# Rice Crop Rotation: A Solution for Weed Management

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Additional information is available at the end of the chapter

## Abstract

The challenges for weed management have increased in rice cultivation due to the high number of cases of herbicide-resistant weeds, especially the widespread distribution of imidazolinone-resistant weedy rice. Therefore, there has been particular interest in preventive, physical, and cultural methods in recent decades. In this context, the adoption of the rice-soybean rotation is reported to be one of the most important factors for weed management in rice fields. Additionally, the use of a diversified crop rotation enables the implementation of a broader herbicide program, which is an important feature influencing weed population dynamics. Rice-soybean rotation has been adopted by farmers to control problematic weed species, reduce seed bank of troublesome weed species, and prevent rice grain yield and quality losses caused by its interference. This crop rotation scheme has brought several benefits when it comes to weed management; however, there are also some drawbacks when adopting this strategy such as the limited productivity of soybean and new weed species becoming problematic, such as *Conyza* species. Thus, this chapter explores the advantages and disadvantages of adopting crop rotation in Brazilian lowlands, and proposes a set of strategies to successfully implement crop rotation in lowland soils as a tool for weed management.

**Keywords:** rice-soybean rotation, herbicides, residual activity, weed resistance, agriculture

## 1. Introduction

Weed management strategies are described as biological, cultural, chemical, or mechanical practices employed in an integrated manner to prevent and satisfactorily control weed infestations.

Since the introduction of herbicides, after the Second World War, the chemical approach has been the major method of weed control [1] and the reliance on herbicides, with limited diversification of mechanisms of action, has led to the appearance of increased cases of herbicide-resistant weed species. Additionally, the lack of active ingredients with new mechanisms of action [2] and public concern associated with environmental and health hazards, further emphasizes the need to rethink herbicide use [3].

Brazilian rice production has changed considerably in the past decades, partially due to the availability of high-yielding varieties and improved production techniques that have increased productivity by approximately 50% in the Southern region. Considerable progress has been also achieved in terms of weed control with the introduction of the Clearfield® technology, which allowed producers to selectively control weedy rice (*Oryza sativa* L.) by using rice genotypes tolerant to the imidazolinone herbicides. The introduction of these varieties increased the yields by more than 2.5 t/ha, allowing productivity levels to be greater than 10 t/ha in these areas [4]. However, the continued monocropping exerted a selection pressure on the weed community, favoring weed species with phenotypes and phenology that are similar to rice, such as weedy rice and *Echinochloa* spp. Moreover, the intensive use of imidazolinone herbicides concomitantly with minimal alternative cultural practices being adopted, led to the appearance of resistant biotypes of these species.

Facing the widespread distribution of imidazolinone-resistant weedy rice in Brazil, there has been particular interest in preventive, physical, and cultural methods during recent decades. Weed control strategies in general should follow integrated weed management (IWM) principles, relying less on the use of the herbicides and, whenever feasible, including non-chemical methods [5]. IWM practices have not been adopted by all rice producers in Brazil and one of the greatest constraints is the pragmatic solution provided by the use of herbicides as compared to the long-term strategies used in IWM. In practice, IWM strategy is costly in short term and the biggest challenge is to persuade farmers to spend money in preventing problems, such as herbicide resistance, that they still do not have, but probably will face in their own fields in the near future. Herbicide resistance usually evolves due to a poor weed control program, based mainly on the chemical approach, which is largely under the farmer's own control. Thus, the recent cases and obstacles caused by herbicide resistance are changing farmers' perceptions, making them now more positive toward the adoption of non-chemical weed management methods as part of an IWM strategy.

In this context, a very diverse crop rotation is reported to be one of the most important factors in diversifying weed communities and affecting their seed bank dynamics. It is believed that a crop rotation scheme composed of crops with great variability in their biological traits can be the most effective tool for controlling weeds [6] and avoiding weed resistance. The variation of cropping sequences creates an unstable environment, which prevents the annual recurrence of particular weed species [7]. Crop rotation strategies may not eradicate troublesome species, but they can limit their growth and reproduction.

Factors such as the choice of crops and cultivars, plant row spacing, crop seeding rate, sowing date, and use of fertility-building measures have to be taken into account when planning crop sequences. These measures, when properly planned and implemented, can enhance a crop's competitive ability against weeds. Variation in crop sowing dates is one of the best strategies to reduce

the seed bank size because it allows for changes in the timing of direct control strategies, such as tillage and herbicide spraying, and disrupts the germination periods of the weed species [8]. Weed germination is affected by crop cultivars and plant spacing due to changes in the canopy and thus the quality of the light that reaches the soil [9]. The incorporation of crops into rotation schemes that release allelopathic substances can be used as a tool to reduce the germination and emergence of some weed species [10]. Therefore, the right choice of crops and the sequence in which they appear is a strong tactic for preventing the establishment of several weed species in the field.

Additionally, the use of a diversified crop rotation enables the implementation of a diversified herbicide rotation scheme. The use of herbicides is considered by some researchers to be the main factor influencing seed bank dynamics [11], as they can drastically reduce weed populations. Based on this scenario, this chapter aims to explore possibilities of crop rotation sequences in Brazilian lowlands, addressing the benefits and drawbacks of each crop sequence when it comes to weed management and crop productivity. Furthermore, the authors aim to propose a set of strategies that can be used to successfully implement crop rotation in lowland soils as a tool for weed management.

## 2. Weed resistance in Brazilian rice fields

An overview of the current resistant status of herbicide resistance and the efficiency of chemical control against weed species in Southern Brazil adds a new perspective to better understand the need of non-chemical weed management methods, such as crop rotation, as part of an IWM strategy in lowlands. **Table 1** summarizes the herbicides available for rice production in Brazil by mechanism of action, and provides the reader with valuable information about the control efficiency of these compounds against the most troublesome weed species. The problems with weed resistance in rice go far beyond weedy rice, with cases of herbicide-resistant biotypes being reported for *Echinochloa* spp. (*E. crus-galli*, *E. crus-pavonis*, and *E. colona*), *Eleusine indica*, *Cyperus* spp. (*C. rotundus* and *C. difformis*), and *Sagittaria* spp. (*S. montevidensis*), which are mainly associated with the intensive use of ALS-inhibiting herbicides, poor crop rotation schemes, and cropping strategies such as irrigation systems. ALS-inhibiting herbicides are known to be highly efficient in low doses against a broad range of weed species and this is probably one of the main reasons associated with the great acceptance of the Clearfield® technology, reducing the use of other herbicides that were widely used before such as, pendimethalin, oxadiazon, oxifluorfen, thiobencarb, bentazon, propanil, and quinclorac.

*Echinochloa* spp. is also resistant to acetyl-CoA carboxylase (ACCase) inhibitors and quinclorac (AUX, auxin-mimic herbicides), while *Eleusine indica* and *Sagittaria* spp. are also resistant to ACCase and photosystem II (PS II) inhibitors, respectively. Quinclorac was widely used during the 1990s in Brazil to control *Echinochloa* spp. and *Aeschynomene* spp., and some researchers believe [12] that the first case of herbicide resistance in rice cultivation in the country is associated with this herbicide, which selected resistant plants of *Echinochloa* spp.

The current resistance problem evidences the urgent need of alternative management strategies to efficiently control these species and reduce the reliance on chemical control. The occurrence of resistant weed species, such as weedy rice, can reduce rice yields from 5 to 100%

| HRAC Group | Mechanism of action | Herbicide | Application Timing | *Echinochloa* spp. | *Oryza sativa* | *Eleusine indica* | *Urochloa plantaginea* | *Digitaria horizontalis* | *Cyperus* spp. | *Aeschynomene* spp. | *Sagittaria* spp. | *Heteranthera reniformis* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | ACCase | Cyhalofop-p-butyl | POST | R | * | R | | | * | * | * | * |
| A | ACCase | Fenoxaprop-p-ethyl | POST | | * | R | | * | * | * | * | * |
| B | ALS | Bispyribac-sodium | POST | R | * | * | * | * | R | | R | * |
| B | ALS | Penoxsulam | PRE/POST | R | * | * | * | * | R | | R | * |
| B | ALS | Imazapyr + Imazapic | PRE/POST | R | R | * | | | * | R | | | * |
| B | ALS | Imazethapyr | PRE/POST | R | R | * | * | * | R | * | * | * |
| B | ALS | Imazethapyr + Imazapic | PRE/POST | R | R | * | * | * | R | * | * | * |
| B | ALS | Ethoxysulfuron | POST | * | * | * | * | * | * | | R | * |
| B | ALS | Pyrazosulfuron-ethyl | POST | * | * | * | * | * | R | * | R | |
| B | ALS | Metsulfuron-methyl | POST | * | * | * | * | * | * | | R | |
| C | PS II | Bentazon | POST | * | * | * | * | * | * | | *R | * |
| C | PS II | Propanil | POST | | * | | | * | | | | |
| D | PS I | Paraquat | NP | | | | | | * | * | * | * |
| E | PPO | Carfentrazone-ethyl | POST | * | * | * | * | * | | * | | |
| E | PPO | Saflufenacil | POST | * | * | * | * | * | * | | | * |
| E | PPO | Oxadiazon | PRE | | | | | | * | | * | * |
| E | PPO | Oxyfluorfen | PRE | | | | | | | * | * | * |
| F4 | DOXP | Clomazone | PRE | | * | | | | * | | * | * |
| G | EPSPS | Glyphosate | NP | | * | | | | | | * | * |
| K1 | MA | Pendimethalin | PRE | | * | | | | * | * | * | * |
| O | AUX | 2,4-D | PRE/POST | * | * | * | * | * | * | * | * | * |
| O | AUX | Quinclorac | POST | R | * | * | * | * | * | * | * | * |
| - | PS II + AUX | Propanil + Triclopyr | POST | | * | * | * | * | * | | * | * |

☐Information not available; ▮no control; ▮control < 50%; ▮control 50–70%; ▮control 71–95%; ▮control > 95%.

*Product not registered to control the weed species. ACCase: lipid synthesis inhibition (inh. of ACCase); ALS: inhibition of ALS (branched chain amino acid synthesis); PS II: inhibition of photosynthesis PS II; PS I: PS I electron diversion; PPO: Inhibition of protoporphyrinogen oxidase; DOXP: Inhibition of DOXP (1-deoxy-d-xylulose-5-phosphate or clomazone) synthase; EPSPS: Inhibition of EPSPS (5-enolpyruvylshikimate-3-phosphate) synthase; MA: Inhibition of microtubule assembly; AUX: Synthetic auxin. Pre: Pre-emergence; Post: Post-emergence; NP: Application on needle point, glyphosate applied over the first-day emerging rice, R: Resistant. HRAC: Herbicide Resistance Action Committee. Font: SOSBAI, 2016 and Agrofit, 2017 < Available at: http://agrofit.agricultura.gov.br/agrofit_cons/principal_agrofit_cons>.

**Table 1.** Application timing, control levels of the most troublesome weed species in Brazilian Rice.

[13], resulting in large economic losses [14]. Thus, greater use of cultural methods, such as crop rotation, should be taken into account to reduce the weed population, resulting in less dependence on herbicides, selection pressure, and herbicide resistance.

The majority of weed resistance cases in rice are reported for ALS inhibitors, indicating that herbicide use tends to shift to other mechanisms of action to efficiently control ALS-resistant weed species. For example, clomazone and propanil provide a great control (>95%) of *Echinochloa* spp. in Brazil as indicated in **Table 1**; however, biotypes with resistance to those herbicides have been already reported in Arkansas and California due to their frequent use [15, 16]. Thus, it is likely that herbicide resistance might evolve in Brazil for these species as a consequence of the increasing frequency in which they are sprayed.

The future introduction of a new herbicide-tolerant technology for paddy rice in Brazil, the Provisia™ Rice System, includes post-emergence ACCase-inhibiting herbicides as an alternative to improve the control of resistant grass species such as weedy rice [17]. Therefore, this technology tends to increase the use of these herbicides, which is a mechanism of action considered

to pose a high resistance risk [18]. In the past 30 years, more than 35 grass species have evolved resistance to ACCase-inhibiting herbicides worldwide, especially due to target-site resistance mechanism [19], which threatens the long-term use of this technology in paddy rice. Therefore, this new technology shows great potential to reduce problems with resistant grass species but to ensure the longevity and optimize its efficiency, it is necessary to carefully follow the recommendations for use.

It is possible to observe that there is a great amount of herbicides registered for weed control in rice (**Table 1**). However, weed resistance has been reported for several molecules, especially for weedy rice and *Echinochloa* spp. There are some herbicides that provide satisfactory control of resistant biotypes when sprayed in pre-emergence, for instance, *Echinochloa* spp. resistant to ALS inhibitors can be controlled with the application of pendimethalin (MA) and clomazone (DOXP), with great control levels being reported (up to 95%) in experimental studies. However, it is likely that some plants will escape pre-emergence control and the herbicide options for post-emergence are quite limited because the species are already resistant to most of them.

**Table 1** also shows that herbicides such as oxadiazon and oxyfluorfen (PPO) do not control *Echinochloa* spp. and weedy rice when applied in pre-emergence. However, when applied on a water layer before sowing the crop (label instructions), these herbicides can provide better control of such weeds. The application of these herbicides is quite complex and growers must follow carefully the label instructions to achieve greater control efficiency. Moreover, these herbicides are likely to contaminate the environment and can cause crop injuries, which are some of the reasons for their greatly reduced usage in recent years.

It is also important to mention that the control levels given in **Table 1** for all herbicides are only expressed when they are applied following the instructions of the manufacturer, with specific doses and at the correct development stage of the crop and weed.

Based on the aforementioned facts, the need to include other control strategies, such as crop rotation that would enhance the number of molecules that can be used to control these species is evident. Nevertheless, it is important to mention that weed control levels provided by cultural measures are often meager in comparison to the efficacy of herbicides and, thus, do not reduce their need, at least in the short term. Moreover, the costs and the unpredictability of many cultural strategies are the main reasons why farmers are reluctant to adopt them, and IWM strategy will only be prioritized when the occurrence of resistant weed biotypes causes extreme failures and almost complete lost in herbicide efficacy [20].

## 3. Crop rotation in Brazilian lowlands

Lowlands in Southern Brazil are mainly cultivated with rice in the summer period and kept uncultivated during the fallow season. Crop residues left on the soil surface can be used for cattle grazing and in some cases, cover crops are sown during the winter. In general, long-term crop rotation is not included in this cropping system due to the introduction of chemical fertilizers and pesticides, mechanization, and improved crop varieties [21]. However, crop

rotation is one of the essential practices in sustainable agricultural systems, because of its effects on soil fertility, control of pathogens and pests, including weeds.

Yield reduction due to weed competition in rice cropping is estimated between 10 and 15% of potential production [22, 23]. Nevertheless, it was the widespread distribution of imidazolinone-resistant weedy rice that promoted the introduction of new crops in areas under rice monoculture. This strategy aims to reduce the seed bank of troublesome weed species and prevent rice grain yield and quality losses caused by weed interference. There are several mechanisms responsible for this effect, including allelopathy, changes in fauna, and disturbance patterns, which could diversify selection pressures by influencing seed bank dynamics. Some studies have shown that the seed bank of troublesome species in rice cultivation is greatly reduced when monoculture is abandoned [24, 25]. Rotation also affects species communities by determining the tillage frequency and effects attributed to cropping practices, such as herbicide programs, crop seed rate, and sowing time [26, 27].

Moreover, the introduction of other crops, such as soybean, in lowlands increases soil fertility due to nutrients cycling and reduces some disease pressure. Even though the positive effects of a very diverse crop rotation scheme that includes legumes and cereals are well recognized, the greatest constraints for the introduction of this strategy in lowlands are the drainage problems and the absence of species that endure long periods of water surplus in the soil. The poor natural drainage in these areas is usually the result of the flat relief associated with a shallow soil profile and impermeable sub-surface layer [28]. The physicochemical characteristics of the soils and the low natural fertility are other factors that affect crops performance in these fields [29].

Several studies aimed to evaluate the performance of various summer and winter crops to be used in a rotation scheme with rice in lowlands and will be explored in more detail in the following sub-sections.

### 3.1. Summer crops

Summer crops such as maize (*Zea mays*), sorghum (*Sorghum bicolor*), and soybean (*Glycine max*) have been explored in a crop rotation scheme with rice. Researchers have been trying to identify cultivars of these crops that can adapt to lowlands [30].

The performance of maize in these soils is quite limited because their physicochemical features do not favor the development and productivity of this crop. Lowlands soils in Southern Brazil are generally acidic, with low pH (ranging from 4.5 to 5.4), and maize plants develop better in soils with pH close to 7. Therefore, liming the soil is an essential practice in these soils to allow maize cultivation [31]. The choice of a maize cultivar with vigorous stalk, adequate height, low spike insertion, reduced lodging, and breaking resistance is another aspect that has to be considered when including this crop in a crop rotation system with rice [30].

On the other hand, sorghum is a species that adapts well in lowland soils because it has a great tolerance to drought periods and water excess when in the advanced stages of development (more than five leaves), producing up to 70 t/ha of biomass that can be used for cattle grazing. Therefore, the introduction of this species in a rotation system with rice can be a tool to reduce the seed bank of troublesome species in these areas (**Figure 1**), though trading of
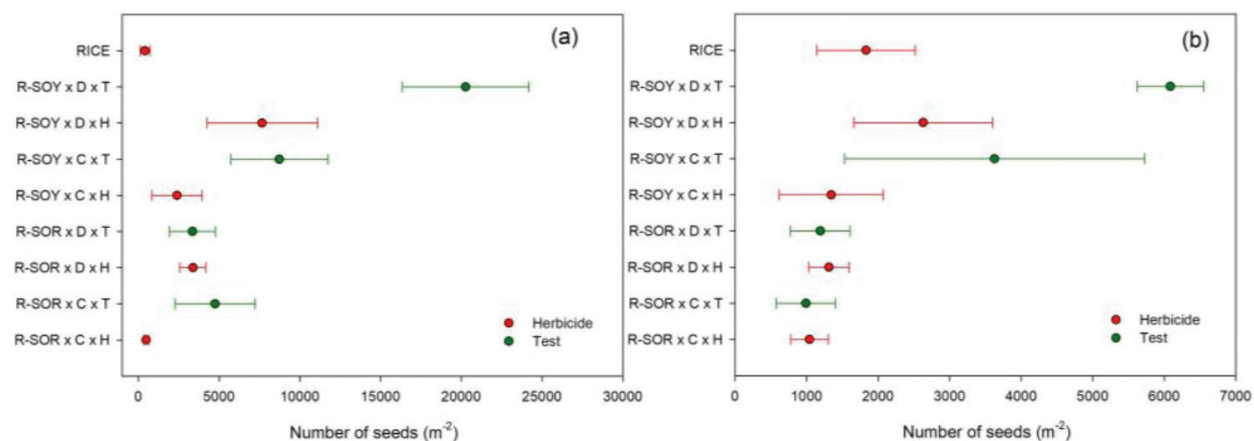
**Figure 1.** Number of seeds of *Echinochloa* spp. (a) and *Urochloa plantaginea* (b) under two tillage systems (conventional and direct drilling) and herbicide application (H- with or T-without) as a function of two crop rotation schemes: R-SOY—rice-soybean and R-SOR—rice-sorghum, two tillage systems (C- conventional and D- direct drilling) and herbicide application (with or without). Treatment means were compared on the basis of 95% confidence intervals.

the production can be a real obstacle to its wide cultivation. Moreover, the performance of this crop in lowland soils is highly associated with the choice of cultivar, adequate sowing date, and the use nitrogen fertilizers [30].

From the crop rotation point of view, the introduction of maize and sorghum in areas under rice monoculture brings several benefits for weed management; however, the inclusion of a legume species adds much more diversity to this system. Thus, soybean is probably the most promising crop to be used in a crop rotation scheme with rice, allowing farmers to increase their income, control weeds more efficiently by diversifying herbicide mechanisms of action of the herbicides and cultural practices. Moreover, leguminous species increase nitrogen (N) availability in the soil due to symbiotic $N_2$-fixation, lowering fertilizer needs for the following crop and increasing the yields of cereals grown in succession [31].

Studies evaluating the performance of soybean in Brazilian lowlands showed that this crop may be highly productive in these soils, reaching more than 4.000 kg ha$^{-1}$ [32]. However, soybean is still less profitable than rice in lowland soils because the crop is quite sensitive to water excess, especially during germination and emergence. Water surplus in soil during flowering and grain filling can also affect soybean productivity, though the crop is slightly less sensitive to this stress at those development stages [33]. Thus, it is clear that the feasibility of the rice-soybean rotation depends on the progress of research works for the adaptation of different genotypes to flooding and poor drainage conditions. Moreover, the compaction of lowland soils and reduced nitrogen fixation due to low rhizobium activity are other limiting factors to soybean productivity. Nevertheless, soybean has been shown to be a valuable tool in controlling weedy rice and aquatic weed problems as well as reducing some disease pressure.

In a study conducted at Embrapa Temperate Agriculture (Pelotas-Brazil), evaluating the effects of two crop rotation systems: rice-soybean (R-SOY) and rice-sorghum (R-SOR); two tillage systems: conventional and direct drilling; and herbicide application: with or without; on the seed bank of *Echinochloa* spp. and *Urochloa plantaginea* (**Figure 1**), it was reported that in

general, the number of seeds of both species in the seed bank was higher under rice-soybean rotation than in rice-sorghum rotation.

The seed bank of both species under R-SOR rotation was not affected by tillage systems and herbicide treatment. In R-SOY rotation, the number of seeds of *Echinochloa* spp. was higher in direct drilling than in conventional tilling in the control treatments (without herbicides). Moreover, the inclusion of herbicides reduced the seed number of this species in both tillage systems under R-SOY rotation. On the other hand, the soil seed bank of *U. plantaginea* in a R-SOY rotation in the control plots was not affected by tillage, but the inclusion of herbicides reduced the number of seeds per m² in direct-drilling plots. These results showed that rice-sorghum rotation is a good option to reduce the seed bank of *Echinochloa* spp. and *U. plantaginea* independently of tillage system and herbicide treatment. The success of a rice-soybean rotation to reduce the seed bank of these species depends on the tillage system and the inclusion of herbicides. When this system is not well manipulated, there is a risk of increasing the number of seeds in the seed bank as seen in the combination of this crop rotation (R-SOY) with direct drilling.

Another study, conducted at the same institution, tested several herbicide treatments that can be considered when soybean is introduced into a crop rotation system with rice to control troublesome species such as weedy rice, *Echinochloa* spp. and *U. plantaginea* (**Figure 2**). The results showed that all treatments efficiently controlled *U. plantaginea*, which was also suppressed in
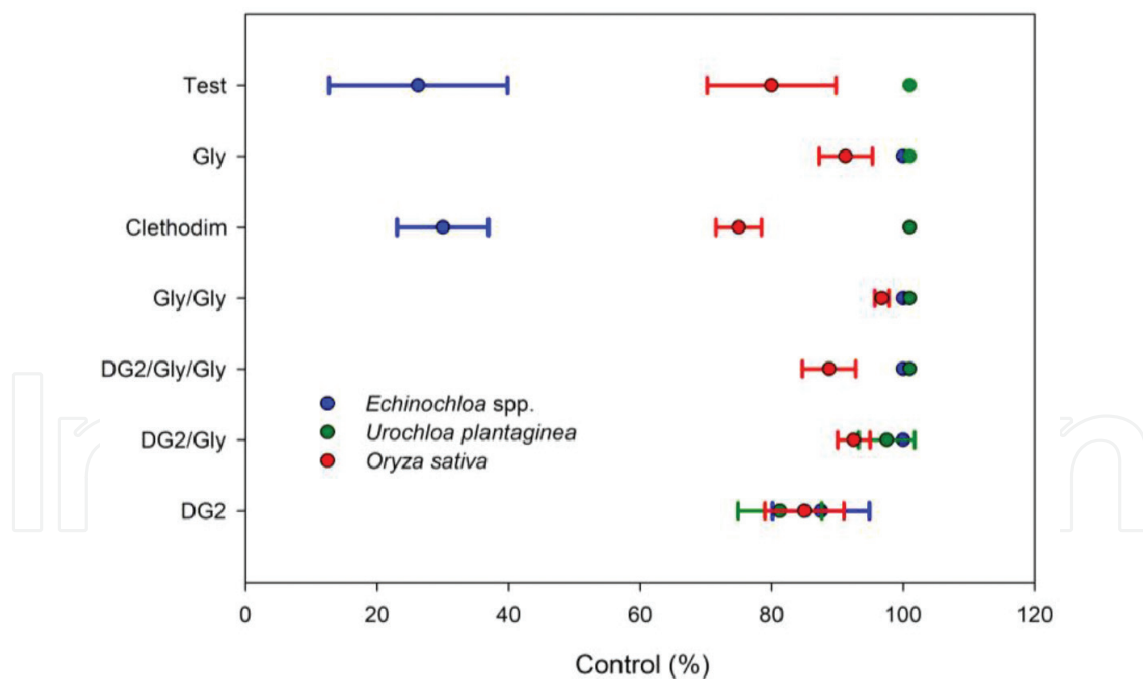


**Figure 2.** Control (%) of *Echinochloa* spp., *Urochloa plantaginea*, and *Oryza sativa* (weedy rice) with different herbicides treatments, considering a rice-soybean rotation. Gly-one post-emergence application of 3 L ha⁻¹ of glyphosate; clethodim—one post-emergence application of 600 mL ha⁻¹ of clethodim; Gly/Gly—two post-emergence application of 3 L ha⁻¹ of glyphosate; DG2- one pre-emergence application of s-metolachlor (dual gold); DG2/Gly- one pre-emergence application of s-metolachlor and one post-emergence application of 3 L ha⁻¹ of glyphosate; DG2/Gly/Gly- one pre-emergence application of s-metolachlor and two post-emergence application of 3 L ha⁻¹ of glyphosate. Treatment means were compared on the basis of 95% confidence intervals.

the control plot (test) due to the high infestation of *Echinochloa* spp. The control of *Echinochloa* spp. was satisfactory (> 80%) in all treatments, except when clethodim was sprayed, which showed similar results with the untreated plots (test). Clethodim resulted in lower control percentage for weedy rice as well, which were not statistically different from the control plots. Post-emergence applications of glyphosate demonstrated good control for weedy rice. Moreover, a single application of s-metolachlor (DG2, **Figure 2**) provides more than 80% control for the three species. Thus, to avoid the pressure selection and future cases of weed resistance in soybean, the application of a pre-emergent followed by a post-emergent herbicide is a good control strategy in this scenario. Based on the results of this study, it is possible to observe that the herbicide rotation scheme is made viable by the inclusion of soybean into a crop rotation system in lowland soils, and can greatly reduce weed occurrence and consequently, the seed bank of some troublesome species in rice cultivation.

Nowadays, soybean is considered the best option in a crop rotation scheme with rice in lowland soils, although it presents some obstacles. The variation of cropping sequences with the inclusion of soybean creates an unstable environment for most weeds, which prevents the annual recurrence of particular weed species that are promoted by rice cultivation. Crop rotation, in general, adds more diversity into the systems; however, a monotonous rotation scheme composed only of rice and soybean can exert a selection pressure on the weed community, favoring species most adapted to both crop environments. Therefore, weed species such as *Conyza* spp. that were not problematic in these areas when under rice monoculture, can be favored due to the introduction of soybean in the system. Moreover, *Echinochloa* spp. and weedy rice can become problematic for soybean cultivation if their control is not satisfactory and end up evolving resistance to frequently used herbicides such as glyphosate.

### 3.2. Winter crops

Winter cover crops, which are grown during an otherwise fallow period, are a possible means of improving weed control in rice cultivation. Cover crops are well known to improve nutrient dynamics, soil organic matter content, microbial activity, water retention, and prevent nitrate leaching [34]. Moreover, returning of crop straws has been suggested to improve overall soil conditions, reduce the requirement for N fertilizers, and support sustainable rice productivity. However, while the benefits of cover crops for nutrient management are well documented, weed effects are less verified.

Rice demands high amount of potassium (K), which is mainly accumulated in the straw residues, and is easily lost by leaching and surface runoff after crop harvesting. Therefore, the inclusion of cover crops composed of grass species that tend to produce a great amount of biomass and absorb nutrients such as nitrogen and potassium, are a great strategy for nutrient cycling, substantially avoiding nutrient losses [35].

Moreover, pertinent choices of cover crop species can suppress the growth of serious weeds and protect the soil during winter, resulting in a better soil structure as opposed to leaving soil bare. Italian ryegrass (*Lolium multiflorum*) is a grass species that has been widely used during winter in paddy soils and is a good option for cattle grazing and as cover crop. The species has great biomass production and high nutritional value for animals, as well as impressive

ability to re-grow after grazing, being highly competitive for nutrients, water, and sunlight [36]. Italian ryegrass can naturally establish itself from soil seed bank after the first year of cultivation in a given area, reducing costs with its plantation [37]; besides, it is well adapted to lowland soils. Moreover, when this species is cultivated, weed growth and development are inhibited due to the alellopathic substances released by the crop [38, 39].

**Figure 3** shows how important the inclusion of cover crops is to hamper weed infestations. In the left side of the picture, the area was left uncultivated favoring weed establishment, especially *Conyza* spp., whereas in the right side, Italian ryegrass was sown, which greatly reduced the infestation weeds.

Moreover, **Figure 4** gives the density of the weed flora (plants per $m^{-2}$) in a given area cropped with soybean for 2 years. In winter, the first half of the area was left fallow, while ryegrass was grown in the other half. The weed flora was mainly composed of *Conyza* spp, *Soliva* spp., and *Richardia brasiliensis*. Weed density was assessed in the beginning of spring, showing a clear reduction in the number of plants where the cover crop was established in comparison to leaving the soil bare. It was also possible to observe that weed density in fallow plots was approximately 10 times bigger than the one assessed in the plots with Italian ryegrass. Similar results were obtained by other authors who found that this species is an effective choice of cover crop to suppress weed communities due to its great biomass production and alellopathic properties [38, 40, 41].

It is clear that the introduction of Italian ryegrass into a crop rotation system with rice has many benefits in lowland soils. Nevertheless, the inadequate management of the crop residues can jeopardize the establishment of rice in succession due to the great amount of biomass that is kept on the soil surface. When the amount of crop residues left on the soil surface is greater than 30 t $ha^{-1}$ it is difficult for the seed drill to cut the straw as the residues act as a physical barrier [40], resulting in the poor establishment of the following crop. Moreover, the alellopathic properties of this species can be considered another drawback for its inclusion in a crop rotation scheme, especially in no-tillage systems, affecting rice germination and emergence [41].
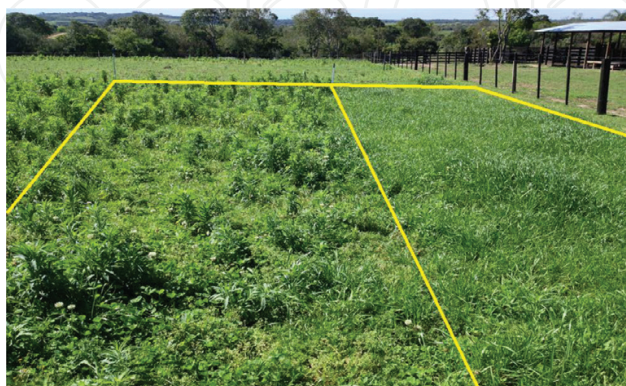


**Figure 3.** Weed infestation in experimental plots with (right) and without (left) Italian ryegrass (*Lollium multiflorum*) in southern Brazil.
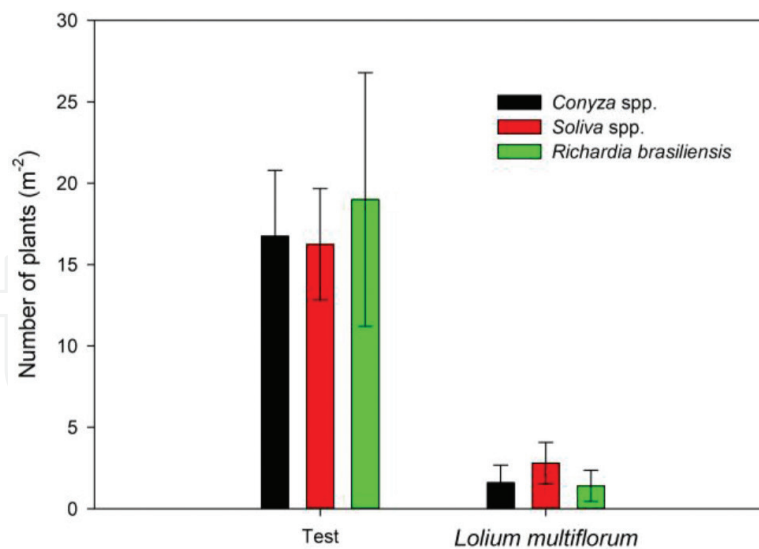
**Figure 4.** Number of plants (m⁻²) of *Conyza* spp, *Soliva* spp., and *Richardia brasiliensis* in plots without (fallow) and with *Lollium multiflorum* as a cover crop in Southern Brazil.

Glyphosate is normally used to control this species prior to sowing the summer crop due to its broad spectrum of action, efficiency, and low cost. However, the intensive use of this herbicide has left resistant biotypes of Italian ryegrass, which are becoming more frequent [42]. Other herbicides, such as the popularly known graminicides that inhibit the ACCase enzyme can be used to efficiently control biotypes resistant to glyphosate. These herbicides can be used in a mixture with glyphosate or with another herbicide with broad spectrum of action such as paraquat or ammonium-glufosinate [43, 44]. However, it is important to consider that biotypes of Italian ryegrass resistant to ACCase inhibitors have been already reported and, therefore, require careful use.

The efficiency of these herbicides is highly dependent on the development stage in which they are applied. Nevertheless, the main constraint in the use of these compounds in lowland soils is associated with the negative effects that they can cause in rice plants due to their residual activity. Residual herbicides tend to dissipate slowly in paddy soils due to poor drainage, and when the interval between spraying and sowing rice is short, crop establishment is likely to be affected.

Therefore, it is essential to determine the correct sowing and desiccation time of the cover crops, because the decomposition of crop residues can be quite slow in lowland soils, due to the great soil moisture and physical-chemical features of this type of soil. Thus, the herbicides used can affect the establishment and consequently the yield of the following crop. The ideal timing should be set according to cover crop traits, cultivation density, developmental stage, soil cultivation technique adopted, and level plus type of herbicide used [45].

Another option for winter rotation is the mixture of grass species and legumes, which has high nutritional value for animals if the crop is used for grazing; it can benefit rice cultivation due to the nitrogen (N) input in the soil and a great improvement of the physical-chemical properties of the soil. Among the legumes species that can be introduced in a crop rotation

system in lowland soils, common bird's foot trefoil (*Lotus corniculatus* L.) and white clover (*Trifolium repens*) seem to be good alternatives for Brazilian lowland scenarios, as they survive to some degree in soils with poor drainage. However, little is known about the benefits of these species in relation to weed management when introduced into a crop rotation system in lowland areas, due to the lack of more detailed studies.

## 4. Recommendations to successfully implement crop rotation in lowlands

In the last decade, there has been an increasing interest in the introduction of new crops in lowland soils in Southern Brazil, which are mainly cultivated with rice in summer and used for cattle grazing in winter. This interest is driven by several factors such as to increase the profitability of the production system and reduce the problems that have been caused by herbicide-resistant weeds. As mentioned in the chapter, sorghum, maize, and soybean are the main crop choices to be included in a crop rotation scheme with rice; however, the success of these crops is highly dependent on manipulating the ecosystem according to their needs, especially making sure that poor soil drainage and fertility will not hamper the productivity of these crops. Moreover, ensuring good soil drainage during the winter as well, would allow farmers to introduce other grass species, such as *Avena sativa*, that can be very useful for cattle grazing for instance but are quite sensitive to waterlogging.

There are several strategies that can be adopted to enhance the natural drainage in these areas, even though they are quite flat. The use of furrows works quite well and can be used as an irrigation system as well [46]. Drought periods are quite common over the summer in Southern Brazil, and considering the water requirements of maize and soybean, irrigation might be needed to ensure crops productivity in this region. The digital elevation model (DEM) is another technique that can be used for the design and allocation of drains in the area, enhancing the natural soil drainage. The DEM can be obtained with geodesic data collected by a global navigation satellite system (GNSS), with accuracy improved by a real-time kinematic (RTK) positioning. This system provides a detailed survey of the area and through the analysis of the water flow, the drainage system is designed [46].

On the other hand, instead of only manipulating the environment to meet the needs of sorghum, maize, and soybean plants, the development of crop cultivars that tolerate periods of water surplus in the soil would be a great tool to ensure their adaptation to lowland soils. To date, several genes that control the behavior of plants under water stress have been already identified and characterized. However, the information gathered so far is not enough for the development of crop cultivars that would tolerate water excess in the soil; there is still a long way to go. To enhance this knowledge and amend the strategies that have been used for plant breeding, researchers are developing high-performance sequencers and making use of statistical and transformation techniques [47]. Therefore, farmers should expect in near future the introduction of high-yield crop varieties of soybean and maize that are well adapted to the paddy soils ecosystem. Nevertheless, there are some varieties of soybean and maize available in the

market in Southern Brazil that perform better in lowland soils in terms of productivity and could be an option for producers, even though they do not tolerate waterlogging periods. For instance, among others, BMX Apolo, BMX Ícone, BRS Taura RR, BR IRGA 6070 RR, and BR IRGA 1642 IPRO are good choices of soybean cultivars, whereas P30F53H, 2B655Hx, and 2B688Hx are maize cultivars that are most promising to show high yields in lowlands [48]. Even though high-yielding cultivars of these crops are already available in the market, it is important to mention that new cultivars aiming for greater yields and stress tolerance are frequently launched. Thus, producers and professionals in this sector must keep themselves informed.

It is important to mention that there is no magic recipe to ensure the success of crops such as maize, soybean, or sorghum in lowland soils as each field has some peculiar attributes that should be taken into account and climatic conditions change all the time. Moreover, the introduction of a diverse crop rotation system alone is not sufficient to guarantee that the density of troublesome weed species will be reduced. However, the introduction of this strategy allow farmers to diversify herbicides (with different mechanisms of action), soil cultivation type, and timing and sowing dates, that together are capable of disturbing the ecosystem and hampering the establishment of recurrent weed species.

The most important thing to consider in the real world when establishing new cropping systems in a farm is to plan and introduce it in small areas in the beginning, allowing the necessary cultural modifications to be applied. This will make the crop rotation functional and productive, avoiding a possible economical drawback in case of problems in the first tests of the new crop rotation scheme.

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## References

[1] Owen MDK. Diverse approaches to herbicide-resistant weed management. Weed Science. 2016;(Special Issue):570-584

[2] Green JM. Current state of herbicide in herbicide-resistant crops. Pest Management Science. 2014;**70**:1351-1357

[3] Grundy AC. Predicting weed emergence: A review of approaches and future challenges. Weed Research. 2002;**43**:1-11

[4] Merroto A Jr, Goulart ICGR, Nunes AL, Kalsing A, Markus C, Menezes VG, Wander AE. Evolutionary and social consequences of introgression of nontransgenic herbicide resistance from rice to weedy rice in Brazil. Evolutionary Applications. 2016;**7**:837-836

[5] Swanton CJ, Weise SF. Integrated weed management: The rationale and approach. Weed Technology. 1991;**5**:657-663

[6] Nichols V, Verhulst N, Cox R, Govaerts B. Weed dynamics and conservation agriculture principles: A review. Field Crops Research. 2015;**183**:56-68

[7] Bond W. What is the weed seed bank. In: Weed Management Handbook. 9th ed. London, United Kingdom: British Crop Protection Council; 2002

[8] Bàrberi P, Cascio Lo B. Long-term tillage and crop rotation effects and weed seed bank size andcomposition. Weed Research. 2001;**41**:325-340

[9] Fenner M. Seed Ecology. New York: Chapman and Hall; 1985

[10] Khanh TD, Chung IM, Xuan TD, Tawata S. The exploitation of crop allelopathy in sustainableagricultural production. Journal of Agronomy and Crop Science. 2005;**191**:172-184

[11] Cardina J, Herms CP, Doohan DJ. Crop rotation and tillage system effects on weed seedbanks. Weed Science. 2002;**50**:448-460

[12] Andres A, Concenço G, Melo PTBS, Schmidt M, Resende RG. Detecção da resistência de campim-arroz (Echinochloa sp.) ao herbicida quinclorac em regiões orizicolas do Sul do Brasil. Planta Daninha. **1**:221-226

[13] Burgos NR, Singh V, Tseng TM, et al. The impact of herbicide-resistant rice technology on phenotypic diversity and population structure of United States weedy rice. Plant Physiology. 2014;**166**:1208-1220

[14] Lee S, Jia Y, Jia M, Gealy DR, Oslen KM, Caicedo AL. Molecular evolution of the rice blast resistance gene pi-ta in invasive weedy rice in the USA. PLoS One. 2011;**6**:e26260

[15] Norsworthy JK, Scott R, Smith K, Still J, Estorninos LE Jr, Bangarwa S. Confirmation and management of clomazone-resistant barnyardgrass in rice. In: Proceedings of the 62nd Southern Weed Science Society Meeting; Orlando, Fla, USA, Abstract 210; 2009

[16] Yasuor H, TenBrook PL, Tjeerdema RS, Fischer AJ. Responses to clomazone and 5-keto-clomazone by *Echinochloa phyllopogon* resistant to multiple herbicides in Californian rice fields. Pest Managment Science. 2008;**64**:1031-1039

[17] Webster EP, Linscombe SB, Bergeron EA, McKnight BM, Fish JC. Provisia rice: A future option in rice. 2017. Web page: http://wssaabstracts.com/public/29/abstract-271.html [Accessed: October 6, 2017]

[18] Heap I. International Survey of Herbicide Resistant Weeds. 2006. Web page: http://www.weedscience.org. [Accessed: April 6, 2017]

[19] Délye C, Zhang X-Q, Michel S, Matéjicek S, Powles SB. Molecular bases for sensitivity to acetyl-coenzyme A carboxylase inhibitors in blackgrass. Plant Physiology. 2005;**137**:794-806

[20] Chauvel B, Guillemin JP, Colbach N, Gasquez J. Evaluation of cropping systems for management of herbicide-resistant populations of blackgrass (*Alopecurus myosuroides* Huds.). Crop Protection. 2001;**20**:127-137

[21] Power JF, Follett RF. Monoculture. Scientific American. 1987;**256**:57-64

[22] Moody K. Weed control in wet-seeded rice. Experimental Agronomy. 1993;**29**:393-403

[23] Baltazar AM, Smith RJ Jr. Propanil-resistant barnyardgrass (*Echinochloa crus-galli*) control in rice (*Oryza sativa*). Weed Technology. 1994;**8**:576-581

[24] Avila LA, Marchezan E, Machado SL, Silva RP. Evolução do banco de sementes de arroz vermelho em diferentes sistemas de utilização do solo de várzeas. Planta Daninha. 2002;**18**:217-230

[25] Andres A, Avila LA, Marchezan E, Menezes V. Rotação de culturas e pousio do solo na redução do banco de sementes de arroz vermelho em solo de várzea. Revista Brasileira de Agrociência. 2001;**7**:85-88

[26] Smith RG, Gross KL, Januchowski S. Earthworms and weed seed distribution in annual crops. Agriculture, Ecosystem & Environment. 2005;**108**:363-367

[27] Scherner A, Melander B, Kudsk P. Vertical distribution and composition of weed seeds within the plough layer after eleven years of contrasting crop rotation and tillage schemes. Soil and Tillage Research. 2016;**161**:135-142

[28] Pinto LFS, Miguel P, Pauletto EA. Solos de várzea e terras baixas. In: Cultivo de soja e milho em terras baixas do Rio Grande do Sul. Pelotas -RS, Brazil: Embrapa; 2017. pp. 23-43

[29] Sousa RO, Camargo FA, Vahl LC. 2006. Solos alagados: reação de redox. In: Meurer EJ (Org). Fundamentos de química do solo. 3rd ed. Porto Alegre: Evangraf, p. 185-211

[30] Gomes AS, Magalhães AM Jr. Arroz irrigado no sul do Brasil. Brasília-DF: Embrapa Informação Tecnológica; 2004. pp. 74-95

[31] Parfitt JMB. Produção de milho e sorgo em várzea. Pelotas: Embrapa Clima Temperado; 2000. p. 146

[32] Timm PA, Campos ADS, Bueno MV, Aires T, Silva JT, Schreiber F, Parfitt JMB, Scvittaro WB, Timm LC. Avaliação de cultivares de Soja produzida em sistema de camalhão em terras baixas. In: Proceedings of the X Congress Do Arroz Irrigado, Gramado – RS. Brazil; 2017

[33] Oliveira ACB. Cultivares de Soja. In: Cultivo de soja e milho em terras baixas do Rio Grande do Sul. Pelotas -RS, Brazil: Embrapa; 2017. pp. 127-140

[34] Wittwer RA, Dorn B, Jossi W, van der Heijden MGA. Cover crops support ecological intensification of arable cropping systems. Scientific Reports. 2017;**7**:41911

[35] Scivittaro WB, Sousa RO, Silva LS. Manejo da fertilidade do solo para o cultivo de soja e milho. In: Cultivo de soja e milho em terras baixas do Rio Grande do Sul. Pelotas -RS, Brazil: Embrapa; 2017. pp. 105-125

[36] Lopes MLT, Carvalho PCDF, Anghinoni I, et al. Sistema de integração lavoura-pecuária: desempenho e qualidade da carcaça de novilhos superprecoces terminados em pastagem de aveia e azevém manejada sob diferentes alturas. Ciência Rural. 2008;**38**:178-184

[37] Trezzi MM. Antagonismo das associações de clodinafop-propargyl com metsulfuron-methyl e 2,4-d no controle de azevém (*Lolium multiflorum*). Planta Daninha. 2007;**25**: 839-847

[38] Moraes PVD et al. Manejo de plantas de cobertura no controle de plantas daninhas na cultura do milho. Planta Daninha. 2009;**27**:289-296

[39] Soares GLG, Vieira TR. Inibição da germinação e do crescimento radicular de alface (cv. "Grand rapids") por extratos aquosos de cinco espécies de Gleicheniaceae. Revista Floresta e Ambiente. 2000;**7**:180-197

[40] Rizzardi MA, Silva LF. Influência das coberturas vegetais de aveia-preta e nabo forrageiro na época de controle de plantas daninhas em milho. Planta Daninha. 2006;**24**:669-675

[41] Trezzi MM, Vidal RA. Potencial de utilização de cobertura vegetal de sorgo e milheto na supressão de plantas daninhas em condição de campo: II – efeitos da cobertura morta. Planta Daninha. 2004;**22**:1-10

[42] Powles SB, Yu Q. Evolution in action: Plants resistant to herbicides. Annual Reviews in Plant Biology. 2010;**61**:317-347

[43] Vargas L, Roman ES, Rizzardi MA, Toledo EB. Manejo de azevémresistente ao glyphosate em pomares de maçã com herbicida select (clethodim). Revista Brasileira de Herbicidas. 2006;**1**:30-36

[44] Spader V, Cristiane É, Lopes P, Geraldo E. Residual activity of ACCaseinhibitor herbicides applied at pre-sowing of corn. Revista Brasileira de Herbicidas. 2012;**11**:42-48

[45] Dabney SM, Delgado JA, Reeves DW. Using winter cover crops to improve soil and water quality. Communications in Soil Science and Plant Analysis. 2001;**32**:1221-1250

[46] Parfitt JMB, Winkler AS, Pinto MAB, Silva JT, Timm LC. Irrigação e drenagem para cultivo de soja e milho. In: Cultivo de soja e milho em terras baixas do Rio Grande do Sul. Pelotas -RS, Brazil: Embrapa; 2017. pp. 45-78

[47] Mertz-Henning LM, Nepomuceno AL, Nakayama TJ, Neumaier N, Farias JRB. Avanços biotecnológicos para o desenvolvimento da tolerâncias de soja e milho ao estresse por encharcamento do solo. In: Cultivo de soja e milho em terras baixas do Rio Grande do Sul. Pelotas -RS, Brazil: Embrapa; 2017. pp. 317-336

[48] Emygdio BM. Cultivares de Milho. In: Cultivo de soja e milho em terras baixas do Rio Grande do Sul. Pelotas -RS, Brazil: Embrapa; 2017. pp. 141-162