Sustainability of Irrigation Fruit Farming in Terms of Water Supply-demand Situation: Case Study of the Middle Basin of São Francisco River, Northeast Brazil

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Abstract This study intended to consider the sustainability of irrigation fruit farming in terms of water supply-demand situation from the viewpoint of tolerance to drought events in Petrolina and its surrounding area in Brazil, where large-scale irrigation projects have been developed for semi-arid regions. Based on the field survey, we analyzed the actual situations of water intake and distribution on the water supply side and irrigation agriculture on the water demand side. The decrease in water resources in this region in recent years has been dramatic. However, this study revealed that the irrigation fruit farming in this region has managed to sustain itself without decreasing the area of cultivation and the harvest of produce even under the water shortage scenario of recent years. The biggest reason for this is the introduction of water-saving irrigation systems in this region in the late 1980s and the spread of these systems among most of the farmers in the region today. Meanwhile, there is also another issue unique to the region; the electricity cost has soared in the event of drought because the region relies on obtaining most of its electricity from hydroelectric power generation. It can be said that irrigation fruit farming in this region carries the dual risk of irrigation water shortage: the direct risk of irrigation water shortage due to recent continuing water scarcity and the indirect risk of insufficient irrigation water due to the restriction of irrigation facility operation with electricity shortage and soaring electricity costs caused by the shortage of power generation water.

Key words sustainability, tolerance to drought, irrigation fruit farming, water supply-demand situation, sertão, the middle basin of São Francisco River

Introduction

Global scale climate changes, often symbolized by global warming in recent years, have had various impacts on the natural environment and industries all over the world. Especially in arid or semi-arid regions, the frequency and strength of droughts show an increasing trend, making water resources even less stable in these areas (Gaiser et al. eds. 2003). These arid or semi-arid regions have traditionally adopted irrigation systems, such as a center pivot system, furrows, borders, or basin irrigation, to manage agricultural development in the region. However, these large-scale systems for conveying water, with inefficient utilization of groundwater or surface water, have caused environmental issues, such as salinization of the soil or impacts on the local ecosystems of river zones, while also being considered vulnerable to extreme climatic changes, such as droughts (Radwan 1998; Smedema and Shiati 2002; Shang and Wang 2013; Li et al. 2014; Bobojonov et al. 2016; Wang and Qin 2017).

In many arid or semi-arid regions of the world, water-saving strategies need to be implemented in the agricultural sector in order to increase the resilience to water scarcity (Törnqvist and Jarsjö 2012). In order to deal with these issues, a more efficient water-saving style of irrigation system in harmony with the environment, such as a micro-irrigation system (drip irrigation, micro spray/sprinkler irrigation), has been developed in recent years. Innovative irrigation practices can enhance water efficiency, gaining an economic advantage while also reducing environmental burdens (Levidow et al. 2014). Economically, water-saving irrigation is cost-effective in coping with climate change, and has benefits for climate change mitigation and adaptation, and for sustainable economic development (Zou et al. 2013). The relative cost of micro irrigation will decline when water prices or allotments are adjusted to reflect the off-farm and long-term environmental impacts of irrigation and drainage activities (Oster and Wichelns 2003). On the other hand, improperly managed ‘hi-tech’ systems can be as wasteful.
and unproductive as poorly managed traditional systems (Levidow et al. 2014). After all, the sustained long-term productivity of irrigated lands in arid or semi-arid zones crucially depends on correctly managing water and soil resources (Banin and Fish 1995).

The subject area of this study, Nordeste, which is the northeast part of Brazil, also contains a semi-arid tropical zone called the sertão in its inland area. In Nordeste, a southeast wind from the Atlantic Ocean hits the Brazilian Plateau at an altitude of 500–1,000 m above sea level and turns into an ascending updraft that falls as rain on the windward side of the coastal area. However, the sertão in the inland area on top of the Brazilian Plateau usually has unstable climatic conditions with little rain, and droughts have occurred repeatedly throughout the history of this area; thus, due to its environmental conditions, the region has been considered one of the harshest and most undeveloped areas in Brazil. This is the reason that the main traditional agricultural output of this region has been extensive cattle breeding. Otherwise, agriculture was limited to the cultivation of grains and vegetables for self-supporting purposes with unstable and limited amounts of harvest, except for the booming cotton-growing industry (Andrade 1968; Yamamoto et al. 1986; Gaese 2003; Magalhães 2017).

Severe droughts hit the sertão from 1877 to 1879 and offered a major opportunity to develop full-scale countermeasures for the region. In 1909, IOCS: Inspetoria de Obras Contra as Secas (Inspection Agency for Works against Drought) was established, and many public reservoirs (acude) were constructed in various locations in the sertão. The IOCS was later transformed into DNOCS: Departamento Nacional de Obras Contra as Secas (National Department for Works against Drought). After the 1940s, national policies were developed and implemented to reduce damage from drought events and promote social and economic development throughout the region. In 1959, SUDENE: Superintendência do Desenvolvimento do Nordeste (Superintendence for the Development of the Northeast) was established as a special agency to manage these policies. Furthermore, SUVALE: Superintendência do Vale do São Francisco (Superintendence for the San Francisco Valley) was established in 1967 and was later transformed into CODEVASF: Companhia de Desenvolvimento do Vale do São Francisco (Company for the Development of the San Francisco Valley) to promote large-scale development projects using the São Francisco River running through

Figure 1. Location of the target area of this study.
the sertão as a water source. They promoted the dramatic development of irrigation agriculture in the middle basin of São Francisco River. The most noteworthy development was the construction of Sobradinho Dam, completed in 1978, which was the largest dam constructed in Latin America at the time of completion. This dam enabled the development of new large-scale agricultural land, allowing more profitable harvest production (Hall 1978; Araújo ed. 1982; Tendler 1993; Saito and Yagasaki 1995; Magalhães 2017).

The target area of this study, Petrolina in the state of Pernambuco, is located in the middle basin of São Francisco River in the sertão, approximately 700 km inland of Recife, the state capital of Pernambuco (Figure 1). Since the 1990s, Petrolina and its surrounding area have dramatically increased production of fruit, such as mangoes and grapes, utilizing irrigation facilities to become one of the most distinguished irrigation fruit-growing areas of Brazil.

However, following the afore-mentioned projects to counter droughts, no demonstrative research can be found regarding to what extent those projects resolved the harm caused by drought and improved the stability of agricultural production in the sertão today. In recent years, the sertão has again experienced the most severe shortage in rainfall of the past several decades (Engle et al. 2017). Large-scale irrigation projects allowing the development of this region were made possible by the rich water resources of São Francisco River, including the Sobradinho Dam. Therefore, demonstrative research to clarify the current water supply-demand conditions for the whole agriculture and individual farmers in this region will be significant to deepening our understanding of the sustainability of irrigation agriculture in arid or semi-arid regions.

Based on the above discussion, this study intended to consider the sustainability of irrigation fruit farming in terms of water supply-demand situation from the viewpoint of tolerance to drought events in Petrolina and its surrounding area in Brazil, where large-scale irrigation projects have been developed for semi-arid regions. Based on the field survey, we analyze the actual situations of water intake and distribution on the water supply side and irrigation agriculture on the water demand side, under the record-breaking shortage of rainfall in recent years. The field survey was conducted from August to September in 2015, 2016 and 2017.

The Irrigation Situation in Petrolina and its Surrounding Area

The change in precipitation and the recent shortage of rainfall

The target area of this study, Petrolina in the state of Pernambuco, has a steppe climate for its climate classification, and its distinctive features are a high temperature throughout the year and a wide variation in rainfall that is distinguished by wet and dry seasons.

Figure 2 shows the transition of annual precipitation in Petrolina. The annual rainfall ranges from 200 mm to 1,000 mm. Within this range, under 400 mm, which can be considered insufficient rainfall, has occurred periodically. After 2011, such a shortage of rainfall has occurred every year.

According to Figure 3 which shows the average monthly precipitation, half the year, from May to October, is generally the dry season and the other half of the year, from November to April, is generally the wet season. The key to seeing whether the year had a drought or not depends on whether or not there was enough rain-

![Figure 2](image-url)
fall during the wet season. For instance, the year 1993 had very low annual precipitation, with only 5.5 mm precipitation in March, when it should rain the most. In recent years, the March precipitation was 73.3 mm in 2011, while the precipitation did not reach 10 mm in 2012, 2013, 2014 and 2017. Furthermore, the only months with over 100 mm of precipitation were December 2013 and January 2016.

Such a low level of rainfall during the wet season in recent years has also been found in the water source area of São Francisco River. Thus, the available storage percentage of Sobradinho Dam has declined significantly since 2014 (Figure 4). The water of this dam is used for hydroelectric generation, as well as for irrigation and industrial use in the downstream area; it is also supplied to the Nordeste area for domestic water, where water resources are poor. Hence, we see a cycle that during the dry season with little precipitation, the water storage percentage drops because the water demand exceeds the water supply, whereas during the wet season, the water supply exceeds the water demand, yielding the recovery of the water storage percentage. However, the rainfall was extremely low in the wet season of 2014, starting in November, and the water storage percentage barely recovered until May of the next year. This resulted in a critical situation, as the water storage percentage dropped to 1.1% in November 2015 at the end of the dry season. Although the water storage percentage recovered by increased rainfall after January, it remained only 33.4% in March 2016, and it dropped again during the dry season to 5.9% in November of the same year.

Figure 3. Average monthly precipitation in Petrolina (1988–2017).
Source: data from EMBRAPA.

Figure 4. Transition of available storage percentage of Sobradinho Dam.
Source: data from DINC.

Table 1. Large-scale irrigation projects in the middle basin of São Francisco River

| name of project               | state | completion year | irrigation area (ha) | maximum water intake (m³/s) |
|--------------------------------|-------|-----------------|----------------------|-----------------------------|
| Bebedouro I/II                | PE    | 1968/1981       | 1,650                | 3.7                         |
| Mandacaru                     | BA    | 1973            | 769                  | 0.7                         |
| Tourão                         | BA    | 1978            | 15,873               | 19.9                        |
| Maniçoba                       | BA    | 1981            | 8,261                | 6.4                         |
| Cúraçá                        | BA    | 1982            | 4,366                | 7.2                         |
| Senador Nilo Coelho/Maria Tereza | PE    | 1984/1997       | 23,245               | 23.2                        |
| Pontal                         | PE    | in progress     | 7,800                | 7.5                         |
| Salitre                        | BA    | in progress     | 33,000               | 42.0                        |

PE: Pernambuco, BA: Bahia
Sources: data from CODEVASF and DINC.
From the above facts revealed by the data, we can see that Petrolina faces droughts periodically, and especially since 2011, it has been in a severe water shortage situation because of low rainfall every year in the wet season.

The development of large-scale irrigation projects and changes in irrigation systems

In Petrolina and its surrounding area, the middle basin of São Francisco River, eight large-scale irrigation projects have been conducted since the 1960s (Table 1), and two more are currently in progress. The first was the Bebedouro I Project that SUVALE executed based on the São Francisco Valley Irrigation Master Plan with the aid of FAO (the Food and Agriculture Organization of the United Nations). The current irrigation area is 1,650 ha, with the area including the Bebedouro II Project. The water taken from São Francisco River, with a maximum water intake of 3.7 m³/s, is sent to each farmland by the main water channel network. The irrigation system at the initial development was called “sulco”, which allows water to flow through the natural gradient of channels inside the farms and ditches dug at the root of fruit trees. However, the water supply was not sufficiently efficient, since it was just water flushed along trees, and much of the water flowed into the drainage without being absorbed by those trees.

From the 1970s to the early 1980s, four projects were conducted around Juazeiro in the state of Bahia, located on the other side of Petrolina across the São Francisco River. The organization responsible for these projects was CODEVASF. In its early stages, the main irrigation method in these developed farmlands was a system called “aspersão”, which sent water to the farmlands using pumps and pipes and sprinkled water from the tops of trees using large sprinklers. Since CODEVASF only developed the farmland and the main channel in the irrigation projects of that time, settling farms themselves had to install irrigation facilities inside the farmlands. On the one hand, according to Saito and Yagasaki (1995), there were some corporative farms entering the business of owning a few hundred to a few thousand hectares of farmland, with the large-scale introduction of the center pivot irrigation system, mainly around the development areas of these four projects. However, many of these corporate farms have since withdrawn, and the center pivot irrigation system, which was considered to be a wasteful system in terms of water use, is barely seen today.

On the Petrolina side of the land, the Senador Nilo Coelho Project was completed in 1984. This is the largest scale project among the eight projects completed as of today. Since CODEVASF developed the aspersão irrigation facility for each farmland as the infrastructure of this project, settling farms all used them first.

As described above, the irrigation methods initially adopted in large-scale irrigation projects, such as sulco, aspersão, and the center pivot systems, were wasteful in water use. This happened because it was considered that crops grew better with more water. The biggest reason for these types of irrigation systems was the development of water resources in the middle basin of São Francisco River as a drought prevention project described before, namely, the completion of Sobradinho Dam in 1978.

Meanwhile, water-saving irrigation systems, such as “gotejo” and “micro aspersão” were first installed around 1984 by a large-scale orchard farm funded by an Israeli company. Gotejo is a drip type irrigation method that drips water directly to the roots of trees through thin tubes placed along the trees. Micro aspersão is an irrigation method that sprinkles water only to the roots of trees using small sprinklers. Once it was proven that these water-saving irrigation systems can achieve the same or better quality and quantity of crops with less water, they have been rapidly adopted in Petrolina and all over its surrounding area from the late 1980s. In the four projects executed on the Juazeiro side, larger lands could be irrigated with the same amount of water by the promotion of a switch from the conventional aspersão system to water-saving irrigation systems around 1990. This has enabled a larger irrigation area today than the irrigation area planned at the initial stage of development. In addition, in the Senador Nilo Coelho Project on the Petrolina side, the installation of water-saving irrigation systems, such as gotejo, micro aspersão, and “diffusor” with small sprayers hung along trees to sprinkle water, rapidly increased in around the 1990s, along with the significant development of fruit farming. This enabled the irrigation of larger areas of farmland using the same amount of water intake that had been planned. Accordingly, the Maria Tereza Project was completed in 1997 as an addition to this project (Table 1).

Those projects currently under construction include the Pontal Project on the Petrolina side and the Salitre Project on the Juazeiro side. The former is a plan to send electrically pumped water from the São Francisco River to 7,800 ha of farmland in the north-east area of Petrolina via the 78 km-long main channel. The latter is a project to irrigate 33,900 ha of farmland on the southwest Juazeiro, and approximately 6,000 ha has been completed at the first stage. This is also a plan to send water to the upstream region of Salitre River by electrically pumping
irrigation water from the São Francisco River.

The above is a brief summary of the development background and transitions of the irrigation system found in each large-scale irrigation project. In the following chapters, we will focus on the irrigation areas of Senador Nilo Coelho/Maria Tereza Project, and describe the transitions of water supply amount and the countermeasures applied on the water supply side against water shortage. We also explain the details of the transitions of the irrigation system of the farmers on the water demand side and the variety of farm products they are growing.

Water Supply and Countermeasures against Water Shortage in Large-scale Irrigation Projects

The details of Senador Nilo Coelho/Maria Tereza Project

Senador Nilo Coelho/Maria Tereza Project (hereafter referred to as NC/MT) is the largest scale project among the irrigation projects conducted in the middle basin of São Francisco River. This project initially started its construction in 1980 as the Senador Nilo Coelho Project of CODEVASF. It started supplying water partly in 1983, and construction was completed in 1984. The approved maximum water intake was 23.2 m³/s to irrigate approximately 20,000ha of farmland at the time of the original plan. Along with the development of farmland, CODEVASF also introduced aspersão irrigation facilities, and the settling farmers used it first. However, actual water intake never reached the planned maximum amount, and water resources had some margin for capacity. This occurred because the application of water-saving irrigation systems, such as gotejo and micro aspersão, rapidly became available and their use spread widely after the late 1980s. Then, there was a plan to expand the irrigation area of the Maria Tereza Project by utilizing this surplus water resource. This project started in 1994 and was completed in 1997. As a result, the irrigation farmland of NC/MT became approximately 23,000ha. The total area of development, including villages, life-related facilities, and lands without irrigation facilities called “sequeiro,” was approximately 55,000ha. Among the irrigation projects developed by CODEVASF, NC/MT is the project in which the water-saving irrigation systems are most widely spread; as of 2015, NC/MT has gotejo and micro aspersão as its water-saving irrigation methods covering more than 80% of the project’s area. Therefore,
the actual water intake did not reach the planned maximum amount of 23.2 m³/s, even across the whole area of NC/MT; the actual maximum intake amount is approximately 18 m³/s.

The entire development area is divided into 22 districts: each district has a community village (living quarter) of settlers, and life-related facilities, such as school and clinics are provided for every five districts or so. However, many farm owners do not always stay in the communities within the development area and build their residences in the urban area of Petrolina.

There are three types of irrigated farmland, in terms of their different scales: a small plot is 6 ha, a middle plot is 7–20 ha, and a large plot is 21 ha or more. Usually, these plots are sold together with sequeiro as a set; a small plot is provided to small-scale farmers and is operated by a single household or individual unit, and most of the middle plots and all large plots are provided to corporate enterprises. As of 2015, the number of plots for sale was 1,961 small plots, 312 middle plots, and 49 large plots. All the developed areas have been sold, but there are some plots of farmland without any planting. On the other hand, it is also true that many small-scale farmers that own small plots are expanding their planting areas to sequeiro, where CODEVASF did not provide irrigation infrastructure. Shortly after the development, most of the farmers used to grow vegetables, such as tomatoes and green peppers. However, planting has gradually shifted to fruits since around 1990, and now, over 90% of the planted products are fruits, mainly mangoes and grapes.

The irrigation water is supplied to the entire developed area through the main channel totaling 158 km in length, taken from the sluice gate installed at the Sobradinho Reservoir. The water is then sent to each farmland by a total of 39 electric pumps installed for each district, along with the main channels and reservoirs (Figure 5).

**Water supply and countermeasures against water shortage by DINC**

CODEVASF had been responsible for the maintenance of irrigation facilities and supply of irrigation water from the early development stage of NC/MT until 1989, but the operation was transferred to DINC (Distrito de Irrigação Nilo Coelho: Jurisdiction of Senator Nilo Coelho Irrigation Project) in 1989. Today, DINC is responsible for a series of operations, including taking raw water from the dam lake and sending it to the entire development area, operating and maintaining the related water supply facilities, and collecting fees from the users of the supplied water.

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Figure 6 shows the transition of annual water intake from the Sobradinho Reservoir by DINC. According to this figure, it was kept at approximately 200 million m³ range until 2011, but rather increased to around 300 million m³ after 2012 when the rainfall shortage became serious. By looking at the average monthly intake amount (Figure 7), we can see a tendency toward a gradual increase in water intake during the dry season with little rainfall, starting in May, and a gradual decrease during the wet season with much rainfall, starting in November. From this fact, it is possible to say that DINC does not decrease water intake to save the limited water resources in the months and years when the available water storage percentage of dams drop and the water resource amount declines due to low rainfall. In fact, the opposite is rather true—we should understand that DINC supplies the sufficient amount of water not provided by precipitation that is required to grow farm products. This also means that water supply is adjusted to the water demand to maintain the yield and quality of crops of each farm, even during water shortage periods. The details of the actual situation of farmers on the water demand side will be described in
the next chapter.

The water use fees collected by DINC from each water user consist of two types: the fixed fee, which is decided according to the area of the sold plot, and the rate fee, which is charged depending on the amount of irrigation water used. The actual fixed fee was 64 Real per hectare per month until 2015. The rate fee varies slightly according to the electric power price for sending water (when water is sent at the peak of power demand, the price is high), while it is around 85 Real per 1,000 m³ per month. The DINC’s operations are covered mainly by the revenues of these fees, but the recent water shortage has caused a rise in the price of electricity all across Brazil, where about 80% of the nation’s electricity demand depends on hydroelectric power, and the electricity price that DINC pays to the power company for operating the irrigation facilities has risen. In particular, there was a considerable price increase for electric power in 2015. As a result, the annual electricity cost escalated to 23 million Real from 14 million Real following this price increase. Due to this, DINC raised the water use fees collected from water users from January 2016 to 67 Real per hectare per month for the fixed fee, and around 91 Real per 1,000 m³ per month for the rate fee.

The reservoir of the dam, as a water source, discharges 1,200 m³/s of water to generate power and maintain the water level of the reservoir during normal periods without any water shortages. However, in recent years, it has become necessary to decrease the discharge amount because of the decreasing inflow from the upstream to the dam caused by the continuing low rainfall. Specifically, the water storage percentage of Três Marias Dam, situated in the upstream water source area, dropped to 28% as of September 2016, and the water inflow to the Sobradinho Reservoir downstream was restricted to approximately 400 m³/s. This situation was the same in the dry season of 2017. Meanwhile, the discharge water amount of the Sobradinho Reservoir was 600–800 m³/s, which is the minimum amount required for hydraulic power generation, water supply for the demand of the downstream side of the dam, and the sustaining of the river environment. As a result, the available water storage percentage of the Sobradinho Dam also decreased, and it fell into a critical situation again—it was not as serious as the year before, but it was 5.9% by November 2016 (Figure 4). The water storage percentage recovery was poor, even after entering 2017, and a restriction on water intake was carried out every Wednesday against the water users of the whole basin, including DINC, from July. This kind of measure is unprecedented and reflects the serious reality of aggravating water shortages.

As a countermeasure against the situation that the water level of the reservoir is lower than the sluice gate (in the event of the available storage percentage becoming zero), DINC planned to install new pumps to draw water below the minimum water storage level (in other words, “dead water”) at different points from the existing sluice, in order to lead water to the main channels. These pumps are the types that float on the surface of the water, which can operate regardless of the water level. The cost is 40 million Real for 16 pumps, and the federal government covers the cost of five out of the eight, the state of Pernambuco covers the cost of two and the city of Petrolina covers the cost of one. One pump has an intake capacity of 1 m³/s, thus totaling 16 m³/s for a total of 16 pumps. They can fulfill almost the entire current water demand, since today’s maximum water intake is around 18 m³/s. By 2017, 10 out of 16 pumps were already installed. As the area of the reservoir is so vast, even the “dead water” taken from the water level lower than the minimum water storage level would still be quite large. Nonetheless, these countermeasures reflect the determination of DINC to maintain the water supply amount at the current level, no matter how serious the water shortage becomes. These pumps have not yet shown any actual operational track records, but if it is required for these pumps to be operated, the electricity cost for their operation will be added on top of the fees of water users.

As for the soaring electricity prices, all the water conveying pumps within the operation areas of DINC have been replaced with energy-saving pumps since October 2015. In particular, these new pumps can eliminate energy waste by sending water with more than the necessary pressure (electricity) by finely adjusting the water-sending pressure according to the water amount. The estimate shows that it can save about 20% of the total electricity.

In summary, DINC has not reduced its water supply, even in the current condition of water shortage caused by continuing low rainfall, and they introduced countermeasures, in order to prevent a reduction in water supply in the future. Meanwhile, an increase in water use fees is inevitable because of the rising electricity cost; therefore, they are taking measures to save power use.

The Transition in Cultivated Crops and the Irrigation Systems of Fruit Farmers

In this chapter, we describe in detail the transition and current status of agricultural management and the irriga-
tion systems of fruit farmers as water users by looking at some case farms. In order to do so, we categorize those farms according to the scale of the sold plots of NC/MT: family-operated small-scale farms with 6 ha of farmland and enterprise-operated large-scale farms with over 21 ha of farmland (Table 2). This is because there are significant differences in the selection of cultivated crops and the introduction of irrigation systems depending on the scale of the farm.

### The cases of small-scale farms

**Farms established in the 1980s** Figure 8 shows the transition of farm area, cultivated crops, and irrigation systems in four cases of small-scale farms as examples for this study.

Case farm 1 was established in 1986. The farm owner had been previously engaged in agriculture in the state of Paraíba in Nordeste, but moved to Petrolina for its well-developed irrigation facility allowing year-round farming. When the farm was established, tomatoes, soybeans and watermelons were grown on 6 ha of farmland. During the year-long harvesting period, tomatoes were planted first and harvested in 120 days. Next, soybeans were planted and harvested in 60 days; then, watermelons were planted and harvested in 90 days. In 1989, use of the 6 ha of farmland was altered by planting 4 ha of bananas and 2 ha of coconuts; in 1992, that 2 ha of coconuts was replaced by acerolas. At that time, the irrigation method was still aspersão. In 1998, bananas were replaced by guavas, since all the banana trees fell down because of strong winds. At the same time, a micro aspersão irrigation system was installed across 4 ha of guava farmland. The reason for this installation was to reduce both the labor force and water use. By changing the irrigation method from aspersão to micro aspersão, the amount of water used per area could be reduced to approximately 60%. In 1998, 3 ha of sequeiro was newly cultivated and mangoes were gradually planted. Initially, they extended the aspersão irrigation system, but replaced it with micro aspersão in 2001. As for the farmland for acerolas, 1 ha of the 2 ha of farmland was changed to a self-supporting vegetable field in 2002. The other 1 ha of acerola farmland was installed with a micro aspersão irrigation system. The vegetable field remained as aspersão, but planting ceased in 2015. In 2008, another 2 ha of sequeiro was cultivated, and the farmland for acerolas was expanded to 3 ha. In 2016, another 2 ha of sequeiro was cultivated, replacing the former acerola field by transplanting it, and then, a part of the former acerola field (0.5 ha) was altered to be a banana field and a meadow for livestock.

Figure 9 shows the land use and irrigation system in case farm 1, after undergoing the above-described process. The 6 ha of land on the north side of the farm is the original irrigated farmland. On the south side, there is 7 ha of farmland cultivated from sequeiro; further to the south the remaining sequeiro. A total of 4 ha of the original farmland are banana fields and the remaining 2 ha are non-planting areas. There are 3 ha of mango fields and

### Table 2. Current cultivated crop and irrigation system for the six case farms

| No. | establishment year | total planted area (ha) | cultivated crop and area (ha) | irrigation system and area (ha) |
|-----|--------------------|------------------------|-----------------------------|-------------------------------|
| 1   | 1986               | 10.0                   | banana, 4.0                  | micro aspersão, 10.0          |
|     |                    |                        | acerola, 3.0                 |                               |
|     |                    |                        | mango, 3.0                   |                               |
| 2   | 1987               | 12.5                   | mango, 6.0                   | micro aspersão, 6.0           |
|     |                    |                        | acerola, 3.5                 | aspersão, 5.0                 |
|     |                    |                        | banana, 3.0                  | aspersão/micro aspersão, 1.5   |
| 3   | 1996               | 6.0                    | mango, 4.0                   | micro aspersão, 5.0           |
|     |                    |                        | acerola, 1.0                 | aspersão/micro aspersão, 1.0   |
|     |                    |                        | passion fruit, 1.0           |                               |
| 4   | 2000               | 6.4                    | acerola, 6.4                 | aspersão/micro aspersão, 4.7   |
|     |                    |                        |                              | micro invertido, 1.7          |
| 5   | 2002               | 30.7                   | grape, 30.7                  | difusor, 27.7                 |
|     |                    |                        |                              | micro aspersão, 3.0           |
| 6   | 2001               | 53.6                   | grape, 30.6                  | micro difusor, 30.6           |
|     |                    |                        | mango, 23.0                  | micro aspersão, 23.0          |

Source: field survey by authors.
3 ha of acerola fields in the sequeiro-cultivated farmland. As for the irrigation facility, a pipe of 100 mm diameter is used for the aspersão irrigation system developed by CODEVASF as infrastructure from the north side of the farm, running through the center of the 6 ha of original irrigated farmland. On both sides of the pipe, installation points for the aspersão’s water sprinkling pipes are provided at 24 m intervals, but only 1 ha of the former vegetable field, which was used until 2015, is currently in operation. A pump with a filter is installed at the end of the 100 mm diameter infrastructural pipe, and pipes with smaller diameters run from there to both the original irrigated farmland and sequeiro-cultivated farmland. Tubes equipped with small sprinklers for micro aspersão extend vertically from these pipes at 6 m intervals for the banana and mango fields and at 4 m intervals for the acerola fields. These facilities were installed individually by the farm owner. The monthly water use amount is 10,000–12,000 m$^3$. The amount of water used is about the same from the time when only 6 ha of farmland was irrigated by aspersão because the entire planted farmland of 10 ha is currently installed with a water-saving micro aspersão irrigation system.

There are four full-time workers on the farm, including the wife of the farm owner, their third son and fourth daughter, and one outside employee. About 15 temporary part-time workers are employed for the mango and acerola harvesting season. They live in the city of Petrolina or the neighboring area of the farm. The farm owner has seven children, and the first son and first daughter run a farm on their own. The second son works at the first son’s farm. The second daughter is a teacher at an elementary school.
school, and the third daughter is a pharmacist.

The owner of case farm 2 previously operated agriculture in the state of Piauí in Nordeste, while he also worked away in Petrolina since the 1970s as a seasonal migrant agricultural laborer. This motivated him to move to Petrolina, and he established this farm in 1987. Similar to case farm 1, soybeans, watermelons and tomatoes were grown on 6 ha using the aspersão irrigation system when the farm was established. In 1989, 1 ha of the 6 ha farmland was switched to acerola, as well as another 2 ha in 1991. The reason for planting acerola, like case farm 1, is that a Japanese company producing acerola-related products moved to Petrolina in 1990, promoting surrounding farmers to grow acerola. During the 1990s, 3 ha of the sequeiro was cultivated, and mangoes were planted there, in addition to the former vegetable field on 3 ha. They cultivated another 3.5 ha of sequeiro in 2001 and planted acerolas on 2 ha and guavas on 1.5 ha. This guava farm on 1.5 ha was also changed to acerola in 2008. All irrigation methods were the aspersão system up to this time, and the sequeiro-cultivated farmland was irrigated by extending the existing facility by the farm owner himself. An original 3 ha of acerola field was altered to a banana field in 2012, and the micro aspersão irrigation system was installed on the 6 ha of mango fields, including the sequeiro-cultivated farmland and 3.5 ha of acerola field. This was conducted to reduce both the labor force and water use, as with case farm 1. Concerning the acerola field, the conventional aspersão was used together with micro aspersão, and it switched back to using aspersão on only 2 ha in 2014. The reason for this is that, for acerola, it is considered better to water not only to their roots but also to the entire tree, in order to prevent the flowers from withering or getting infected by harmful insects. The monthly amount of water used for the whole farmland is approximately 9,000 m³.
The full-time workers at the time of the establishment of the farm were the farm owner and four sons. As the third and fourth sons became independent and worked as a caretaker for a school and a worker for another farm, respectively, four people, including the oldest son, the second son, and one outside employee make up the current workforce. In addition, 20 to 25 temporary part-time workers are employed during the harvest season of acerola. The farm owner has two more children, as the eldest daughter is a housewife and the second daughter is an assistant nurse.

Farms established after the 1990s The farm owner of case farm 3 is a former accountant from São Paulo, with experience of working in Japan as a temporary laborer. In 1996, after returning from Japan, he came to Petrolina, where his elder brother was engaged in agriculture, and he also bought farmland and started farming. In its earlier days, the farmland consisted of 3 ha of mangoes, 3 ha of coconuts, and 1 ha of bananas, while mango trees were succeeded from the previous owner. The irrigation systems were micro aspersão (installed by the previous owner) for mangoes and aspersão for coconuts and bananas. In 1998, 2 ha of the 3 ha coconut field were installed with a micro aspersão irrigation system, and grapes were grown there, but this was stopped in 2011. The remaining 1 ha was switched to a mango field using a micro aspersão irrigation system in 2002. The 1 ha of banana field was also installed with a micro aspersão irrigation system and changed to grapes in 2006, and in 2013 it was changed to a passion fruit field. On the one hand, 1 ha of sequeiro was newly cultivated in 1998, with the installation of a micro aspersão irrigation system and sugar-apple was planted, but that was changed to passion fruit in 2002. Acerola was introduced to that 1 ha of land in 2006, and the irrigation method was also changed to the combined use of aspersão and micro aspersão systems. The current monthly water use amount is approximately 12,000 m³.

The labor force consists of three full-time workers in addition to the farm owner, and additional six temporary part-time workers are employed during the harvest season of the acerolas. The farm owner’s wife is a banker and they have two teenage children.

The farm owner of case farm 4 bought the current farmland in 2000 to start working in agriculture while also working as a government employee in the Department of Agriculture. When the land was purchased, a micro aspersão irrigation facility had already been installed, and coconut and guava trees were planted on 11 ha of farmland by the previous owner. In 2008, the guava trees were infected by harmful insects. All plants, including coconuts, were cut down along with the guava, and acerola was planted on 6.9 ha of the land, while lemons were planted on 2.5 ha of the land. The irrigation method of the acerola field varies according to breed and is divided into three methods: with the application of the micro aspersão system only; combined use of the aspersão and micro aspersão systems; a method called micro invertido, where small sprinklers are installed upside down on top of trees to sprinkle water downward. These are ideas for watering the entire body of acerola trees, while installing and utilizing water-saving irrigation systems. The acerola field was reduced by 2 ha in 2014, and lemon cultivation was stopped in 2016, while acerola was newly planted on 1.5 ha of different farmland in 2015. Currently, only acerola is grown on 6.4 ha of farmland. The current monthly water use is approximately 15,000 m³.

The farm owner himself does not engage in agricultural work by employing five full-time workers. In addition, 50 temporary part-time workers are employed in the harvest season of acerola. The farm owner’s wife is a member of the faculty at a university, and they have two children who go to university.

To summarize the four cases of small-scale farms, the two farms established in the 1980s, when fruit tree cultivation and water-saving irrigation systems started to spread in Petrolina, were similar for producing vegetables by aspersão irrigation in their early days. However, there are differences in the process of adopting fruit farming afterward and in the current status of irrigation systems. For the farms established after the 1990s, they have adopted fruit tree cultivation and water-saving irrigation systems from the beginning, as they had already been widely available throughout the region. Small-scale farms in this region grow a variety of fruit trees, with mangoes and acerolas as the major products, while guavas, coconuts, and bananas are also produced. Some farms have fully shifted to water-saving irrigation systems, while there are also farms that have not updated their irrigation facility from the original aspersão system due to reasons such as requirements for the property of cultivated fruit trees. Today, the micro aspersão system has become the main water-saving irrigation method, while there are some methods that have been uniquely developed and improved by the farmers themselves.

The cases of large-scale farms
Case farm 5 was established by the current farm owner’s father in 2002. The farm owner himself does not
engage in farm work but devotes himself to business management, and the farm constantly employs around 100 employees. Grapes were first planted on a 6.16 ha portion (Areas A and B in Figure 10) of the land in 2002. Later, the grape field expanded by adding 4.08 ha (Area C) in 2003; 4.38 ha (Area D) in 2004; 5.67 ha (Area E) in 2007; and 10.45 ha (Areas F and G) in 2014, which currently covers an area of 30.74 ha and is producing five varieties of grapes (crimson, thompson, vitoria, isis, and sugar crisp). The irrigation system was micro aspersão, the water-saving type, ever since they first started the 6.16 ha grape field. In 2012, they changed part of the irrigation system to diffusor in a 3.13 ha portion of the grape field. This diffusor system is also used for all the farmland expanded after 2003 from the outset. In 2003, diffusor was the latest still uncommon irrigation system in the region. While diffusor uses more water and has a wider watering range than gotejo, it uses less water and has a smaller watering range than micro aspersão.

Figure 10 shows the land use and irrigation system in case farm 5. A water channel installed by CODEVASF runs along the west side of the farm, conveying water to three reservoirs on the farm. Water is distributed to each portion of the farm from the reservoirs using four electric pumps. Irrigation tubes extend along the grape trees from branch water pipes at 2.0-m intervals from Areas A to E and at 1.5-m intervals in Areas F and G. There are approximately 35,000 grape trees in the entire farm, and each tree needs to be watered for two hours per day. Each tree also requires 50 liters of water during the period of 45–70 days after pruning, when trees need water most, and 15 liters during the period when trees are left to rest after harvest. It takes between 8 and 10 hours to water all of the trees. The amount of water used is increasing in line with the expansion of the farmland, which currently amounts to 29,000 to 33,000 m³ per month. Even though the water fee is increasing as a result, they have no intention of saving any more water because they intend to supply a sufficient amount of water for crops and also, they have been using water-saving irrigation systems from the beginning.

Case farm 6 was established in 2001. At the time of establishment, the area of the farmland was 10.44 ha and grapes were grown from the beginning. The farmland expanded to 19.38 ha in 2003 and 30.55 ha in 2005, producing six varieties of grapes (sugar crisp, crimson, thompson, vitoria, isis, and sugar crisp). The irrigation system was micro aspersão, the water-saving type, ever since they first started the 6.16 ha grape field. In 2012, they changed part of the irrigation system to diffusor in a 3.13 ha portion of the grape field. This diffusor system is also used for all the farmland expanded after 2003 from the outset. In 2003, diffusor was the latest still uncommon irrigation system in the region. While diffusor uses more water and has a wider watering range than gotejo, it uses less water and has a smaller watering range than micro aspersão.
scarlota, sable, midnight beauty, and arra15). Irrigation system since the establishment of the farm has been micro diffusor, the water-saving type, which can water a wider range with higher efficiency than diffusor. One of the co-owners, who was a university graduate of the Department of Agriculture and once worked as an agricultural advisor, learned about this method in Israel and immediately introduced it to his own farm. Besides grapes, they started a 9 ha mango yard in 2012, which expanded to 23 ha in 2014. The irrigation system used for mangoes is micro aspersão.

The amount of water used per month is 35,000 m³ for the grapes and 25,000 m³ for the mangoes. Water is supplied using three electric pumps from the reservoirs, under the supervision of CODEVASF, to the water distribution facility located at the center of the farm, and then distributed to each farmland. In the past, the farmland used to be watered at regular hours every day, but currently, soil conditions are constantly monitored and the land is watered only when necessary. The water fee is thereby reduced, but they need to employ staff in charge of monitoring.

The present farm owners are two sons of the original farm owner. The elder brother is responsible for farm work and the younger brother is responsible for business management, and they employ 80 full-time workers. During the harvest season of grapes for export, they employ approximately 50 temporary workers.

Large-scale farms of more than 21 ha can be said to be innovative farms, leading the agricultural industry of the region, but most of them grow multiple varieties of grapes, as in the case of the two farms mentioned above. Although grapes are highly profitable due to their higher price than other products, it is difficult to start grape production on farms, except for large-scale farms, due to the high initial investment cost and labor cost. The statistics for the planted areas of crops in the entire region show that mangoes are first because both small-scale and large-scale farmers grow them, and grapes are second because large-scale farms grow them. All irrigation systems for large-scale farms are water-saving types. Diffusor is widely used in grape fields besides micro aspersão, while micro diffusor, an improved version of diffusor, is also used.

Discussion and Conclusion

By investigating the irrigation fruit farming developed in Petrolina and its surrounding area in the middle basin of São Francisco River, located at the center of the semi-arid sertão in Nordeste, this study conducted a detailed analysis of the actual conditions on both the water supply side and the water demand side of this region under the record-breaking shortage of rainfall in recent years. In conclusion, it is intended to consider the sustainability of irrigation fruit farming in such tropical semi-arid regions in terms of water supply-demand situation, including tolerance against droughts.

The decrease in water resources in this region in recent years is so dramatic that the fruit-growing industry might be abandoned due to droughts from water shortage. However, the amount of water supplied by DINC rather increases in the event of little rain. This means that both DINC and farmers give priority to supplying enough irrigation water to supplement the shortage of water from rain, rather than saving water more strictly in low rainfall situations. This study revealed that the irrigation fruit farming in this region has managed to sustain itself without decreasing the area of cultivation and the harvest of produce even under the water shortage scenario of recent years. The biggest reason for this is the introduction of water-saving irrigation systems in the region in the late 1980s and the spread of these systems among most of the farmers in this region today. However, in other words, the widespread use of water-saving irrigation systems cannot allow a further decrease in the amount of water used even for such events as the severe rain shortage of recent years. Considering the above findings, the irrigation fruit farming of this region today has managed drought tolerance, while conventional aspersão irrigation systems would have had serious difficulties in the industry.

The irrigation fruit farming in this region has managed to sustain itself for over 30 years, even though there has been periodic rain shortage. This has been made possible through tolerance against water shortage and by achieving production value over a certain level without lowering the quality and yield of harvest through wide-spreading water-saving irrigation systems. Furthermore, the introduction of water-saving irrigation systems enabled new development of sequeiro by utilizing the saved water to increase harvesting fields, rather than decreasing the total amount of water used throughout the whole agricultural territory. However, further increases in agricultural territory will raise issues concerning water shortage tolerance. Today, well-developed, widely spread water-saving irrigation systems can be found throughout the region, while the development of the agricultural territory is about to reach the limit in terms of water demand and supply to farmland. Currently, two large-scale irrigation projects are still under development. However, new development
of farmland that increases water demand amid difficulties of further water conservation on existing farmland, might bring issues concerning the water use of the whole region, including existing farmlands, exposing the entire irrigation fruit farming of this region to risk.

Meanwhile, there is also another issue unique to this region; the electricity cost has soared in the event of drought because this region relies on obtaining most of its electricity from hydroelectric power generation. It is true that water-saving irrigation systems are tolerant of water shortages, but the latest irrigation methods and large-scale irrigation projects strongly rely on electricity. The electricity shortage and escalation of electricity cost affects the management and operation of DINC’s irrigation water supply service. Therefore, the water use fee for each farm is also increasing. Table 3 shows a comparison between the annual production value and water use fee for the six case farms in this study. The water cost ratio in the table refers to the ratio of annual production value to the cost of annual water use. According to this table, smaller-scale farmers have a higher water cost ratio, meaning that they are burdened relatively more by rising electricity costs. Therefore, depending on the scale of the farm and irrigation system, it is possible to see that there will be both farmers who can still sustain their production by using the same amount of water and those who are forced to restrict the operation of irrigation facilities because of soaring electricity costs. Consequently, some farmers would not keep the water use amount and eventually be forced to decrease the scale of farming or even abandon the business, which would lead to a decline in the entire irrigation fruit-growing industry in this region.

Even though the dual risk for irrigation water shortage has been increasing, especially among small-scale farmers, it is also true that most of the farm households have other incomes from non-agricultural businesses. This situation might be the result of population increase and urban development in the city of Petrolina and its surrounding area, brought about by large-scale irrigation

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**Table 3.** Comparison between the annual production value and water use fee for the six case farms

| No. | total planted area (ha) | annual production value (Real) | amount of water used (m³/month) | water use fee (Real/month) before price increase | water use fee (Real/month) after price increase | annual water use fee (Real) before price increase | annual water use fee (Real) after price increase | water cost ratio (%) before price increase | water cost ratio (%) after price increase |
|-----|-------------------------|--------------------------------|--------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 1   | 10.0                    | 444,548                        | 11,000                         | 1,575                           | 1,671                           | 18,900                          | 20,052                          | 4.3                              | 4.5                              |
| 2   | 12.5                    | 685,294                        | 9,000                           | 1,565                           | 1,657                           | 18,780                          | 19,878                          | 2.7                              | 2.9                              |
| 3   | 6.0                     | 233,600                        | 12,000                          | 1,404                           | 1,494                           | 16,848                          | 17,928                          | 7.2                              | 7.7                              |
| 4   | 6.4                     | 408,320                        | 15,000                          | 1,685                           | 1,794                           | 20,215                          | 21,526                          | 5.0                              | 5.3                              |
| 5   | 30.7                    | 4,234,098                      | 31,500                          | 4,642                           | 4,923                           | 55,708                          | 59,081                          | 1.3                              | 1.4                              |
| 6   | 53.6                    | 5,639,760                      | 60,000                          | 8,530                           | 9,051                           | 102,365                         | 108,614                         | 1.8                              | 1.9                              |

Source: field survey by authors.

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**Figure 11.** Dual risk for shortage of irrigation water in the middle basin of São Francisco River.
projects, which have created new employment opportunities in the non-agricultural industries. If so, such an increase in population and urban development also has a strong connection with the sustainability of irrigation fruit farming in semi-arid regions, which depends on unstable natural rainfall. Therefore, it is a task for the future to consider the sustainability of the entire region through comprehensive analysis from a viewpoint which includes non-agricultural sectors.

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Notes

1. The development areas of Bebedouro I and Bebedouro II, Senador Nilo Coelho and Maria Tereza are adjoining; thus, locally, they are recognized as a series of projects today.
2. Sequeiro originally meant the land that was not suitable for cultivation because of the large amount of stone in the soil. However, the land has been developed by many farmers, and land reclama-
tion to farmland is widely promoted.
3. The initial sales plot of irrigation farmland was 6 ha, but many farmers have cultivated sequeiro by themselves; thus, the total area of their farmlands exceeds 6 ha today.
4. There are also medium-scale farms with 7 to 20 ha, but here we will focus only on small-scale individual farms and large-scale corporate farms with more distinct differences because most of the medium-scale farms are also corporate farms for enterprises as well as large-scale farms.
5. Aspersão needs to switch and relay the pipes at each range of sprinkling water to irrigate the entire farmland. This requires a lot of work. Meanwhile, gotejo and micro aspersão do not require such work.

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