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ECOLOGICAL SUSTAINABILITY AND WEED SELECTION IN LONG-TERM CROP ROTATION INVOLVING OFF-SEASON MAIZE IN TROPICAL BRAZIL

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ABSTRACT – Maize is important in crop rotation in Tropical Brazil, with vast off-season following soybeans. Off-season maize is being grown intercropped with forages to supply pastures to cattle after maize harvest and to help with weed suppression. There is, however, scarce information on weed dynamics in the soybean and maize + forage cropping system, mainly in the long term. The objective was to evaluate weed infestation and the ecological sustainability of successive years of off-season maize cultivation, under crop succession with soybean. The phytosociological method was used to assess the importance value of weed infestation in five areas: T1 four years of soybean/off-season maize + brachiaria; T2 four years of soybean/cowpea bean; T3 four years of soybean/off-season maize; T4 six years of soybean/off-season maize; T5 nine years of soybean/off-season maize. In general, T1 had lower absolute infestation, and the longer the maize-soybean succession, the more weeds there were. The main species found were *Digitaria horizontalis, Gnaphalium coarctatum, Commelina benghalensis*, and *Conyza ssp.,* all occurring only in areas with longer maize and soybean succession. Therefore, different cropping systems influence weed composition and absolute infestation levels. The use of maize intercropped with brachiaria can be a tool in weed control for maize producers.

Keywords: phytosociology, *Zea mays*, cowpea bean, Brachiaria, corn producers

Weed infestation in agricultural areas is responsible for reductions in crop grain yields (Lacerda et al., 2020). Given this, adopting practices such as crop rotation and intercropping helps control weeds, reduces herbicide use, and increases farmers' net income (Correia, 2017). These benefits to cropping systems will be most evident when associated with the no-till planting system (Maciel, 2014).

No-till is well established in Brazil, promoting crop diversification and improving soil, physical, chemical, and biological properties through continuous soil mulching, and is widely accepted and practiced by Brazilian farmers (Nunes et al., 2020). Among the main Brazilian cropping systems, soybean (1^{st} crop – September - March) followed by off-season maize (2^{nd} crop – March - June) is annually cultivated in 9.6 million hectares (Conab, 2021) in the Cerrado (Brazilian Savannah) region of Brazil. This crop succession increases farmers' net profit and improves the quality of life all rural communities.

Furthermore, the maize 2^{nd} crop is most often not planted alone; farmers usually adopt maize with forage intercrop, so that the forage establishes itself into the maize field, causing no perceptible harm to the main crop, and after maize harvest the forage is already established and can be pastured by cattle in July and September in a period usually characterized by forage shortage in the Brazilian Cerrado. Despite the economic and cultural benefits of inserting maize in succession to soybean, either alone or intercropped with forages, this crop sequence also helps greatly in managing hard-to-kill weed species; those tolerant or resistant to the main herbicides used in this crop rotation (Ceccon et al., 2013; Concenço et al., 2014).

The presence of mulch on the soil surface, promoted mostly by the forage species and its stubble, serves as a physical barrier to weed establishment, blocking most sunlight (Büchi et al., 2020) and helping greatly reduce weed occurrence. However, there is little information on the dynamics of weed infestation in off-season maize cultivation under no-till over the years, compared with other autumn-winter species following a summer soybean crop.

In this context, the effectiveness of surface mulch as a weed management strategy depends strongly on the cropping system, as the crop species employed may exhibit limited biomass production and residue persistence, even under no-tillage conditions.

Furthermore, reports indicate that crops with deficient mulching ability may be equally responsible for weed problems (Andrade, 1995; Correia, 2017). In this way, crops widely grown for food in dry environments, such as cowpea (*Vigna unguiculata*), may increase weed infestation in agricultural cropping systems because they have deficient ground cover throughout the cropping season (Linhares et al., 2016).

The knowledge advancement on changes in weed diversity due to the cultivation history, or previous cultivation, represents an important tool for managing weeds as a whole, and helps reduce both the demand for herbicides and the occurrence of resistant weed species (Mechi et al., 2018; Werlang et al., 2018; Fachinelli et al., 2021).

We hypothesize that mulching promoted by the maize-forage intercrop may help reduce the occurrence of problematic weed species (competitive ones), thereby replacing them with ruderals that cause little to no harm to soybean or maize crops.

From these perspectives, the objective of this study was to evaluate weed infestation and the ecological sustainability of successive years of off-season maize cultivation under crop rotation with soybean.

Material and Methods

The research was carried out in the experimental area of Embrapa Agropecuária Oeste, in DouradosMS, Brazil (22° 13’ S; 54° 48’ W; 408 m als), in clayey Oxisol. The region’s climate, according to the Köppen climate classification, is Aw, with hot summers and dry winters. The experimental design was a randomized blocks design with plots measuring 80 m² and three replications. Five treatments were studied (Table 1).

The phytosociological evaluation in each treatment consisted of sampling plots by the random quadrats method proposed by Barbour et al. (1998), being carried out at the end of the second crop cycle (June). A rigid quadrat measuring 0.5 x 0.5 m (0.25 m²) was randomly launched twice into each plot (n = 12). At each sampled point, weeds were identified, counted, collected, and stored in paper bags by species, then placed in an oven at 65 ºC for 72 hours to determine the aboveground dry mass.

The importance indexes, plant density (n m^2), and aboveground dry mass (g m^2) of weeds were presented in histograms by treatment, with the respective sampling standard errors. For each species, density (ability to reproduce), frequency (spatial distribution of species), and dominance (ability to occupy the available space) were estimated, which were used to obtain the importance value of each species in each area, according to Pandeya et al. (1968) and Barbour et al. (1998). The importance value (*IV*) is the arithmetic mean of the species’ overall performance in each area, as follows:

$$rDe = \frac{I}{TI} * 100 \quad \text{eq. (1)}$$

$$rFr = \frac{Q}{TQ} * 100 \quad \text{eq. (2)}$$

$$rDo = \frac{Dm}{TDM} * 100 \quad \text{eq. (3)}$$

$$IV = \frac{rDo + rFe + rDo}{3} \quad \text{eq.(4)}$$

where rDe = relative density (%); rFr = relative frequency (%); rDo = relative dominance (%); IV = importance value (%); I = number of individuals of the species x in area r; TI = total number of individuals in area r; Q = number of samples evaluated in the area where species x is present; TQ = total number of samples in area r; Dm = dry mass of individuals of the species x in area r; TDM = total dry mass of weeds in area r. The importance value (IV) locates each weed species within the community according to its ability to cause damage based on the three parameters mentioned above.

Areas were also intra-analyzed for species diversity using the Simpson (D) and Shannon-Weiner (H') indexes (Barbour et al., 1998), and the Shannon-Weiner Evenness Proportion (SEP) sustainability coefficient was determined according to McManus and Pauly (1990). Simpson's diversity coefficient (D) quantifies, in simple terms, the probability that two individuals randomly collected in the same area belong to the same species (equation 5). The Shannon-Weiner diversity coefficient (H'), on the other hand, is most affected by the appearance or disappearance of rare species and is, therefore, more effective in detecting small changes in the weed community (equation 6).

$$D = 1 - \frac{\sum ni*(ni-1)}{N*(N-1)} \quad \text{eq. (5)}$$

$$H' = \sum (pi*\ln(pi)) \quad \text{eq. (6)}$$

Where D = Simpson diversity coefficient; H' = Shannon-Weiner diversity coefficient (based on density); ni = number of individuals of species "i"; N = total number of individuals in the sample; pi = proportion of individuals in the sample belonging to species "i".

The SEP coefficient is an index that infers the sustainability of management applied to productive systems from static data by dividing the Shannon-Weiner diversity coefficient calculated from species dominance by the same coefficient calculated from species density (equation 7).

$$SEP = \frac{Hd'}{H'} \quad \text{eq. (7)}$$

Subsequently, the areas were compared using Jaccard's asymmetric binary similarity coefficient. Based on Jaccard's coefficients, the similarity matrix was elaborated, and from this, the dissimilarity matrix was obtained as follows:

$$J = \frac{c}{a+b+c} \quad \text{eq. (8)}$$

$$Di = 1 - J \quad \text{eq. (9)}$$

where J = Jaccard's similarity coefficient; a = number of species in area a; b = number of species in area b; c = number of species common to both areas; and Di = dissimilarity.

The hierarchical grouping was obtained from the matrix of distances (dissimilarities) determined by Barbour et al. (1998) using the unweighted pair group method with arithmetic mean (UPGMA) (Sneath & Sokal, 1973). Group validation was performed using the cophenetic correlation coefficient, obtained from Pearson's

Table 1. List of treatments as a function of different numbers of years under soybean cultivation and second-crop systems.

Treatment	Cropping history
T1	Four years of soybean as the main crop, followed by off-season maize–brachiaria intercropping
T2	Four years of soybean as the main crop, followed by cowpea as the second crop
T3	Four years of soybean as the main crop, followed by off-season maize as the second crop
T4	Six years of soybean as the main crop, followed by off-season maize as the second crop
T5	Nine years of soybean as the main crop, followed by off-season maize as the second crop

linear correlation between the cophenetic and original distance matrices (Sokal & Rohlf, 1962).

All indices and coefficients were obtained in the statistical program R (R Core Team, 2026), using a dedicated R phytosociological script designed for the agricultural context (Concenço, 2014).

Results and discussion

The level of weed infestation depended on the treatment, with differences clearly tied to the duration of the management when maize is not intercropped with a forage species (Figure 1). The treatment with off-season maize for 9 years (T5) showed a higher weed density (~ 250 plants m^{-2}) compared to the other treatments with 6 years (T4) and 4 years (T3) of offseason maize. Furthermore, the summer crop (soybean) also greatly influenced weed occurrence, even when succeeded by maize+brachiaria. The most efficient treatment for suppressing weed reproduction was soybean/maze + brachiaria (~10 weed individuals per square meter) (Figure 1).

While the increase in weed density was remarkable for maize (2nd crop) grown alone after soybean, the same was not observed for aboveground dry mass, as there was random variation across years (Figure 1, T3-T5). This result may indicate that, even at higher densities, weeds are likely to experience difficulties maintaining high growth rates during the maize crop, as aboveground dry mass did not increase linearly with species density. This weak weed suppression imposed by maize was insufficient to prevent weed seeding, as their density increased over the years. This result demonstrates that maize has a mean weed-suppression ability, as shown in other studies (Concenço et al., 2012; Fachinelli et al., 2021), and thus should be intercropped with other species whenever possible, to avoid increasing weed problems in the cropping system.

The lower consistency of aboveground dry mass as a function of either cropping system or years of management (Figure 1), compared to weed density, is a likely indicator that the competitive ability of weed species infesting soybean/ maize cropping systems in Brazilian Cerrado may be centered on density, as highlighted by Thiel et al. (2018).

It is noteworthy that maize, when grown alone, can contribute to the gradual increase in weed infestation over the years (Figure 1). Fachinelli et al. (2021) reported that growing soybean (1st crop) followed by brachiaria (2nd crop) for successive years resulted in a gradual reduction in weed infestation, unlike the opposite effect observed with the maize 2nd crop. The forage (brachiaria in the present study) seems to be an important component in Brazilian Cerrado cropping systems, aiming to reduce weed occurrence.

Going deeper into weed infestation, the phytosociological analysis (Figure 2) reported *Conyza* spp., *Echinochloa crus-pavonis*, *Digitaria horizontalis*, *Amaranthus* sp., *Cyclospermum leptophyllum*, *Leonotis nepetaefolia*, *Gnaphalium coarctatum*, *Bidens pilosa*, *Commelina benghalensis*, and *Richardia brasiliensis* as the main weed species in the experiment. Species occurrence level was also dependent on treatment.

Weed species composition varies across treatments within each cropping system, with changes in importance values, density, and species distribution within the community (Silva et al., 2018). Several studies report the significant influence of cropping system components and management on weed occurrence and composition (Correia et al., 2011; Fachinelli et al., 2021). Therefore, whenever possible, it is recommended to prioritize crops that help reduce harmful species, especially problematic weeds, especially in areas with heavy infestation. This scenario may be problematic for small farms, but should not be a problem on big farms in Brazilian Cerrado regions, where area rotation may be most easily achieved if some specific fields are heavily infested with hard-to-kill weed species.

When there was a history of soybean/maize + brachiaria (T1), there was also a predominance of specific weeds, namely *Amaranthus* spp—the most prone one to overcome the competition with the forage (Figure 2). There was a great shift in weed composition, however, when soybean was followed by cowpea (T2). In this scenario, *G. coarctatum* and *C. benghalensis* accounted for ~ 88 % of the infestation's importance value. Information on weed infestation in cowpea following soybean is scarce (Pereira et al., 2020). In this context, phytosociological surveys allow a better understanding of weed dynamics (Ikeda & Vivian, 2012). Furthermore, there seems to be

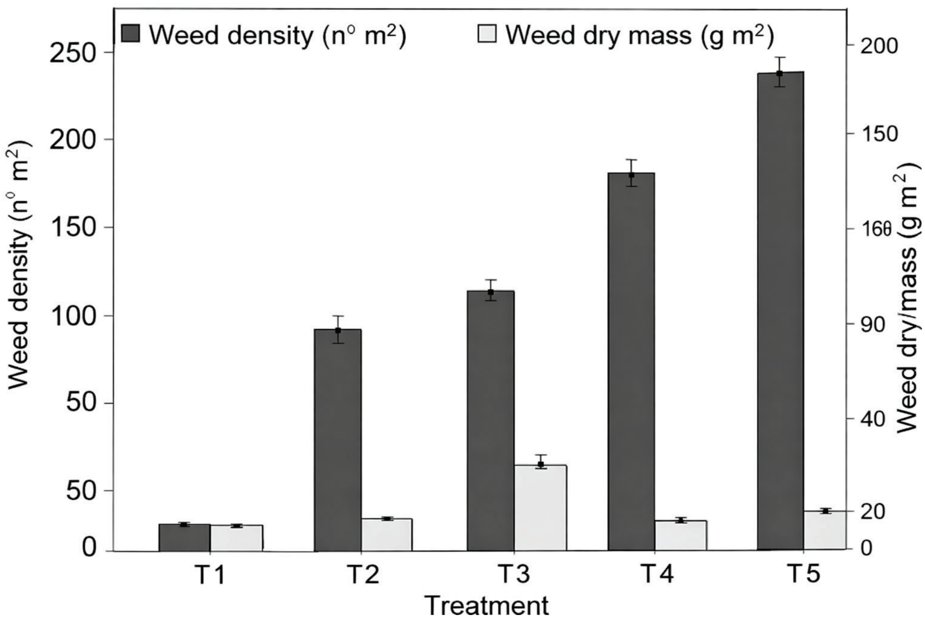

Figure 1. Weed density and aboveground dry mass of the weed community, as a function of years and crop rotation. Embrapa Agropecuária Oeste, DouradosMS, Brazil.

a tendency for the importance of infestation to be distributed among a greater number of species, rather than being concentrated in one or a few, as the number of soybean/ maize cycles (T3 - T5) increased (Figure 2).

In treatment 3, seven weeds were present, and the species with the highest importance value was *E. crus-pavonis*, while in T4 and T5 (longer periods of soybean–maize succession), nine weeds were present, with emphasis on *G. coarctatum* in both.

In general, *C. benghalensis* was present in all areas in the study and, most of the time, showed significant differences in the phytosociological parameters across all treatments. Due to its persistence in the area, such as regrowth and sexual and asexual reproduction, *C. benghalensis* increases the density and longevity in agricultural areas (Lemos et al., 2012), which may contribute to its importance among the assessed treatments.

Another species present in almost all areas, except T1, was *D. horizontalis*. Other studies report this species in soybean/maize succession (Hirata et al., 2018; Santos et al., 2018). The most infested area by this species was T5 (soybean/ maize for 9 years). This weed is favored and has greater adaptation in this production system; thus, its level of infestation warrants attention from farmers adopting this succession for several years. Furthermore, this weed is almost impossible to control chemically in maize + brachiaria intercrop, as it is also a grass.

Conyza sp. was present only in the off-season maize grown for 6 or 9 years (T4; T5).

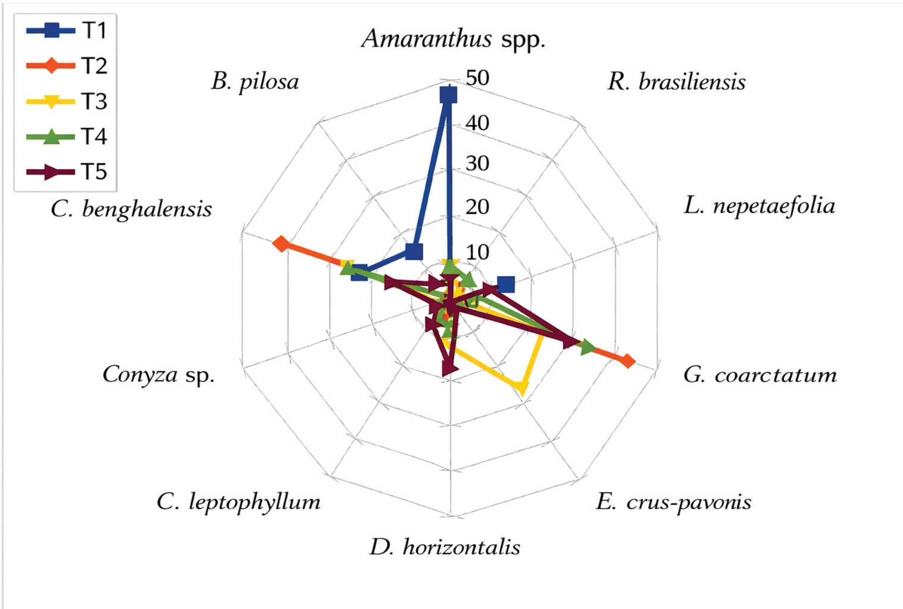

Figure 2. Importance value (IV) of weed species, as a function of treatment. Embrapa Agropecuária Oeste, 2017. T1 four years of soybean/ off-season maize + brachiaria; T2 four years of soybean/ cowpea bean; T3 four years of soybean/ off-season maize; T4 six years of soybean/ off-season maize; T5 nine years of soybean/ off-season maize.

Even with a low importance value, it is essential to monitor *Conyza* sp. in the area. Mechi et al. (2018) report that reinfestation of *Conyza* occurs most often after successive years of off-season maize, compared to areas with one year without intercropping in the off-season. Based on the benefits of the maize-brachiaria intercropping in weed control (Melo et al., 2019), it is highly recommended for farmers, mainly those who also raise cattle.

The dissimilarity clustering analysis, based on the distances calculated by Jaccard's and structured by UPGMA (Figure 3), indicated the existence of two groups: (1) soybean/ maize + brachiaria intercropping, and (2) the other treatments. There was also a clear tendency for weed infestation to become more similar as the number of years of maize cultivation increased, reaching about 80% similarity after 9 years (Figure 3).

Proper field management (crop and herbicide rotation, intercropping, pre-planting weed control, etc.) tends to result in equal species occurrence, whereas repeated management tends to select for specific weeds most adapted to that situation (Concenço et al., 2014; Correia, 2017). Furthermore, selected species through repeated practices tend to be hard to kill and may also be among the most herbicide-resistant (Norsworthy et al., 2012).

The behavior of Simpson's coefficient

(D) was similar to that observed for Shannon-Weiner's (H'), given the natural differences between them (Figure 4). The increase in species diversity can be interpreted in two ways: the first is a view of the system's biodiversity (MacLaren et al., 2019). In this case, the presence of several plant species will help cycle nutrients, explore various environmental niches, and maximize green mass per unit area. While this is important from an ecosystem perspective, it offers no benefit to arable areas in the very short term.

The second implication of diversity is the interference of these species with the crop of economic interest, resulting in decreased productivity (Lacerda et al., 2020). Higher diversity usually indicates a greater number of spontaneous species and, as a consequence, a reduction in the occurrence of problematic ones, making weed control not always easier to achieve but, most often, reducing weed impact on crop yield (Concenço et al., 2013, 2018).

Furthermore, maize diversity was high and almost independent of the number of years of cultivation (T3-T5). This higher diversity (Figure 4), however, was accompanied by higher weed occurrence (Figure 1).

This observation indicates that successive years of maize grown alone in the second crop promote the appearance of new weed species, probably ruderals, without the disappearance of the problematic, competitive ones. In this sense, the increase in maize diversity grown alone (T3-T5) makes sense from an ecosystem perspective, but it offers no benefit to arable fields. In fact, the occurrence of ruderals, although easy to control, may make the chemical control of hard-to-kill weeds difficult, as they will certainly intercept at least part of the sprayed herbicide.

Shannon's sustainability coefficient (SEP) correlates the diversity based on density with the same parameter based on dominance (McManus & Pauly, 1990). Differences between these coefficients close to zero (resulting in SEP ~ 1, Eq. (7)) indicate the longevity of the cropping system, as changes in flora reached relative stabilization (McManus & Pauly, 1990; Correia, 2017).

In this case, from an agronomic point of view, the cultivation of *Brachiaria ruziziensis* intercropped with maize (T1) proves to be an efficient cultivation system for suppressing weeds, avoiding the occurrence of most of them, whether ruderals or competitors (Figure 4). In fact, this cropping system selected mostly *Amaranthus* sp. Although this is not an easy-to-kill weed, it is a broadleaf weed into two grass species (maize and brachiaria), and can be controlled with selective herbicides.

The continuous cultivation of soybean/maize + brachiaria, however, seems unlikely, as it will most likely exhaust specific environmental resources in the medium to long term (SEP near zero). Low SEPs indicate severe environmental stress to species, usually when some resources are scarce (Pandeya et al., 1968; Gurevitch et al., 2009). Even though this system is efficient

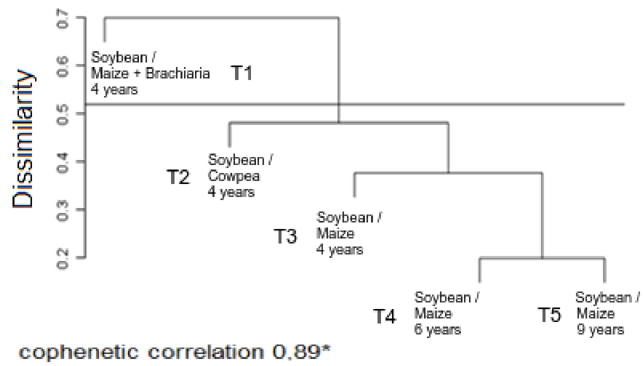

Figure 3. Dissimilarity clustering analysis by the UPGMA method based on Jaccard's binary coefficients, as a function of different years and production systems. Embrapa Agropecuária Oeste, Dourados - MS, 2017. Embrapa Agropecuária Oeste, Dourados - MS, 2017.

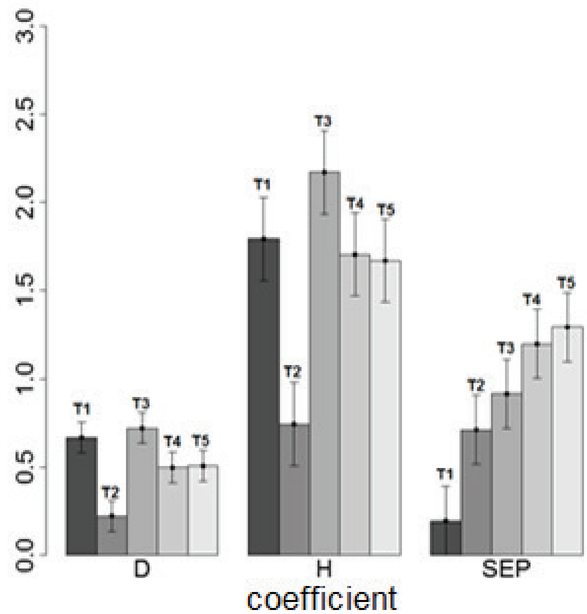

Figure 4. Simpson (D) and Shannon-Weiner (H') diversity coefficients and sustainability coefficient (SEP) as a function of years and production systems. T1 four years of soybean/ off-season maize + brachiaria; T2 four years of soybean/ cowpea bean; T3 four years of soybean/ offseason maize; T4 six years of soybean/ off-season maize; T5 nine years of soybean/ off-season maize.

in weed suppression, it should not be grown for several successive years.

Conversely, maize grown alone (T3 - T5) requires additional weed-control measures, which may increase costs. SEP values much higher than 1 indicate that some abundant environmental resources (nutrients, water, sunlight) are being supplied in excess to the system, and thus only a few species, most specialized in using those specific resources, tend to present exaggerated growth compared to other species (Pitelli & Durigan, 2001; Santos & Cury, 2011). These favored species are usually those most adapted to the cropping system, often hard-to-kill or even herbicide-resistant.

Overall, the soybean/intercropped maize + brachiaria sequence may be cropped for successive years, but not indefinitely, as there is a risk of exhaustion of specific environmental resources. Cowpea beans and maize, grown alone, may be alternated with maize + brachiaria in the second crop, serving as a tool to avoid resource depletion and selection of specific species. Maize or cowpea grown alone in the second crop, however, is not plausible for more than two years.

Conclusions

Different cropping systems influence the weed composition and infestation levels.

Maize + brachiaria intercropping as a second crop in Brazilian Cerrado conditions results in much lower weed occurrence but selects for *Amaranthus* sp. among two cropped grass species. The sustainability coefficients indicate this cropping sequence is viable for more years in a row, but not indefinitely.

Cowpea beans, when grown as a second crop following soybean, increase weed occurrence, especially *Commelina benghalensis* and *Gnaphalium coarctatum*.

Maize, grown alone after soybeans, shows a high increase in weed occurrence, with the potential to select hard-to-kill species, especially *Commelina benghalensis, Gnaphalium coarctatum*, and *Digitaria horizontalis*.

Cowpea and maize, grown alone, may be alternated with maize/brachiaria in the second crop, but it seems not to be plausible for more than two successive years.

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