7. Flooded rice in tropical Brazil

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Among the most cultivated and consumed cereals in the world, rice deserves to be highlighted for several aspects: it is a type of food whose grains leaves the field and is consumed with virtually no industrialization process; serves populations with high and low purchasing power; occupies the second place in production and extension of cropped area, being surpassed only by wheat; it makes approximately 33% of the world production of cereals and plays a strategic role both economical and social for the people of the most populous nations in the world.

In the tropical region of Brazil, rice is grown on about 183,746 hectares, which corresponds to approximately 13.2% of the total area cultivated using the flooded system in Brazil. The tropical lowlands of Tocantins-Araguaia valley occupy about 1.2 million hectares of soil classified as *Inceptisolo* and have great potential for use in the production of irrigated rice. The tropical region has favorable characteristics for agricultural use with the flood irrigation system in the rainy season, suitable for the cultivation of irrigated rice (Figure 91) (Santos, 2004).

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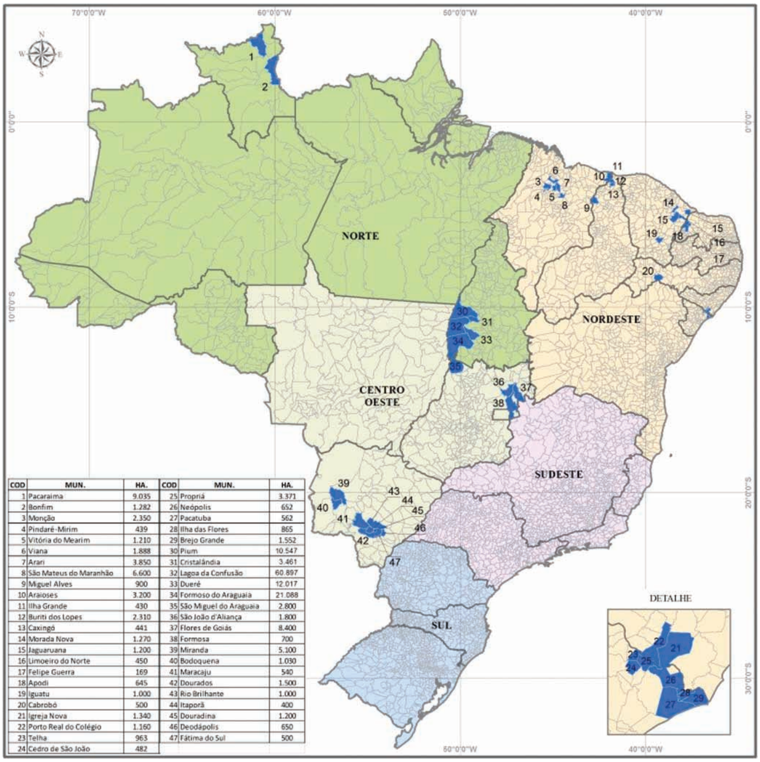

COD	MUN.	HA.	COD	MUN.	HA.
1	Pacaraima	9.035	25	Propriá	3.371
2	Bonfim	1.282	26	Neópolis	652
3	Monção	2.350	27	Pacatuba	562
4	Pindaré-Mirim	439	28	Ilha das Flores	865
5	Vitória do Mearim	1.210	29	Brejo Grande	1.552
6	Viana	1.888	30	Pium	10.547
7	Arari	3.850	31	Cristalândia	3.461
8	São Mateus do Maranhão	6.600	32	Lagoa da Confusão	60.897
9	Miguel Alves	900	33	Dueré	12.017
10	Araioses	3.200	34	Formoso do Araguaia	21.088
11	Ilha Grande	430	35	São Miguel do Araguaia	2.800
12	Buriti dos Lopes	2.310	36	São João d'Aliança	1.800
13	Caxingó	441	37	Flores de Goiás	8.400
14	Morada Nova	1.270	38	Formosa	700
15	Jaguaruana	1.200	39	Miranda	5.100
16	Limoeiro do Norte	450	40	Bodoquena	1.030
17	Felipe Guerra	169	41	Maracaju	540
18	Apodi	645	42	Dourados	1.500
19	Iguatu	1.000	43	Rio Brilhante	1.000
20	Cabrobó	500	44	Itaporã	400
21	Igreja Nova	1.340	45	Douradina	1.200
22	Porto Real do Colégio	1.160	46	Deodápolis	650
23	Telha	963	47	Fátima do Sul	500
24	Cedro de São João	482			

Figure 91. Geographic distribution of municipalities that cultivate irrigated rice in floodplains in the tropical region of Brazil. Source: IBGE (2014).

The state of Tocantins is the third largest producer of irrigated rice in Brazil and the largest producer in the tropical region, with a cropped area of 119.7 thousand hectares. In the 2018/19 growing season, 665.8 thousand tons of paddy rice were produced (Conab, 2019). In the southwestern region of the State of Tocantins, Formoso do Araguaia, Lagoa da Confusão, Cristalândia, Dueré, and Pium municipalities are responsible for 96% of the rice produced in the state, according to Conab (2019). This region is considered one of the most promising for the expansion of irrigated rice in tropical Brazil. As an example of the potential of the region for irrigated rice expansion, the Javaés valley, an immense lowland area between the Araguaia and its tributaries, Urubu, Javaés, and Formoso, with more than 500 thousand ha, considered the largest contiguous area used for gravity irrigation in the world. Rice production in Tocantins lowlands is strategic for the diversification of the food supply and to ensure food security, as currently, 81% of the production of rice comes from the states of SC and RS (Embrapa Arroz e Feijão, 2019).

The irrigated rice chain plays an important role in generating foreign exchange and jobs for the state of Tocantins (Fragoso et al., 2013). During the dry season, the absence of rain, combined with low relative air humidity and low night-temperatures, form an unfavorable environment to the incidence of fungal diseases, being these areas are used chiefly by soybean producers to obtain seeds of good physiological and sanitary quality (Pelúzio et al., 2010; Almeida et al., 2011). Since 2006, the state of Tocantins has growing soybeans in the sanitary break. This permission, granted by the Ministry of Agriculture, Livestock and Supply, respects the climatic and territorial conditions found in the municipalities of Lagoa da Confusão, Dueré and Formoso do Araguaia (Arruda et al., 2016).

It was verified that in the tropical region the average yield in flooded rice is lower than that obtained in subtropical ones. This is usually the result of the harmful effects of certain biotic and abiotic factors on the crop. As biotic factors, we can cite the high incidence of fungal diseases, such as blast (Magnaporthe oryzae), pest insects, such as stink bugs (Oebalus spp.) and weeds, markedly *Aeschynomene spp*, Barnyard grass (Echinochloa spp.), Cyperus spp. and weed rice (Oryza sativa) (Santos, 2004).

As abiotic factors, thermal stresses may be negatively affecting grain yield, due to the elevation of the temperature of the water used for irrigation which, at certain times, reaches high values causing stress on rice plants (Santos et al., 2003). Besides, lower yield in tropical conditions can also be attributed to the reduction of the crop cycle and the lower response to fertilizers, especially nitrogen (N) (Santos, 2004).

In the tropical lowland ecosystem soils of different classes are predominant. Managements that preserve the soil and water must be performed in these systems, with minimal degradation of the environment, which means that future agricultural systems must be economically viable, ecologically sustainable, and socially and politically acceptable (Fageria et al., 1999).

7.1. Water management

In regions in which irrigated rice is predominant, such as in the South of Brazil, the management of irrigation with continuous flooding, without intervals of oxidation, is among the techniques necessary to achieve high yield in the rice paddy. However, in the tropical region, the difference in soil, especially its permeability, climate, and diversity of attributes of water basins, particularly due to the seasonal alteration of the water table, hinder its adoption (Santos et al., 2015).

In Tocantins state, the temperature of irrigation water frequently reaches values above 35 ºC, rising to 52 ºC. As an alternative to continuous flood irrigation, intermittent flood irrigation management is effective in minimizing thermal stress caused by maintaining the water layer on the soil surface. Intermittent flooding can also contribute to reduce greenhouse gas emissions and increase water use efficiency (WUE) (Tarlera et al., 2016).

The continuous flooding of the soil affects its physical attributes, causing soil compaction by increasing its density and reducing macroporosity and total porosity (Mentges et al., 2013). These conditions are unfavorable to the development of most grain crops. Furthermore, although the decomposition of organic residues in anaerobic soils is slower than in aerobic ones (Kögel

- Knabner et al., 2010), soil disruption can accelerate losses of soil organic carbon and N associated with soil organic matter. Therefore, intermittent flooding is also an option to improve soil quality and favor the cultivation of mesophyte species, such as soybeans, in the off-seasons.

In a study carried out in the municipality of Dueré, Tocantins state, for two consecutive growing seasons, Santos et al. (2003) found that the maintenance of saturated soil, but without the formation of the water layer, during the whole development cycle or until flowering resulted in greater grain yield, compared to continuous flooding throughout the cycle or until the panicle differentiation (R1), while taller plants were found under continuous flooding conditions throughout the development cycle and higher milling and whole-grain yield are attained by this management.

Also in the tropical region, in Goianira, Goias state, it was found that the absence of the water layer throughout the season provided grain yield equivalent to that obtained with continuous flooding, which resulted in higher water use efficiency (WUE). The water volume irrigated was 30% and 63% lower in intermittent flooding and saturated soil management, respectively, compared to the continuous flooding. As a result, WUE went from 0.28 in the continuous flood management to 0.46 kg of grains m^{-3} of water in the saturated soil, considering the rain that occurred in the period, and from 0.44 to 1.13 kg of grains m^{-3} irrigated water, respectively. The larger water demand verified under continuous flooding was due to the greater losses resulting from percolation and lateral flow, which, in turn, results from the high sand content of the soil, around 50%.

The highest WUE due to intermittent flooding, however, is conditioned by the adequate time interval between the disappearance of the water layer from the paddy and its replacement. Medeiros et al. (1995), in Roraima, compared continuous flooding, intermittent flooding, soil saturation, and combinations of these irrigation systems. The authors found that the most efficient system, with the lowest pumping cost, was the intermittent flooding throughout the development cycle, with soil humidity equivalent to matrix potentials between -20 and -40 kPa and an average watering shift of four days.

The duration of the soil drying in intermittent flooding is the most important factor that affects the yield. Moderate intermittent flooding, in which photosynthesis is not inhibited during the soil drying period and plants can rehydrate at night, provides not only water saving (23.4 to 42.6%) but also increases grain yield from 6.1 to 15.2% and WUE from 27 to 51%, compared to continuous flooding (Yang et al., 2017). According to these authors, for it, water replenishment must be done at a soil water potential of -10 to -15 kPa or in a leaf water potential at noon of approximately -0.60 to - 0.80 MPa, or the water table kept 10 to 15 cm below the surface of the soil.

Moderate intermittent flooding can improve the grain quality, reduce the accumulation of arsenic (As) in the grains and reduce the emission of CH_4, thus decreasing the global warming potential and the intensity of greenhouse gases. However, a severe regime of intermittent flooding, in which photosynthesis is severely inhibited during the period of soil drying and plants cannot rehydrate overnight, can dramatically reduce grain yield and quality, although it has the potential to increase the WUE and reduce CH_4 emissions when compared to continuous flooding (Yang et al., 2017).

7.2. Nitrogen management

For the conservation and sustainability of crops yield, appropriate soil fertility management is an important practice, including the nitrogen (N), which is one of the most important management practices among the techniques necessary to achieve high yield potential in the irrigated rice paddy. N is the nutrient of the greatest metabolic demand for plants, and its deficiency is usually a limiting factor for the growth of crops. N is a component of chlorophyll, affects the expansion of the plant leaf area, which increases the efficiency in the interception of solar radiation and the photosynthetic rate and, consequently, the grain yield (Fageria & Stone, 2003). N has extremely complex dynamics in the rice paddy, with great variability in its chemical forms, due to the water content of the soil (aerobic or anaerobic conditions), which directly reflects in the efficiency in the use of the nutrient by the plants.

The deficiency of N in irrigated rice is frequently observed in tropical lowland soils. Among the main reasons for its occurrence are losses resulting from various processes, such as the volatilization of ammonia in the soil, the gas losses of nitrogen oxides (NO_2, N_2O, NO) and elemental nitrogen (N_2), nitrate leaching in the soil out of the reach of the root system and losses of NH_3 by the plants (Fageria & Baligar, 2005), and the decrease in the organic matter content, as a result of successive cropping (Munda et al., 2018).

The nitrogen use efficiency in rice is around 30-35%, whereas approximately 50% of N is lost to the environment (Zhu & Chen, 2002). The apparent recovery efficiency of nitrogen fertilizer (the percentage of fertilizer N recovered in the above-ground vegetable biomass at the end of the growing season) is only 33% on average (Yang et al., 2017). In this scenario, the adoption of technologies based on intermittent flooding could reduce the accumulation of N in plants while enhancing the nitrogen use efficiency by stimulating its losses by the increase of ammonia volatilization, nitrification, and denitrification (Rhine et al., 2011).

Most of the soil's N is found in organic forms, which must be mineralized to allow its release and make it available to plants.

Therefore, it is not possible to determine a calibration curve for this nutrient. For the recommendations of N for irrigated rice in subtropical regions, soil organic carbon is used as an indicator of nutrient availability and based on the expectation of a response to the fertilization (Scivittaro & Gomes, 2006). In tropical regions, the local recommendation for nitrogen fertilization of irrigated rice has been the application of part of the N in the furrow at the time of sowing and part of it in top dressing.

There is a risk of supplying the nutrient in an inadequate quantity and outside the season of greatest demand on the plant in the tropical region, due to the common practice of presetting doses and times of application of N. For a better adjustment between these periods, the monitoring of N in the leaf and chlorophyll levels has been suggested as an alternative to conventional methods for this diagnosis.

In studies carried out in tropical regions by Santos et al. (2017), the stages in which the N Sufficiency Index values (NSI) obtained with the use of the chlorophyll meter indicated that the need for the first application of N was at V3 - V4, preceding or at the beginning of tillering, and the second application of N was V7 - V8, that is to say, on the occasion of effective tillering, were defined according to the scale of Counce (2000).

The lack of synchronism between the time of the nitrogen top dressing and the time of the largest demand for N by the plants results in a low nitrogen recovery efficiency by irrigated rice in tropical Brazil. Because it is predefined, the dose of N used can be under or overestimated. This can lead, on the one hand, to a decrease in grain yield, and on the other hand, to an increase in costs due to the unnecessary use of fertilizers, which, in its turn, leads to a decrease in the farmer’s profit, in addition to negatively impacting the environment resulting from the nitrate leaching, greater greenhouse emission gases from the denitrification process, which means a risk of environmental pollution. For better adjustment between these periods, the monitoring of leaf N and chlorophyll content has been suggested as an alternative to conventional methods for this diagnosis.

The use of the chlorophyll meter, portable equipment that provides readings (SPAD units), which correspond to the content of pigment present in the leaf and has been used to estimate the leaf N content, since chlorophyll and N correlate positively in the same crop (Turner & Jund, 1991; Carvalho et al., 2012; Pocojeski et al., 2012) as well as to grain yield. The use of the chlorophyll meter is a handy alternative to conventional methods for defining the need for N in irrigated rice in tropical lowlands.

It is possible to sustain long-term production in tropical lowlands with minimal environmental degradation. Growing rice sustainably means reducing costs and avoiding waste of energy and raw materials. It means increasing productivity, the competitiveness of capital, and labor and opening new markets, creating quality jobs, and increasing profitability.