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Mathematical Programming Models to Increase Land and Water Use Efficiency in Semi-arid NE-Brazil

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ABSTRACT

Construction of the Itaparica dam and reservoir induced changes in the agricultural production systems of the Itaparica micro-region, at the lower-middle São Francisco river basin. Extensive traditional systems were replaced by e.g. irrigated fruit production. However, over twenty years after the dam construction, many farmers are still facing income insecurity. A survey, consisting of expert interviews and structured on-farm interviews, has been conducted to analyze current production systems. A Linear Programming farm optimization model was applied to determine optimal land allocation considering changing production conditions. Income depended strongly on low wages for day laborers, free irrigation water, and stable prices of the main crop, coconut. Diversification of production and improved market access can help to improve farmers' income situation. Moderate water pricing can raise the awareness of water scarcity and lead to implementation of water saving production methods.

Keywords: Agriculture, linear programming, irrigation, water efficiency, decision support, rural development, Itaparica, Brazil.

1 Introduction

Since the 1950s Brazil's government promoted irrigated agriculture to reduce the consequences of droughts and rural poverty in the semi-arid region of the country's northeast (Untied, 2005). The construction of several dams and reservoirs along the São Francisco River to provide energy to the growing economy and cities of northeast Brazil supported this intent (World Bank, 1998). Aside from their primary function, dams provide additional uses such as flood control, fishery, water storage for human and livestock consumption as well as for irrigated agriculture (Selge and Gunkel, 2013). Permanent water availability facilitated the implementation of irrigated agriculture under naturally unfavorable conditions for intensive agricultural production (Untied, 2005). One of those dam projects was the construction of the Itaparica dam and reservoir at the lower-middle São Francisco River, completed in 1988. Besides resettlement of about 10,400 households, its implementation induced significant changes of the traditional local agricultural production. Intensive irrigated vegetable and fruit production replaced extensive traditional systems, which had consisted mainly of dryland farming along the riverside and extensive livestock production on large areas in the interior (World Bank, 1998). Resettled smallholders received areas inside irrigation schemes equipped with sprinkler systems (center pivot) and free irrigation water as compensation for their flooded land. However, widespread sandy soils are not suitable for the planned intensive crop production (World Bank, 1998). In addition, farmers are still facing problems with the newly introduced production methods, lack of agricultural education and extension, and limited market access (Carvalho et al., 2013; Untied, 2005). Inappropriate irrigation practices, inaccurate use of agrochemicals, and low producer prices persist (Hagel et al., 2012). Despite governmental efforts to promote agricultural cooperatives and associations, most peasants farm on their own and, thus, have not sufficient market power in negotiation with traders (*atravessadores*), who, in most cases, dictate the prices of agricultural commodities (Hagel et al., 2013). Due to the resulting low income, farmers at the Itaparica reservoir still do not pay any fee for irrigation water. This is in contrast to other regions along the São Francisco River (Untied, 2005).

This study aims at economically analyzing current production systems and identifying the consequences of changing production conditions of perennial fruit production of small farms at the Itaparica reservoir. Farm analysis is conducted using a cost-benefit calculation. Effects of changing production conditions and corresponding changing resource allocations at farm level are analyzed using a linear programming model.

2 Material and Methods

2.1 Study region

The Itaparica reservoir is located in northeast Brazil (*Sertão*) as shown in Figure 1. The reservoir borders the Pernambuco state to its north and the Bahia state to its south (Ferreira Irmão et al., 2013). The Luiz Gonzaga Dam, formerly Itaparica Dam and therefore giving the name to the Itaparica reservoir, is one of the seven dams at the São Francisco River. These seven dams form four hydropower complexes (CHESF, 2014). This study concentrates on the irrigation scheme Apolônio Sales, near the town Petrolândia in Pernambuco. It is one of the four irrigation schemes around the Itaparica reservoir in Pernambuco state (Ferreira Irmão et al., 2013) and presumed to be a model for rather successful implementation of a small-scaled irrigated fruit production.

Climate in the study region is semi-arid, characterized by average annual rainfall of around 300 mm and an average temperature of 25° C. Evaporation potential reaches up to 2,500 mm. According to the Köppen-Geiger Climate Classification, the climate type is BSh. Natural vegetation is the shrub and thorn forest Caatinga (Parahyba et al., 2004). Dominant soils are Arenosols, characterized by low nutrient availability and high water permeability (Araújo Filho et al., 2013).

Due to the semi-arid climate, agricultural production beyond subsistence farming depends on the perennial São Francisco River. Water for irrigation is pumped to the fields on farmers' personal

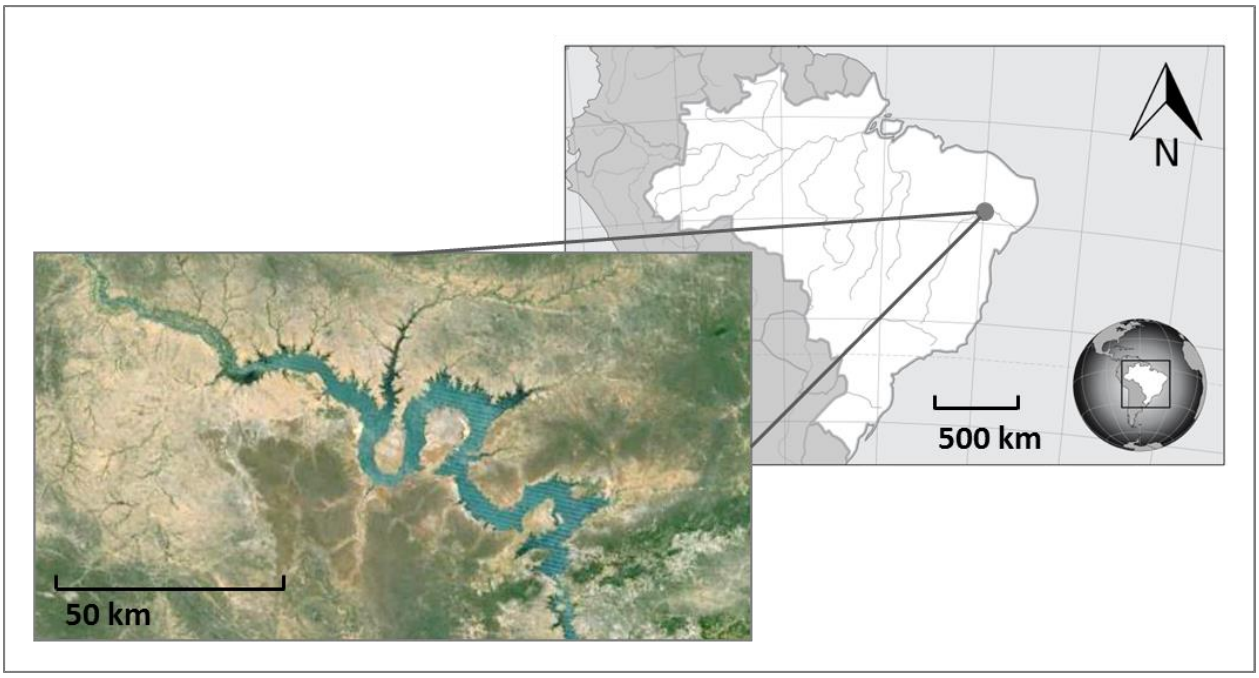

Figure 1. Location of the Itaparica reservoir. (Source: Own figure after Google Earth, 2014 and National Geographic, 2014

responsibility or, in most cases, provided within irrigation schemes (AQUASTAT, 2014). Unlike the humid high section and the adjacent less arid upper middle area of the river where private irrigation schemes dominate; practically all irrigation schemes along the lower-middle part were built or promoted strongly by the public sector (Calvacante, 1997). Due to the construction of hydroelectric power plants and promotion of irrigated agriculture, population and economy grew rapidly in the study region. For many rural households, irrigated agriculture is still the main income source (Ferreira Irmão et al., 2013). Currently, there are 34 public-sector irrigation schemes along the São Francisco River with a total irrigable area of around 120,000 ha (CODEVASF, 2014), whereas the total irrigated area in the river catchment exceeds 600,000 ha (ANA, 2013). Around 77% of the total water withdrawal (214.7 m^3/s of total 278.8 m^3/s) is used for irrigation (ANA, 2013).

2.2 Methodology

To evaluate current production methods and production alternatives, qualitative and quantitative methods were applied. First, secondary data evaluation and sixteen semi-structured expert interviews were conducted to gain an overview on agricultural production. Preparation, realization, and analysis of the interviews were conducted following general guidelines for qualitative data analysis (Bernard, 2006). An income statement for farm production and a Linear Programming (LP) farm optimization model were applied to determine site-adapted farm structures and efficient resource use. Mathematical programming models are widely used to solve resource allocation problems in agriculture (Kaiser and Messer, 2011). Due to their ability to predict farmers' reactions towards changing production conditions, they are suitable decision support tools for policy makers, extension services, and farmers (Berbel and Gómez-Limón, 2000). The model was adjusted to regional characteristics in cooperation with local extension service and uses farmers' preferences determined from twenty semi-structured on-farm interviews (Lienert et al., 2013). Data for the analyses were collected from smallholders in a random sample of 191 structured on-farm interviews. According to Ferreira Irmão et al. (2013) productivity in the irrigation scheme Nilo Coelho, around 300 km to the west of the Itaparica reservoir, is higher and technologically more advanced than in the schemes around the Itaparica reservoir. To get an insight into its agricultural production, 22 interviews were conducted there. A total of 139 interviews were conducted in irrigation schemes at the Itaparica reservoir. The remaining 30 interviews were conducted with independently irrigating farmers along the riverside.

Based on the primary data collected and secondary data received by local authorities, a LP model of a representative farm in the irrigation scheme Apolônio Sales was formulated.

As farmers mentioned in the interviews that they were mainly interested in profit maximization (own interviews and Lienert et al., 2013), the objective function of the model was formulated to maximize the farms' gross margin (GM, income less variable costs):

$$\max GM = \sum GM_i * X_i$$

where,

- GM is the Gross Margin,

- X is the cultivated area,

- and i= 1… n are the cultivated crops (Berbel and Gómez-Limón 2000).

Farmers in the Apolônio Sales scheme had a maximum irrigated land of eight hectares (ha) available. Thus, an area constraint was included into the model:

$$\sum X_i \leq 8\ ha$$

In addition, labor and water constraints were added as shown in chapter 3.3. To spread the risk of low prices or yield loss of one specific crop, farmers of the irrigation scheme chosen grow various annual and perennial crops. To consider this, the maximum area per crop was restricted, based on the cropping pattern of the irrigation scheme and the current allocation of the main represented crops in the irrigation scheme. To simplify the model, a cropping period of one year was assumed. As plantation costs did not differ strongly between the crops, they were not considered in the model. Hiring day laborers is included in the final LP model as shown in Table 1 in the next chapter. Sensitivity analysis was conducted to simulate farmers' reactions to a possible implementation of water pricing and increasing wages. Assumed wage increases and water prices are based on information received from farmers in Nilo Coelho. For possible water prices, secondary data (Do Amaral et al., 2004) were considered additionally.

3 Results

In the region around the Itaparica reservoir, the relation between annual and perennial crop production is balanced. However, the area of perennials increased constantly since the initiation of irrigated agriculture within the irrigation schemes, whereas the importance of annuals decreased (IBGE, 2012). According to interviewed experts, data of local decision makers (CODEVASF, 2013), and secondary literature (Ferreira Irmão et al. 2013), perennial fruit cultivation dominates especially in the irrigation scheme Apolônio Sales.

Coconut (*Cocos nucifera*) is the dominant fruit cultivated on nearly 60% (470 ha) of the irrigated area. The other relevant perennials are banana (*Musa ssp.*) and mango (*Mangifera indica*). Annual crops, mainly maize, peanuts, beans, and watermelon, are grown on soils not suitable for perennials or as intercrops in recently planted perennial plantations.

Table 1 illustrates the average GMs of the main crops within the irrigation scheme, based on data of CODEVASF (2013). All results presented in the following originate from the authors' interviews. Although mangos are harvested once per year, coconut and banana plantations provide yields through the whole year. Due to this and high tree maintenance requirements by the farmers, mango is cultivated on relatively small areas, despite its high GM.

Table 1.
Area and Gross Margin of the main crops in Apolônio Sales 2012

	Cultivated area (ha)	Gross margin (R$/ha)
Coconut	470	2,400
Banana	90	2,700
Mango	42	7,500
Maize	20	3,100
Beans	12	4,100
Peanut	11	4,170
Watermelon	7	4,900

Source: CODEVASF, 2013

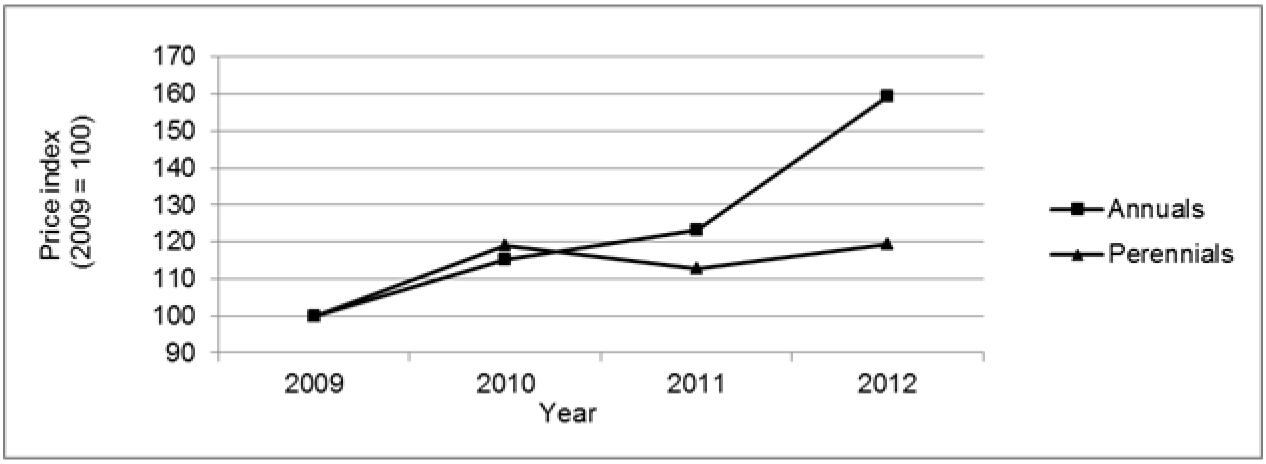

Figure 2. Development of price indices of major annual and perennial crops in Apolônio Sales (Source: Own calculations after CODEVASF, 2013)

3.1 Farmers' income depends strongly on low wages of hired labor

The share of hired labor for the generally labor intensive fruit production was around 60-70% of the total workload. As variable costs, the expenses for day laborers were already included in the GM presented in Table 1. During the study period, the average daily wage of a day laborer was 30 Brazilian Reais (R$), equal to the legal minimum wage. In the adjacent region of Petrolina with higher labor scarcity, the average wage was 40 R$ per day. As shown in Table 2, such an increase of daily wages can strongly affect the GM and therewith the smallholders' income.

Table 2.
Average amount and costs of hired labor in 2013

	Hired day laborers (days/ha/year)	Costs with 30 R$/day*	Costs with 40 R$/day	Costs with 45 R$/day
Coconut	98	2,940 R$	3,920 R$	4,410 R$
Banana	89	2,670 R$	3,560 R$	4,005 R$
Mango	143	4,290 R$	5,720 R$	6,435 R$

* = Average wage during the study period

3.2 Returns from crop production are too low for a regular water price

A fee for irrigation water is not yet included in the GMs for the irrigation scheme. Consequently, and in addition to high implementation costs, most farmers still use old sprinkler systems on coconut and mango plantations, resulting in inefficient water consumption. Due to higher plant densities in banana cultivation, micro-sprinkler systems are broadly used for this crop. The low returns of the current production systems could reduce or become negative with the implementation of a water price. Farmers in the irrigation scheme Nilo Coelho in the adjacent Petrolina region pay around 900 to 1,800 R$ per hectare and year for irrigation water. This fee is divided into implementation costs for the necessary infrastructure, maintenance of the infrastructure, and a usage-bound water price per 1,000 m^3. Do Amaral Santana et al. (2004) even assume water fees in banana cultivation in Bahia state of between 1,700 R$/ha and 2,600 R$/ha. Despite the negative impact of a water price to the farmers' income, irrigation water free of charges leads to an overuse of the scarce resource within the irrigation scheme. Local experts also assumed that large areas next to the irrigation schemes are irrigated illegally.

3.3 LP models to simulate the impact of water pricing and increasing wages

To quantify the role of labor availability and free irrigation water, three LP models were developed as shown in Table 3 and Table 4. To calculate the effect of increasing wages, the hired average labor costs (Table 2) were added to the respective GMs. Equation (I) in the models represents the objective function. Arising expenses for hired labor and water are also considered. Equation (II) illustrates the area constraint. To consider the farmers' preference towards crops with lower risks of income losses (banana and coconut), half of the available area had to be used for those crops (equation III). In average, a family farm had around 5,000 hours of family labor available per year. An additional day laborer (8 hours) could be hired as shown in equation (IV). Because water pricing is not included in the model and yields did not differ significantly between sprinkler and micro-sprinkler irrigation, the different irrigation methods are not considered in this model.

Table 3.
Illustration of LP model with area and labor constraint under current situation

Decision	Coconut (1 ha)	Banana (1 ha)	Mango (1 ha)	Employ day laborer (8 hours)	Solution
Variable	$X_1 = 4$	$X_2 = 0$	$X_3 = 4$	$X_4 = 1{,}040$	Max
Objective					
(I) GM (R$/ha)*	5,340	5,370	11,790	-30	37,320 R$
Constraints					Goal
(II) Area (ha)	1	1	1		≤ 8
(III) Area low risk crops (ha)	1	1			≥ 4
(IV) Labor (h/ha)	1,200	1,550	2,130	-8	≤ 5,000

* Excluded hired labor costs, GMs calculated based on own data and CODEVASF, 2013

As shown in Table 3, banana under current circumstances is theoretically not competitive to coconut. Disregarding the required high level of knowledge for mango cultivation, it is the most competitive perennial crop due to its high GM, as it is more productive per used area and labor. The most scarce factor in this solution is area with a shadow price of 3,802.5. This shadow price is equal to the GM of an additional hectare of mango excluding the required hired labor costs.

The model in Table 4 contains an additional moderate water price. A fee of 53 R$/ha for maintenance and 56 R$ per 1,000 m³ consumed water was assumed, in accordance to information received by farmers in the Nilo Coelho scheme near Petrolina. As the irrigation scheme already exists and because governmental agencies resigned from charging farmers for implementation costs for infrastructure in comparable regions, these costs were not included in the model. In coconut and mango plantations, the sprinkler and micro-sprinkler irrigation systems exist. Thus, both production alternatives were included for both crops in equation (V). Average costs of micro-sprinkler systems, including implementation costs, were subtracted from the GMs (380 R$ in coconut cultivation and 300 R$ in mango cultivation). As bananas are cultivated mainly with micro-sprinkler irrigation, the model contains only this production alternative. The water constraint was added in equation (VI).

As shown in Table 4, water pricing reduced the total GM by around 5,000 R$. It had no influence on the relation between coconut and mango production. Due to its high water demand, banana cultivation became less competitive and was not included in the solution. High water consumption of mango cultivation with sprinkler irrigation caused a switch to production with micro-sprinklers. Shadow prices for an additional area decreased to 3,140.

Finally, an increase of hired labor costs to 40 R$/day was assumed. The composition of the solution did not change, but the total GM declined to 21,875.07 R$. Consequently, the shadow price of irrigable area declined to 477.77. With an increasing wage, the shadow price of an additional hour of family labor increased from 3.75 to 5.

4 Discussion

Analysis of the current production methods showed relatively low income in irrigated fruit production and therefore high economic vulnerability of smallholders. The high dependency on low wages for day laborers make smallholders susceptible to changing production conditions – especially considering the rapid increase of minimum wages in the last decades (MTE, 2014).

The high share of coconut in the irrigation schemes leads to high dependency on prices of coconut, which may drop due to high supply and competition between farmers. Increased variability in production may reduce their dependence on single product prices. Thus, for a profound analysis of optimal area allocation of small farms, a broader selection of appropriate crops should be considered. The competitiveness of mango production seemed quite high, influenced by the relatively high prices obtained during the study, as well as in the period investigated by CODEVASF (2013). However, farmers also mentioned that the average mango price was up to 50% below the price assumed in this study. The higher required knowledge in mango cultivation, especially due to several necessary prunings and variable irrigation, is also not yet considered in this study. One the one hand, the case of mango cultivation indicates the economic potential of site adapted and the diverse irrigated fruit production in the study region. To enable farmers use the existing potential, personal agricultural extension including intensive assistance in alternative crops is strongly recommended. On the other hand, irrigation water, and subsequently irrigable land, is limited. De Loreto et al. (2001) observed an overexploitation of arable land in comparable irrigation projects in Espirito Santo, Southeast Brazil. This leads to the conclusion that income alternatives besides irrigated agricultural are required to lower the economic pressure on the limited irrigable land and thereby ensure sustainable agricultural production.

Improved market access and higher producer prices are crucial to provide secure farm income. However, provided agricultural extension services are available, moderate volumetric water pricing may lead to implementation of more efficient irrigation technologies and water saving techniques. Rodorff et al. (2014) mentioned that the educative use of simulated bills in the study region already reduced water consumption. Still, to reduce illegally irrigated plantations, especially on unsuitable soils without drainage, water pricing can be a suitable tool. Furthermore, the implementation of micro-sprinkler systems in banana cultivation shows the farmers' willingness to implement water saving technologies. Developed models seem to fit well to actual production systems and can serve as easy and understandable decision support tools. Selective policy instruments can help to ensure the local farmers' livelihood under economically fragile production conditions.

Table 4.
Illustration of LP model with area and labor constraint included moderate water prices

Decision	Coconut sprinkler (1 ha)	Coconut micro (1 ha)	Banana (1 ha)	Mango sprinkler (1 ha)	Mango micro (1 ha)	Employ laborer (8 hours)	Buy water (1,000 m³)	Solution
Variable	X_1=4	X_2=0	X_3=0	X_4=0	X_5=4	X_6=1,040	X_7=61,1	Max
Objective								
(I) GM (R$/ha)*	5287	4907	5317	11737	11437	-30	-56	32,275.07
Constraints								Goal
(II) Area (ha)	1	1	1	1	1			≤ 8
(III) Area low risk crops (ha)	1	1	1	0	0			≥ 4
(IV) Labor (h/ha)	1,200	1,200	1,550	2,130	2,130	-8		≤ 5,000
(V) Irrigation water (m³/ha)	9,750	5,616	17,347	19,500	5,522		-1,000	≤ 0

* Excluded hired labor costs

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