Improving the Drainage and Irrigation Efficiency of Lowland Soils: Land-Forming Options for Southern Brazil

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Abstract: Land leveling is used to correct soil surface irregularities to improve surface drainage and irrigation. It also makes the area more manageable for an array of agricultural activities such as planting and harvesting. The objective of this work was to evaluate two designs of land forming, one aimed at optimizing drainage and the other at optimizing surface irrigation, using fields with reliefs typical of the lowlands of southern Brazil. Seven commercial rice fields, ranging in size from 7 to 26 ha, were randomly selected and digital elevation designs generated for each. Land-leveling projects were developed using three designs: uniform slope (US) (control), land forming–drainage (LFD), and land forming–irrigation (LFI). Performance comparisons between the designs were evaluated through impacts on soil movement (SM), maximum cut in 99% of the area (MC), cumulative length of levees (LL), and total number of levees (NL). Results indicate that both LFD and LFI designs would reduce costs and require less soil disturbance compared to leveling to uniform slopes. LFD would require less soil movement and lower maximum cuts than LFI. However, LFI would reduce the lengths and numbers of rice levees that could have long-term economic and agronomic benefits not captured in these analyses. These results demonstrate that all land-leveling and land-forming alternatives should be thoroughly examined before undertaking field operations. Study outcomes will be useful to engineers and producers in evaluating options to improve the agricultural productivity of lowlands in southern Brazil, a region of national and international significance. **DOI: 10.1061/(ASCE)IR.1943-4774.0001483.**

Author keywords: Land forming; Land leveling; Surface irrigation; Drainage; Lowland soils; Global navigation satellite systems.

Introduction

The lowlands of southern Brazil cover approximately 3 million ha and are of national and international significance because of their use in producing rice (*Oryza sativa* L.) and beef cattle (*Bos taurus*) (Theisen 2017). These lands are predominantly flat and feature relatively shallow topsoil with high bulk densities (Lima et al. 2009), low hydraulic conductivities, and impermeable subsurface soils. Thus, poor natural drainage is a key characteristic of this lowland agroecosystem (Parfitt et al. 2017) that has made it favorable for rice production for more than a century (Theisen 2017).

Recently, issues such as weed resistance to rice herbicides and the nonproductive fallowing of cropland that is commonly practiced in Brazil's lowlands have producers and agricultural specialists seeking new cropping options (Theisen et al. 2017; Neto et al. 2019). Broader incorporation of soybeans [*Glycine max* (L.) Merr.] and/or maize (*Zea mays* L.) into the rice rotation would diversify the economic and agronomic options of the region. However, these crops are prone to injury resulting from both waterlogging (Linkemer et al. 1998; Scott et al. 1989; Wenkert et al. 1981; Sartori et al. 2016) and drought stress (Heatherly and Spurlock 1993; Schoper et al. 1986). Thus, successful adoption of alternative agronomic crops into rice cultivated under lowland conditions requires that both drainage and irrigation issues be successfully addressed.

Land leveling is used to correct irregularities in soil surfaces to make agricultural activities such as suface drainage and irrigation more efficient (Walker 1989). Leveling improves water transport and distribution (Enciso et al. 2018), facilitating the use of water-conserving practices such as multiple-inlet rice irrigation coupled with intermittent flood management (Massey et al. 2014). Improved drainage can improve the timeliness of rice planting (da Rocha et al. 2017) and also benefits soybean cultivation by fostering furrow irrigation. Furrow irrigation is the primary means by which soybeans are irrigated the Mid-South (Heatherly 1999),

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a region in the southern US with similar humid subtropical climate, topograhpy, and soils as southern Brazil. Thus, leveling may constitute a viable practice to improve surface drainage and irrigation in the lowlands of southern Brazil (Winkler et al. 2018), fostering broader rotational options for producers.

Caution must be used, however, in applying the practice because leveling that results in cuts exceeding 10-cm in shallow soils may cause problems (Cazanescu et al. 2010; Aquino et al. 2015), such as impaired soil fertility (Walker et al. 2003), increased compaction (Brye et al. 2005), and changes in microbial community structure (Brye et al. 2006). Additionally, at current leveling costs of approximately USD 1 per cubic meter in southern Brazil, extensive soil movement makes leveling uneconomical.

Prior to the development of global navigation satellite systems (GNSS) using real-time kinematic (RTK) correction, uniform slope (US) leveling was the most common leveling technology available to producers to help address drainage and surface irrigation issues (Mandal and Maity 2013). With GNSS-RTK, it is theoretically possible to impose essentially any type of surface on a field because of the high precision (e.g., ± 1 cm in x-, y-, z-directions) of this technology (Santos et al. 2017).

Leveling that results in multiple slopes within the same area is called land forming. It may result in less soil disturbance and lower overall costs than conforming land to a uniform slope (Parfitt et al. 2017). Land forming is an option for improving drainage and irrigation management in the poorly drained lowland soils common to the state of Rio Grande do Sul (RS) in southern Brazil. However, this practice is relatively new to RS and its potential to cause excessive costs and negative impacts requires careful study prior to more widespread adoption.

The objective of this research was to assess the effectiveness and appropriateness of land forming for drainage (LFD) and land forming for irrigation (LFI) designs when applied to fields typical of southern Brazil lowlands. The metrics of interest were the volumes of soil moved, maximum cuts in 99% of the leveled area, and the cumulative lengths and total numbers of levees that would result from these alternative designs relative to leveling to a US.

Materials and Methods

Seven experimental areas in the southwestern coastal region of RS were investigated. This region is predominantly flat with surface roughness at the microrelief level (Munareto et al. 2010). The areas investigated were commercial, irrigated rice fields ranging in size from 7 to 26 ha having slopes that ranged from 0.08% to 0.24%. A planimetric survey of each field was conducted using a tractor equipped with a monitor and GNSS receiver antenna with RTK base station (Aziz et al. 2009; Bueno et al. 2019). The resulting elevation data were processed using WM-Form software to generate a digital elevation model (DEM) for each surface. Both LFD and LFI designs were applied to each field. The US designs were used as controls. Traditionally, US designs represent the best option for land leveling when using laser technology (LT). However, the LT system allows for leveling in only one plane; this is true whether or not slope is applied to the leveled area.

The calculations for each of the three leveling designs were performed using WM-Form software using a cut/fill ratio of 1.2 (Gamero and Benez 1989). These calculations were performed using 3-m grids and a balanced-soil movement criterion. The US designs were calculated using the land leveling mode of WM-Form using the "Best Fit All Now" procedure. The procedure minimizes the amount of soil required to make the original field surface into a flat plane.

The LFD designs were obtained using the drainage mode of WM-Form. Three minimum field slopes (MSs) were employed: 0.025%, 0.05%, and 0.1%. These designs allowed variable slopes, meaning that after land forming, the resulting slope may vary in magnitude and direction. However, the slope always followed the original direction of water flow, causing any surface depressions to disappear.

The LFI designs were also executed with varying slopes in different directions and magnitudes. However, LFI differs from LFD design in that slopes occur in the direction of water flow in a preestablished manner. This allows the surface application of irrigation water via furrow irrigation, which has been adopted to allow the cultivation of soybean and maize in rotation with rice. This design was generated in the subdesigning areas mode and allows the user to choose the direction and the minimum magnitude of a preset slope. As with the LFD designs, MSs of 0.025%, 0.05%, and 0.1% were employed. The direction of the preestablished slope was chosen using the value obtained from the "Best Fit All Now" of the US design.

The US (control), LFD, and LFI leveling designs were compared using the following parameters required to achieve the land-leveling or land-forming design: amounts of soil movement (SM) (m^3 ha^{-1}); maximum cut in 99% of the area (MC) (cm), total length of levees (LL) (km), and number of levees (NL). The levee designs assumed an equipment turning radius of 7 m because this was the most common value for rice fields when using the GNSS-RTK system. The SM and MC variables were obtained directly from the WM-Form software.

Values related to LL and NL were estimated using Farm Works Office software. Preleveling values for the original field conditions were determined by importing the DEMs directly into Farm Works Office. Post land-leveling or land-forming values were obtained by importing project DEMs generated in WM-Form into Farm Works Office. Once the levee designs were elaborated using the preceding criteria, values for LL were provided by Farm Works Office; NL values were obtained simply by counting the number of levees associated with each design.

The different model designs were compared using analysis of variance of the variables SM, MC, LL, and NL. Comparisons among treatment means were made using the Tukey test at $\alpha = 0.05$. These analyses were performed in the R statistical environment.

Results and Discussion

Experimental Areas

Preleveling characteristics of the seven fields are given in Table 1. There was an average LL of 8.50 km when the fields were

Table 1. Original surface characteristics of unleveled, lowland rice fields located in Rio Grande do Sul, Brazil

Field	Area (ha)	Average slope (%)	DBH (cm)	LL (km)	NL	AD (ha)	ND
1	13.09	0.08	40	8.04	32	1.15	7
2	25.97	0.08	55	12.69	55	3.13	15
3	25.99	0.09	55	11.43	37	0.89	14
4	6.67	0.24	40	6.35	35	0.34	9
5	6.97	0.17	40	4.49	24	0.35	9
6	23.34	0.17	55	7.41	42	1.71	16
7	16.31	0.15	55	9.03	41	3.62	5
Mean	16.90	0.14	—	8.50	38	1.60	10.7

Note: DBH = depth of B horizon in relation to the soil surface; LL = cumulative lengths of levees; NL = total number of levees; AD = total area of surface depressions; and ND = total number of depressions.

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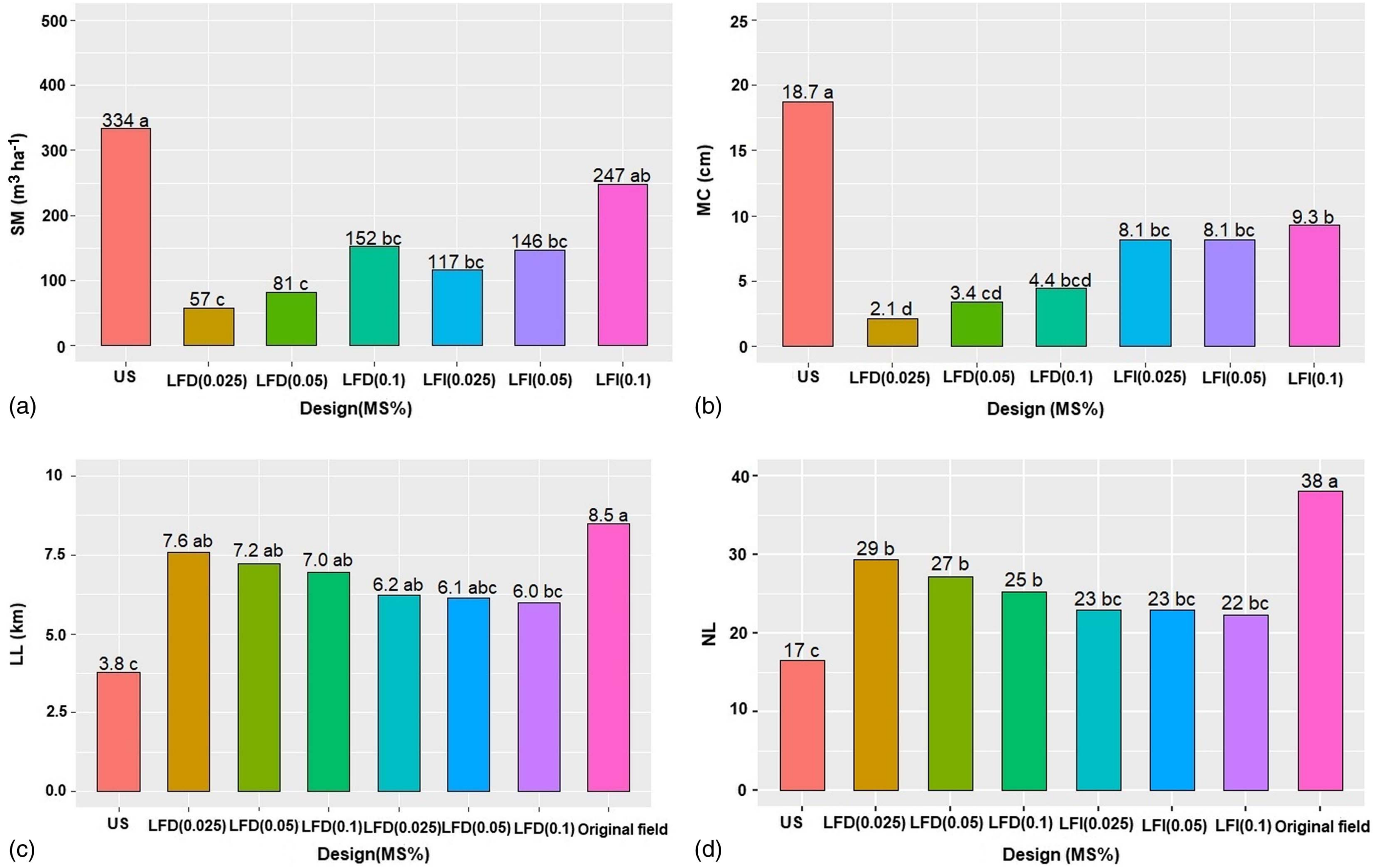

Fig. 1. Statistical comparisons of three land-leveling model designs (US, LFD, and LFI) and field slopes (MS = 0.025%, 0.05%, and 0.1%) applied to seven rice fields located in Rio Grande do Sul, Brazil: (a) estimated amounts of soil moved ($m^3\,ha^{-1}$); (b) estimated maximum cut in 99% of field (cm); (c) estimated cumulative length of levees (km); and (d) estimated total number of levees. Means followed by same letter are not different ($\alpha = 0.05$) according to the Tukey test.

demarcated using a 5-cm contour. Such an interval is typical for the RS lowlands. The maximum and minimum LL values were 12.69 (Field 2) and 4.49 km (Field 5), respectively. NL averaged 38 and ranged from a minimum of 24 (Field 5) to a maximum of 55 (Field 2). The area of depression (AD) averaged 1.60 ha and ranged from 0.34 ha (Field 4) to 3.62 ha (Field 7). The number of depressions (ND) averaged 10.7 and ranged from 5 (Field 7) to 16 (Field 6).

Fields 1, 4, and 5 are composed of Typic Albaqualf soil (USDA NRCS 2014) of loam textural class, pH 5.2, 7.0 $g\,kg^{-1}$ organic C, 4 $mg\,kg^{-1}$ available P, and Ca, Mg, K, Na, and Al at 2.4, 1.1, 0.25, 0.6, and 2.9 $cmol_c\,kg^{-1}$, respectively. Fields 2, 3, 6, and 7 are composed of Argioquoll soil (USDA NRCS 2014) of sandy loam textural class, pH 5.9, 9.4 $g\,kg^{-1}$ organic C, 3 $mg\,kg^{-1}$ available P, and Ca, Mg, K, Na, and Al at 8.8, 0.1, 0.2, 0.0, and 3.7 $cmol_c\,kg^{-1}$, respectively. Typic Albaqualf soils comprise approximately 54.3% of lowland soils in southern Brazil (Pinto 2004). As previously indicated, the poor drainage associated with these soils poses a challenge for soybean and maize production (Sartori et al. 2016).

Leveling to US

As would be expected, the US designs had higher SM and MC than both the LFD [Fig. 1(a)] and LFI [Fig. 1(b)] designs. Although the soil movement estimate of the US did not differ statistically ($\alpha = 0.05$) from the LFI with 0.1% slope, US resulted in lower LL and NL than the other designs and, obviously, the original areas [Figs. 1(c and d)]. Levee lengths did not differ from LFD in MS by 0.05% and 0.1%, respectively [Fig. 1(c)]. Fig. 1(d) shows that there was no difference between US and LFI in NL; this is explained by the high variability of the results obtained for this variable. The average SM was 334 $m^3\,ha^{-1}$ and the average MC was 18.7 cm. Four of seven fields exceeded the 15-cm maximum cut depth. The maximum SM was 623.4 $m^3\,ha^{-1}$ (Field 7) and the minimum was 207.8 $m^3\,ha^{-1}$ (Field 2). The largest MC was 28 cm (Field 7), while the lowest was 13 cm (Fields 2 and 5). Thus, both SM and MC associated with the US design were excessive given the soils of the region (Reichert et al. 2008; Parfitt et al. 2014). These data indicate that US leveling would often result in designs that are neither agronomically nor economically viable for the lowlands of southern Brazil: Agronomically because cuts greater than 5 cm can negatively influence rice yield (Winkler et al. 2018) and economically because large SM would make leveling operations more costly as well as require more time to complete. The latter aspect is important because soils in southern Brazil are often sufficiently dry for a limited period of time, usually only between 3 and 5 months in duration.

In relation to the length of levees, the average LL in the original areas was 8.50 km (Table 1) versus 3.8 km after leveling [Fig. 1(c)]. The average NL also decreased from 38 (Table 1) to 17 [Fig. 1(d)]. The levees were straight rather than crooked because the final surface had a uniform slope. For rice-producing areas in South America, rice levees are often only about 18 cm tall. This allows the levees to be sown with rice and mechanically harvested without impediment. Thus, the advantage of leveling is not only that the

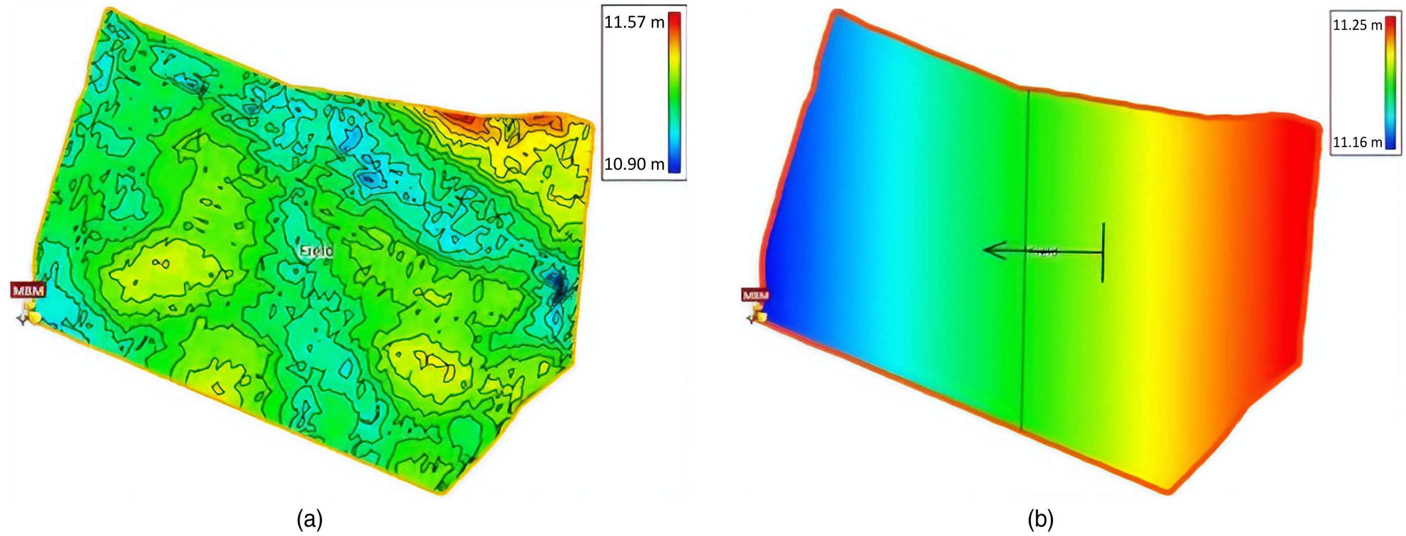

Fig. 2. Digital elevation models of Field 1 (a) before; and (b) after land leveling using the uniform slope model. Each figure is shown using 5-cm contours. MBM = master benchmark.

levees are straight but also that the total length of levees is less. This would translate into reduced input costs (e.g., fuel, labor) for the producer. For example, Bochtis and Vougioukas (2008) report that use of autopilot in the GNSS-RTK system increased operational efficiency and accuracy, facilitating the construction of rice levees in a timely manner.

Fig. 2 depicts Field 1 in its original form and after land leveling using the US design. In Fig. 2(a), surface irregularities at the microrelief level are apparent. These are a characteristic of the RS lowland areas where leveling may be viable (Bitencourt et al. 2016). The locations of depressions where surface water storage occurs after intense rainfall (Winkler et al. 2018) are also visible as indicated in the isolated areas (where the contours are polygons) with low altimetry (ponding areas). Fig. 2(b) shows only one contour line because the difference between the highest and lowest points was less than 9 cm. This resulted in levees that coincided with the contour line.

LFD Design

LFD design results are depicted in Fig. 1, where the average values of each variable are presented for each of the three slopes evaluated. Average SM values were influenced by the MS employed and range from 56.8 $m^3\ ha^{-1}$ (MS = 0.025%) to 152.2 $m^3\ ha^{-1}$ (MS = 0.1%). Depressions in agricultural soils increase the accumulation of surface water (Liu and Singh 2004). Therefore, the criterion of MS is of great practical significance because it determines if superficial water storage is eliminated for slope(s) that always follow the direction of water flow. Surface depressions created during soil formation contribute to drainage issues common throughout the RS lowlands (Pinto 2004). Winkler et al. (2018) verified that slopes of 0.1% greatly improve surface drainage in lowland areas when applied to the total area of land-leveled crops.

The value of minimum slope influenced SM and MC, which in turn impacted costs and soil degradation [Figs. 1(a and b)]. Thus, each land-forming project using the LFD design must be carefully examined because these values are highly variable. For example, there are cases where even using a slope of 0.1%, the volume of soil moved and maximum cut are quite small. This occurred in Fields 5 and 6 where the average MC values increased with minimum slope and ranged from 2 cm at 0.025% slope to 4 cm at 0.1% slope [Fig. 1(a)]. These values did not differ at the 5% level. Thus, unlike those of the US design, the LFD MC values were acceptable for these soils (Parfitt et al. 2004). Regarding the performance of the LFD design on LL, it was found that the average difference between an MS of 0.025% and 0.1% was 0.4 km. This shows that there was no great influence of slope on the cumulative length of levees. The average NL obtained in the original area was 38 (Table 1) but only decreased to 29 and 25 for MS values of 0.025% and 0.1%, respectively [Fig. 1(c)].

The topography of Field 1 is shown in Fig. 3. Fig. 3(a) shows the contour lines generated using the LFD design and 5-cm contours. Compared to the original surface shown in Fig. 2(a), the contour lines in Fig. 3(a) are smoother and fewer in number and overall length. Internal depressions disappeared completely so that low areas remained only at field boundaries. If depressional areas remain in this subarea, land forming should be recalculated using another slope that eliminates the depressions. The tool used by the software is known as the activity area. The LFD design would cause surface runoff to occur toward the field boundaries and would improve the field performance because surface water storage impedes many agricultural activities (Borselli and Torri 2010). In addition to eliminating field depressions, the LFD design would reduce the total number of levees required for rice irrigation [Fig. 3(b) versus Fig. 3(c)], which consequently should lower labor and other costs associated with rice production (Frantz et al. 2015).

Land forming using the LFD design would not result in significant changes in the location of surface drainage outlets (Fig. 4). Fig. 3(a) shows the original outlet locations, while Fig. 4(b) shows the surface drains after LFD application whose location was based on water flow lines and an assumed 7-m turning radius of the tractor-scraper equipment. Figs. 4(c and d) depict the elevation profiles for the outlets indicated by black circles in Figs. 4(a and b), respectively. The profile in Fig. 4(d) shows that the LFD design smoothed the slope leading to the outlet so that water flow off the field is more effective.

LFI Design

As with the LFD design, MS is important in terms of drainage, but it also plays an important role in terms of irrigation because

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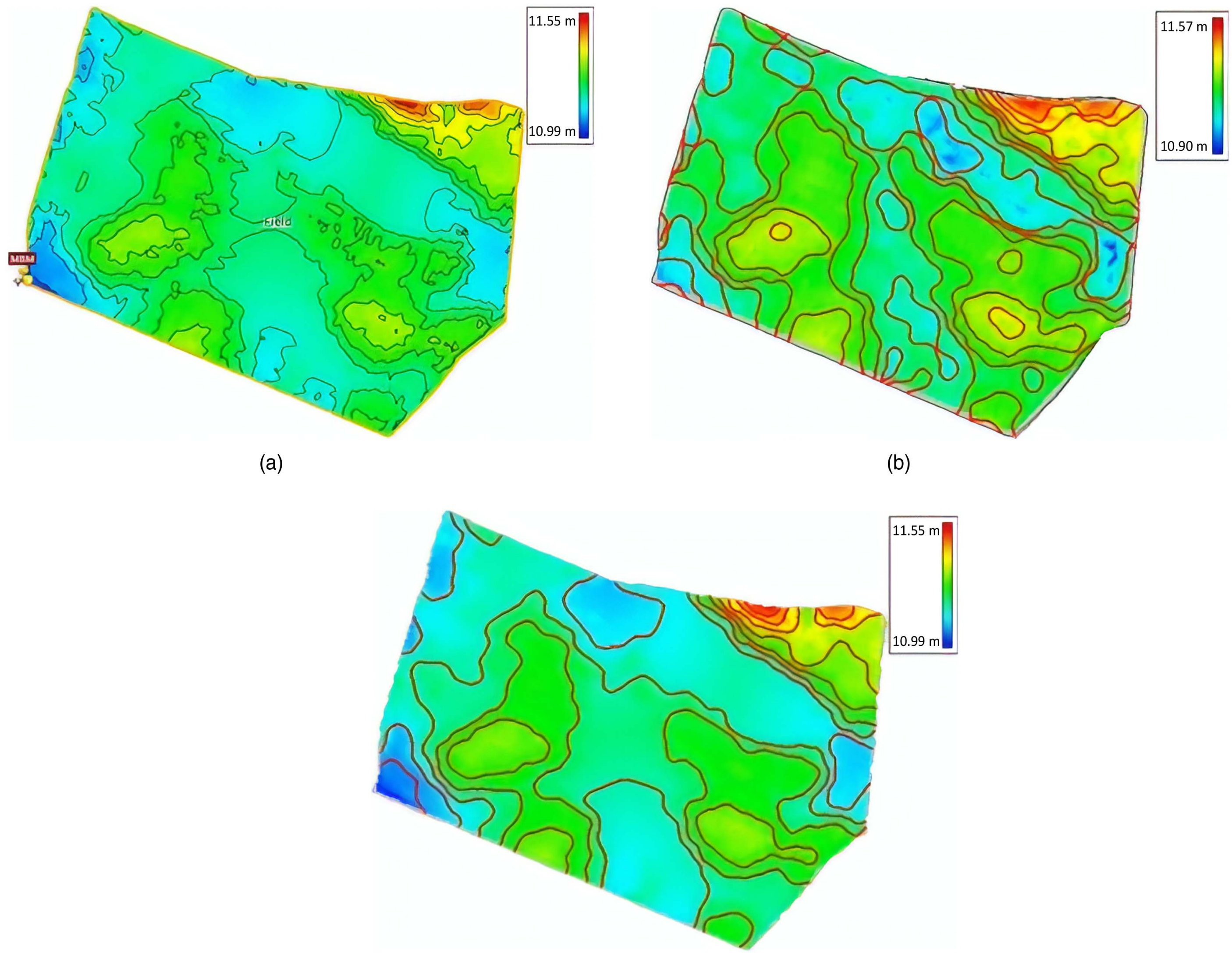

(a) (b) (c)

Fig. 3. Digital elevation design of Field 1 and its contour lines with 5 cm of vertical difference between them (a) after land forming using LFD; and the levees (b) before and (c) after the application of the LFD design. A minimum slope of 0.05% was used. MBM = master benchmark.

land forming to zero slope is not suitable for furrow irrigation (Lima 2015). Thus, as a general rule, zero-grade leveling can be problematic for rice–soy rotation systems. The results in Fig. 1(a) depict how MS influences SM, showing that as slope increased there was a concomitant increase in the amount of soil moved. Here, SM was 116.6 and 247.1 $m^3 ha^{-1}$ at 0.025% and 0.1% slope, respectively. Additionally, at locations where the slope was lower but in the same direction as that of the project design, the original slope was changed to the MS value. Regarding the average values for MC [Fig. 1(b)], these ranged from 8.1 cm when using MS values of 0.025% and 0.05% to 9.3 cm at 0.1% slope. Thus, in contrast to what occurred with SM, the MC did not change ($\alpha = 0.05$) with increasing MS [Fig. 1(b)].

Using the LFI design, LL was reduced when compared to the original area (Table 1), with a mean reduction greater than 3 km. The difference between the highest and lowest LL values was a function of MS and was found to be 300 m. From a practical viewpoint, this did not represent a significant reduction in length. In relation to the NL, the LFI design reduced the levee number by approximately 16 when compared to the original surface conformations. The spatial behavior of the levees after the application of the LFI design is given in Fig. 5. Compared with the original [Fig. 3(b)], there was notable change. SM was largest in Experimental Area 1, which is further demonstrated by the behavior of the levees, assuming intermediate behavior between the US and LFD designs [Figs. 2(b and c), respectively].

LFD and LFI Design Comparisons in Relation to Soil Movement and Maximum Cut

The US land-leveling design resulted in an average SM of 334 $m^3 ha^{-1}$ and MC deeper than 18 cm [Figs. 1(a and b)]. Such soil movement raises the cost of leveling, while cutting of more than 18 cm often causes crop productivity issues (Aquino et al. 2015; Cazanescu et al. 2010; Winkler et al. 2018). The LFD design resulted in less soil movement than the LFI design. The SM values of the LFD design for the minimum slopes of 0.025%, 0.05%, and 0.1% were 56, 81, and 152 $m^3 ha^{-1}$, respectively. For the LFI design, considering the minimum slopes of 0.025%, 0.05%, and 0.1%, SM values were found to be 116, 160, and 247 $m^3 ha^{-1}$,

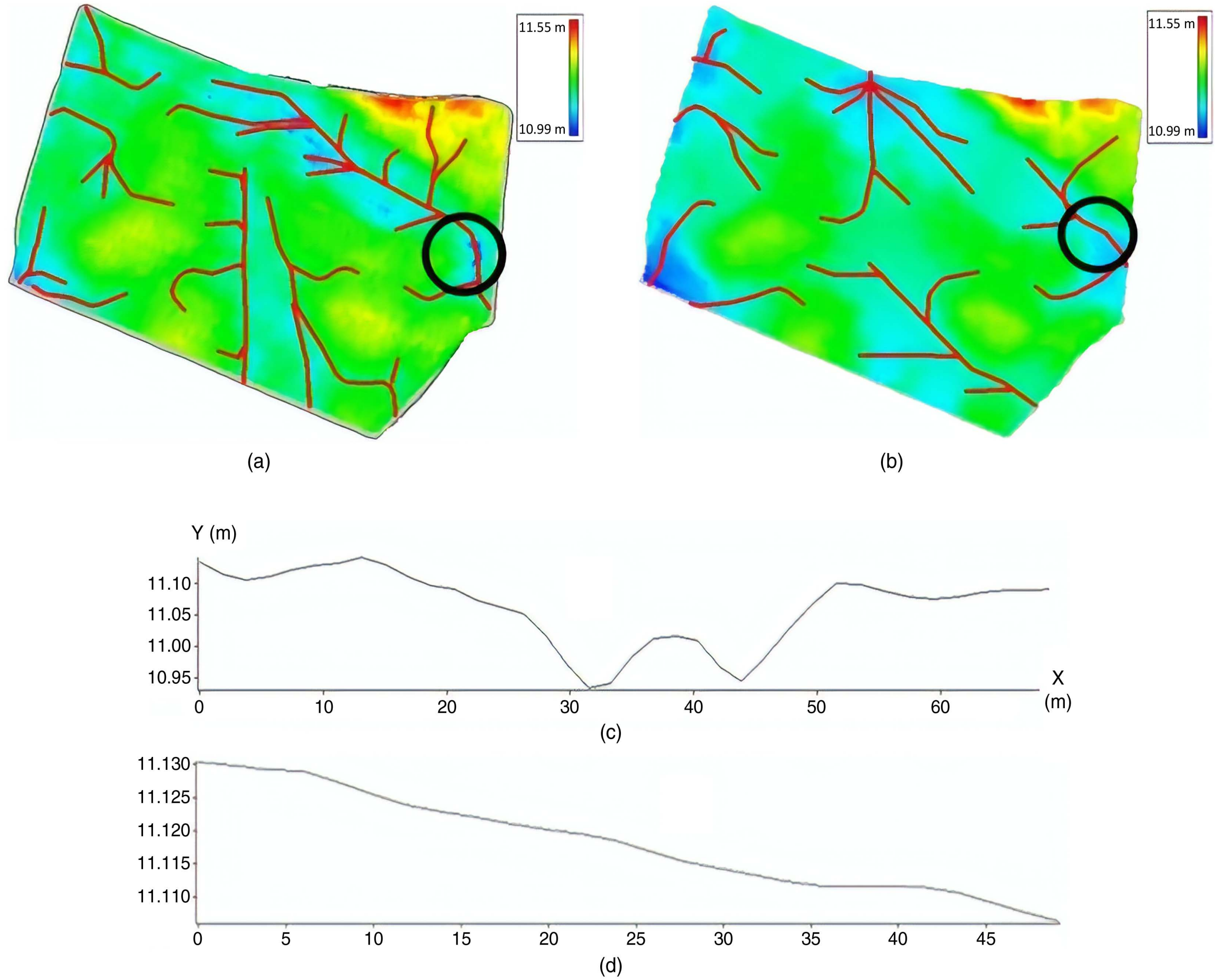

Fig. 4. Digital elevation designs and drainage networks for Field 1: (a) original field; (b) LFD design; and corresponding profiles at points indicated for the (c) original field; and (d) LFD design. A minimum slope of 0.05% was used.

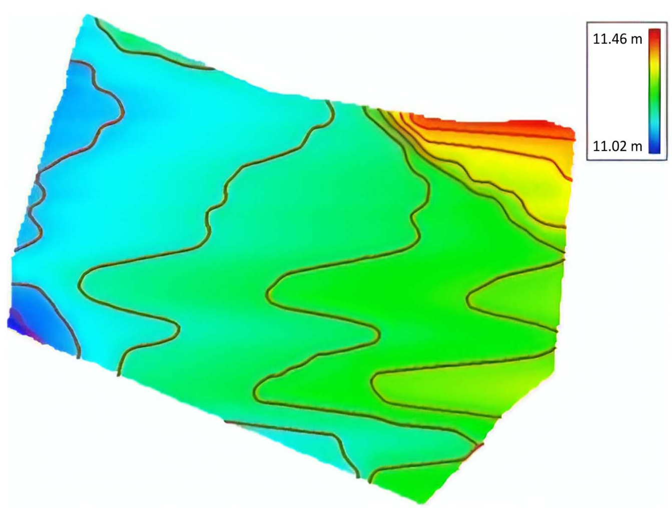

Fig. 5. Digital elevation design of Field 1: LFI design and levees with 5 cm of difference between levees for minimum slope of 0.025%.

respectively [Fig. 1(a)]. In relation to the MC, the LFD design produced lower values than the LFI design [Fig. 1(b)]. These values depended heavily on the original soil surface conformations of each field.

LFD and LFI Design Comparisons in Relation to Levee Lengths and Numbers

The performance of the US design [Figs. 1(c and d)] in relation to LL and NL presented a satisfactory result, shown by the mean LL values decreasing from 9.5 to 3.8 km and NL from 38 to 16 levees. Thus, it can be inferred that the US design, in relation to surface area, is the best fit. However, this design becomes problematic when considering the cost and degradation of the soil, as previously mentioned.

In relation to LL and NL, the LFI design presented better overall performance, with the lowest LL value of approximately 6.0 km compared to approximately 7.5 km for LFD [Fig. 1(c)]. A similar trend was observed for NL, showing 22 levees for the LFI design and 28 levees for LFD [Fig. 1(d)]. As was seen with SM and MC, each field has unique features that must be considered. Thus, all possible alternatives should be thoroughly examined when considering land forming or land leveling.

Conclusions

With the advent of GNSS-RTK technology, producers have options to improve drainage and irrigation distribution in lowlands typical of southern Brazil. Study results demonstrate that all possible alternatives should be examined thoroughly before undertaking land-leveling or land-forming operations. Both LFD and LFI designs are expected to be less disruptive than US leveling in terms of maximum soil cut depths and amounts of soil moved. In general, the LFD design would require less soil movement and smaller maximum cuts when compared to LFI. However, in terms of levee lengths and numbers, the LFI design offers better performance than LFD. Over time, LFI design reductions in energy and labor costs associated with levee construction as well as its fostering adoption of improved furrow-irrigation practices could help offset initial earth-moving costs relative to LFD. Future research should aim to compare the overall economic benefits and potential trade-offs of LFI used in a rice–soy–maize rotation using furrow irrigation versus more conventional LFD designs. Should producers wish to apply the results of this project on their farm, the first step is to create an accurate digital elevation model for the field(s) using GNSS-RTK. Next, the models and methods described would be performed and compared in terms of the estimated costs and benefits. Consultation with experienced extension or technical staff is highly recommended.

Data Availability Statement

Some or all digital elevation models and project models generated in the paper are available from the corresponding author by request, including data for the DEMs of all fields; the uniform slope, land forming for drainage, and land forming for irrigation projects of all fields; the levees and drainage projects of all fields; and the table with amounts of soil movement ($m^3\ ha^{-1}$); maximum cut in 99% of the area (cm), total length of levees (km), and number of levees data of each field for the graphs generation.

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