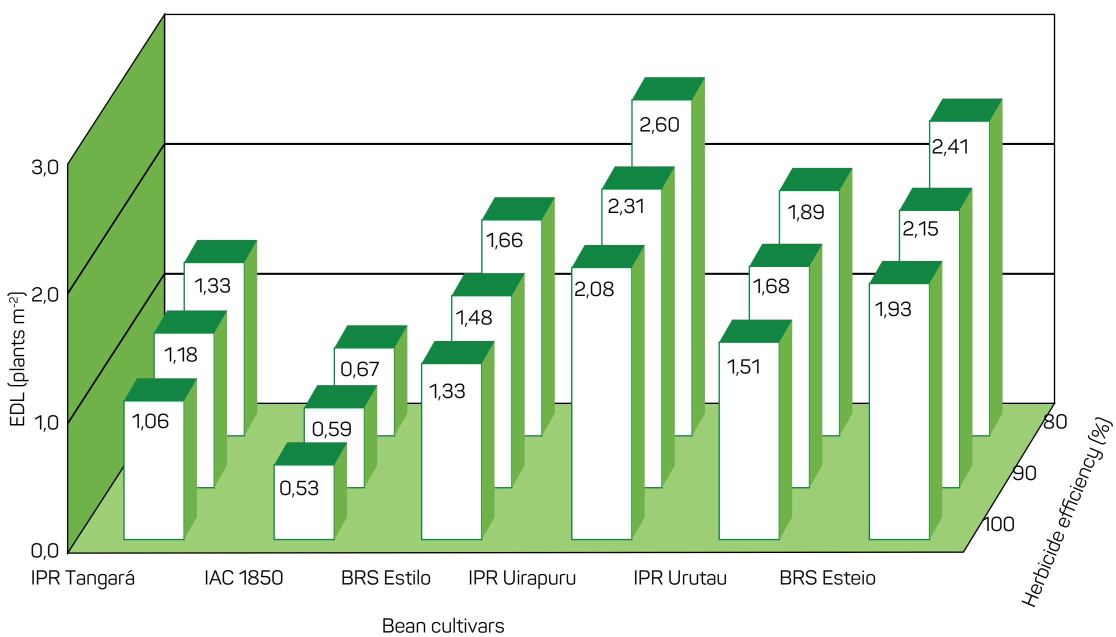


Figure 5 - Economic damage level (EDL) averaged over the two crop seasons (2020/21 and 2021/22) as a function of volunteer soybean density, different cultivars, and efficacy of the herbicide ethoxysulfuron-sodium. UFFS, Erechim *campus*, Erechim/RS, 2023

other hand, the increase in the price of bean reduces the impact of weed control costs, resulting in a greater economic return from the crop. In this scenario, lower losses are accepted and EDL occurs with a lower density of volunteer soybean plants.

The results regarding the price paid per bag of carioca and black beans show variations of about 2.61 and 2.21 times the EDL values, respectively (Figure 3). This suggests that the lower the price paid per bag of beans, the greater the density of volunteer soybeans required to exceed the EDL to compensate for herbicide use. Accordingly, the most competitive cultivars were BRS Estilo, IPR Uirapuru, and BRS Esteio with an EDL greater than 1.00 plants m^{-2} of volunteer soybeans considering the price paid per bag of beans. The greater competitiveness of these cultivars, as explained earlier, is partly due to the genetic differences they present compared to the other cultivars.

Regarding the cost of control of volunteer soybeans, a reduction of 40% reduction was observed when comparing the minimum cost with the maximum cost (Figure 4). Thus, the higher the cost of the control method, the higher the EDL and the more volunteer soybean plants m^{-2} needed to justify the control measures. Several research findings show a direct relationship between an increase in control costs and EDL (Kalsing, Vidal, 2013; Galon et al., 2016; Tavares et al., 2019).

In terms of control efficiency, it was observed that the variation of 80 (EDL of 1.76 plants m^{-2}) and 100% (EDL of 1.41 plants m^{-2}) caused a change in EDL of about 12 and 11%, respectively, compared to the average control of 90% (EDL of 1.57 plants m^{-2}) (Figure 5). It can be concluded that the level of control has a direct influence on EDL. In general, the higher the efficacy of the herbicide, the lower the EDL, i.e., a lower number of volunteer soybean plants m^{-2} is required for the application of control measures. When evaluating the efficacy of fluazifop-p-butyl+fomesafen for beggarticks control in bean, Galon et al. (2016) observed similar results to the present study, although different herbicides and weeds were evaluated.

EDL decrease with increase in productivity, price of a bag of beans, reduction in control costs, and herbicide efficacy against volunteer soybeans, justifying the use of control measures at lower competitor densities. The use of EDL as a weed control tool should be linked to good agricultural practices of weed control in bean crops. Its use is justified only in crops that provide for crop rotation, appropriate plant arrangement, use of more competitive cultivars, appropriate sowing times, correction of soil fertility, etc.

4. Conclusions

The rectangular hyperbolic regression model adequately estimates bean yield losses in the presence of the soybean volunteer densities. The bean cultivars IPR Tangará, BRS Estilo, IPR Uirapuru, and BRS Esteio proved to be more competitive than the other materials studied, IAC 1850 and IPR Urutau, when infested with volunteer soybeans. The highest EDL values ranged from 1.00 to 2.89 plants m^{-2} for the cultivars BRS Estilo, IPR Uirapuru, IPR Urutau, and BRS Esteio when competing with the density of volunteer soybeans. The cultivars IPR Tangará and IAC 1850 had the lowest EDL values, ranging from 0.40 to 2.08 plants m^{-2} in the presence of soybean volunteer. EDL values decrease with increasing grain yield, bean bag price, reduction in voluntary soybean control costs, and herbicide efficacy.

Author's contributions

All authors read and agreed to the published version of the manuscript. JPG, LG, and DCC: conceptualization of the manuscript and development of the methodology. ODHN, VMS and DAH: data collection and curation. LG, JPG and GFP: data analysis. JPG, AFS and DAH: data interpretation. LG, and GFP: funding acquisition and resources. LG, JPG and GFP: project administration. DCC and JPG: supervision. JPG, DCC and ODHN: writing the original draft of the manuscript. LG, AFS and GFP: writing, review and editing.

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