ABSTRACT

CONTEXT

This paper assessed the potential for agricultural development in the Colombian Altillanura, a frontier area of a middle-income country with a history of internal conflict. This region is suitable for growing diverse crops ranging from staple crops and livestock to high-valued commodities such as cacay (a nut whose oil is used in the cosmetic industry).

OBJECTIVE

The model suggested an optimal portfolio of agricultural enterprises for a representative farm that maximizes revenues net of variable costs and returns to resource endowments. Traditional agricultural enterprises were assessed, as well as some others that appear to be promising possibilities for Altillanura.

METHODS

A linear programming model (LP) was designed to support the assessment of the relative profitability of agricultural enterprises in a post-conflict era as a response for the need to reduce agricultural net imports, satisfy a growing domestic food demand and boost economic and social development.

RESULTS AND CONCLUSIONS

A major finding was that labor shortages in the region are a key constraint for perennial crops such as oil palm, cacay, and cashew. Inclusion of mechanized crops like rice, corn, and soybean can help to alleviate this limitation, resulting in the preferred farm choice among the conventional farm activities. Integrated (Crop + Hog) operation is the most profitable among promising enterprises, but its operation size would be constrained by access to processing plants and marketing strategies. Cacay and cashew represent a viable option for farms to increase net returns using high-valued perennial crops.

SIGNIFICANCE

Currently, cattle production on native savannas is the most common agricultural activity in the region, but this model challenged this status quo by identifying other more profitable alternatives that include improved production systems for cattle, hogs, and crops.

Identifying profitable activities on the frontier: The Altillanura of Colombia

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1. Introduction

Expansion of agricultural frontiers plays an important role in the achievement of food security. The United Nations has projected that both agricultural intensification and extensification will be necessary to feed the worldwide population of 9.1 billion expected by 2050. Estimates indicate that even if yields almost double (90% increase), arable land will have to expand by 120 million hectares, primarily in sub-Saharan Africa and Latin America (FAO -Food and Agriculture Organization of the United Nations, 2009).

This paper sheds light on the assessment of agricultural prospects at the frontier using a linear programming (LP) approach. In Colombia, the most relevant agricultural frontier is the Altillanura, with 5.19 million hectares of arable land that may potentially be used for crops, cattle, and forestry. The Altillanura is a subregion of the Orinoquía with a low population density, i.e. one person for every 118.3 hectares (UPRA - Rural Agricultural Planning Unit, n.d.), located in the Eastern Plains of the Andean mountains of Colombia, and extending over the Orinoco river basin. Nevertheless, the region has not reached its full potential – by 2015, only 10% of the 2.04 million hectares suitable for crops were planted (UPRA - Rural Agricultural Planning Unit, n.d.). This lack of development was attributed to adverse factors including the violence associated with 50 years of civil war between the Colombian government and the former FARC (The Revolutionary Armed Forces of Colombia) and other illegal armed groups.

This territory offers great potential for improving gross domestic product and employment. In document 3797 the Colombian National Economic and Social Policy Council (CONPES), established the guidelines of public policy for the development of the Orinoquía that recognize the importance of enhancing infrastructure, territorial planning, incentives for private investment, whilst also strengthening institutional capacities (CONPES, 2014). Over 2016-2018, the DNP (Colombian National Department of Planning) carried out the Orinoquía Master Plan, which aimed to design a long-term planning strategy for the Orinoquía based on the potential use of regional resources, and opportunities arising from the FARC peace agreement. The main goal of that plan was to identify the priorities for regional planning, use of the natural resources, and infrastructure investments, and to develop agricultural systems for the region (DNP- Colombian National Planning Department, 2016). This paper is aligned with both the CONPES 3797 and the Orinoquía Master Plan as it enables better decision-making in support of the inclusive and sustainable development of this region.

Agricultural alternatives to traditional extensive cattle on native savannas enterprise in the region include oil palm, rice, natural rubber, maize, soybeans, and cattle production on improved pasture. Also, there are other promising enterprises such as cacay, cashew, and integrated crops and livestock production. However, most of the land area is still not achieving its agricultural potential. For instance, in Vichada (the largest department in the Altillanura by land area) 78% of agricultural land is in native savanna for extensive cattle production (DANE, 2016), and there is vast room for improvement in the adoption of cattle production technologies proposed by CIAT and AGROSAVIA on grasses and legumes that, with soil amendment, have successfully improved cattle production (Rincón Castillo and Flórez Díaz, 2013; Rivas, 2004; Rodríguez Borray et al., 2015). Nevertheless, farmers who adopt these production systems may experience capital constraints due to the relatively high costs of pasture improvements which comprise not only the grass seeds but also the recurrence of soil amendments to improve soil fertility. As another alternative, the Altillanura has soil and climate conditions that are similar to the Brazilian Cerrado, offering an opportunity for establishing large-scale grain production. Because of the diversity of possible agricultural alternatives in the Altillanura, an approach is needed to identify portfolios of complementary enterprises that make efficient use of resources.

A representative farm LP model was developed and calibrated for the region to assist planners with this task. This article assessed agricultural choices in the Altillanura by addressing the following questions: (1) How does the extensive cattle production system perform compared to other alternatives for cattle production? (2) What is the optimal mix of traditional and promising enterprises that maximize net revenue? (3) To what extent do labor shortages limit the potential of farms in the Altillanura?

In summary, the results of this study make three contributions. This is the first study of farm-level production opportunities in the Colombian Altillanura, one of the few under-developed agricultural frontiers in Latin America. This study implements a linear programming model using a steady-state rotation approach to compare annual and perennial enterprises, accounting for differences in seasonal use of farm-level resources. Second, new primary data regarding labor demand, and cash use on a monthly basis for a diversity of crops in the Altillanura was presented. Third, this assessment addressed relevant policy issues that can be used as a template for the analysis of farm-level production for other regions of Colombia.

2. Methodology

The Orinoquía-LP is an agricultural planning linear programming model developed to analyze agricultural opportunities in the Altillanura at the farm level. The methodology simulated a representative farm including the farmer's decision-making process. For this study, crop alternatives and bovine production systems from eastern Meta and Vichada were incorporated as well as promising activities considered adaptable to the region. The methodology was based on the following steps: (1) collection of relevant data on farming enterprises, (2) description of price and cost structure by enterprise, (3) development of the modeling framework; and (4) definition of farm policy scenarios.

2.1. Collection of relevant data on farming enterprises

Most of the agricultural alternatives described were found in eastern Meta and western Vichada. The base case for the model was calibrated as a representative farm in Vichada, the department with the largest land area of the Altillanura. This study assessed the traditional cattle production system on native savannas versus enhanced production systems with improved pastures – proven to work in the region by the International Center for Tropical Agriculture (CIAT) and the former ICA, which is currently known as the Colombian Corporation of Agricultural Research (AGROSAVIA). Conventional crops and promising options adaptable to the region were also incorporated. The collected data contains monthly input and output information on each enterprise covering its entire lifespan. This information was gathered in 2017, under the Orinoquía Initiative from Purdue University ("Orinoquía Initiative - Colombia Purdue Partnership - Purdue University," 2017), through interviews with 66 institutions from the Orinoquía and 107 farmers, as well as agricultural studies from Colombian research centers in this region, such as AGROSAVIA and Cenipalma.

2.1.1. Cattle farming systems

Five cattle production systems were evaluated: the traditional extensive farming system on native savanna and four cattle activities using improved pastures. Production technology, stage of animal production, stocking rate, and net return are presented in **Table 1** for the five systems.

Enterprise	Production Technology	Stage of animal production	Stocking rate* (AUE/ha)[a]	Yield (kg live cattle/ha)	Net Return (million pesos)[b]	Net return (thousand pesos per ha)[b]
Traditional	Native Savanna	Cow-calf	0.11	17.0	34.7	17.3
Cow-Calf	Improved Pasture	Cow-calf	1.20	177.6	304.5	152.3
Beef fattening	Improved Pasture	Finishing	1.80	759.0	1,094.2	547.1
Pasture + silage	Improved Pasture + Silage	All stages	3.00	468.0	1,788.3	894.2
Crop-Pasture	Crop rotation + Improved Pasture	Finishing	2.70	537.0	2,435.1	1,217.6

Table 1 Productivity of cattle technologies evaluated

a: Animal unit equivalent (AUE) of 450kg
b: 2017 currency exchange rate: 2,951 Colombian pesos = 1 US dollar.

The system described as the *traditional system* in this paper consists of extensive farming where beef cattle are fed on native savanna pastures and water is available from natural sources. The quality of native forages is low, limiting the stocking rate to 0.11 animal unit equivalent (AUE) per hectare. Three categories of animals are raised: heifers, steers, and cows; however, most females are kept for breeding in the herd while males are sold. The main product is 180kg-steers, usually sold in local auctions.

The *cow-calf* enterprise on improved pastures represents a system where calves are raised and grazed on improved pastures until they reach 250-300 kilos when they are sold for backgrounding and finishing. Cows have a parturition rate of 0.67 times per year, with the first pregnancy occurring at 28 months old. The improved pastures (IP) are renovated every five years. Paddocks are 20 hectares with a stocking rate of 1.2 AUE per hectare; herds stay no longer than 4 continuous days in the same paddock but can return in 30 days. Steers are sold before they reach 300 kilos, but heifers are sold when they exhibit deficiencies either in their reproduction patterns or in the development of the offspring. The annual replacement of cows is about 12%.

The *beef fattening* enterprise grazes animals in the fattening stage on improved pastures, with a stocking rate of 1.8 AUE per hectare. Paddock rotation and renovation of pastures are similar to the *cow-calf* system. Animals are received at a weight of 250-300 kilos and fattened for 13-14 months, during which animals gain 200 kilos before being sold for slaughter. Considering the carrying capacity, a net weight gain of 324 kg/ha-year is attained under this system.

The *beef pasture + silage* enterprise included the complete lifecycle of the cattle. Under this system, cattle are fed on improved pasture throughout the year and are supplemented with corn silage during the dry season (i.e., 5-10 kg per day). Corn is planted in addition to the improved pasture and is harvested 80 days after planting. As the silage yield covers the needs of one hectare of cattle production, any excess silage may be sold. This system allows a stocking rate of 3 AUE per hectare, with animal paddock rotation similar to the beef fattening system. Heifers and cow production cycle and replacement follow similar procedures as the cow-calf system.

The *crop-pasture* system is a rotation of crops and grass-fed cattle. Overall, in the same hectare, annual crops are rotated for 4 years, and then cattle are fed on improved pasture for the next 3 years. The crop rotation starts with rice (planted in April-May), followed by soybeans (August-September); in the second year corn is planted (April-May) followed again by soybeans (August-September). The third and fourth years repeat the production pattern of the first two years. Starting in the fifth year, improved pastures are established and maintained for three years to feed the beef during the fattening stage. The improved pastures allow a stocking rate of 2.7 AUE per hectare in plots of 20 ha during the grazing period. Animals are expected to enter into the pasture rotation weighing 250-300 kilos, and after about two years, they must have gained 200 kilos to be sold for slaughter. Net production of cattle is 537 kg/ha-year.

Labor use for animal management is the same for all cattle production systems. Two full-time workers are needed to manage every thousand animals, along with 80 person-days to support the vaccination schedule.

2.1.2. Traditional crop enterprises

Four traditional cropping practices have been selected as representative of Altillanura: *corn-soybeans*, *rice-soybeans*, *oil palm,* and *rubber*. The first two systems *corn-soybeans* and *rice-soybeans* are whole-year non irrigated rotations of a crop (corn or rice) with soybeans. Corn or rice is typically planted in April-May. Corn is harvested late July-August, rice in late June-August. Immediately following the harvest of these crops, soybeans are planted, and then harvested in December-January. Typical yields are 7, 4.5, and 2.6 tons per hectare for corn, rice, and soybeans, respectively.

Oil palm is a perennial crop with an overall 30-year lifespan that produces Fresh Fruit Bunches (FFB) from which the palm oil is extracted. Fruit production starts in the third year, and yields reach their highest level after year eight when the output plateaus until year thirty. Some activities like harvesting are not mechanized under current practices, resulting in high demand for labor relative to other alternatives such as annual crops. Acidic soils and water stress in Altillanura limit the yield potential of oil palm, which is a challenge during the four months of the dry season (December and April). With no irrigation, oil palm crops seldom achieve yields over 21 ton/ha-year at their mature stage and considering their entire lifespan the average annual equivalent yield is 17.38 ton/ha-year, with harvest occurring throughout the year.

Natural Rubber comes from rubber trees, which are a perennial crop with a lifespan of 30 years. Commercial harvesting starts six years after grafted plants are transplanted to the field. The overall yield increases progressively from 600 kg/ha in the first year of harvest to 1,872 kg/ha after four years, and then production plateaus. Production is distributed uniformly within the year from March to December, with no production in the first two months of the year because of the natural defoliation of the tree. This enterprise does not need irrigation but is labor intensive, especially in the tapping activity (one worker for every 5 hectares) and the collection of the coagulated latex.

2.1.3. Promising agricultural enterprises for the Altillanura

Several enterprises have been introduced on a few farms of Altillanura. These enterprises have high net revenue potential due to growing markets for their products and/or transportation cost advantages compared with traditional enterprises. These alternatives are integrated hog production, cashew, and cacay.

The integrated *hog* system is a combination of hog and crop production in which maize and soybean are produced, and the maize is used as hog feed. An advantage of this enterprise is that it reduces substantially input and transportation costs as grains are consumed on the farm, which increases the value added to the pork products and diminishes the dependence on imported sources of feed. This production operation is practiced by Aliar, one of the main pork producers of Colombia with a farm called La Fazenda in Altillanura (Lowenberg-DeBoer et al., 2017b). Given that Colombia is a net importer of soybeans and corn, this type of integration would help to alleviate the dependence on agricultural imports, which represent 80% and 76% of national consumption of these two commodities (Fenalce, n.d.).

Cashew is a nut harvested from a tropical tree. Currently, this product faces growing international demand (INC - International Nut and Dried Fruit Council, 2018). Colombian domestic demand is estimated at 300 MT per year with fast growth in the last years (Lowenberg-DeBoer et al., 2017a). Colombia is a small producer with only 3,150 ha in harvested cashew for 2014 (Pinzón, 2017), where 900 ha were planted in Vichada (DANE, 2016). Thus, there is an opportunity for farmers in Altillanura to enter the cashew market, which has strong support by the MAS program (Model for sustainable agri-businesses), led by the Center of Studies for the Orinoquía and AGROSAVIA (CEO and AGROSAVIA, n.d.).

Cacay is an indigenous Amazon nut tree that has been domesticated for commercial production. The nuts can be used for food consumption or sold as raw material for cosmetic products in international markets. Most cacay nuts are harvested from wild trees in Meta, Vichada, and Caquetá. A startup Colombian company, Kahai, is a pioneer in extracting the oil for cosmetic uses and developing commercial production systems (Lowenberg-DeBoer, 2017). The market for nuts is currently growing and the Colombian cacay industry is facing shortages. This relatively high-value per kg crop that can be stored offers an advantage for farmers in remote areas.

Monthly variable costs, labor requirements, and yields for all cattle production systems and crops are presented in online Appendices III-V.

2.2. Endowments, prices and cost structure of enterprises

In this section, endowments, prices and cost structures that define the representative farm enterprises in economic terms are discussed. These include land endowment, output and labor prices, cash and labor requirements.

2.2.1. Land endowment

In Colombia, the area of land needed by a family to get an income equivalent to at least two monthly minimum wages is called Family Agricultural Unit (UAF). The calculation of UAF was originally specified by the former INCODER (Colombian Institute for Rural Development) and has been updated over time, reflecting differences in the opportunity cost of land, which varies by location. For instance, in 1996 the UAF in Vichada ranged between 956 ha to 1,924 ha, while by 2013 it fluctuated between 216 ha to 436 ha. Currently, commercial farming endeavors are often five to ten times the size of a UAF (Mejía and Mojica Flórez, 2015; OECD, 2015), but similar in size to one UAF according to the earlier classification. In Vichada, 94% of agricultural land belongs to farms with an endowment greater than 1,000 ha (DANE, 2016). Given this wide range of farm sizes, the representative farm was assumed to have 2,000 hectares, although land availability in the model can be easily adjusted. Also, all crops are assumed to be non-irrigated and land is treated as a sunk cost.

2.2.2. Labor and cash requirements

Three sources of labor were modeled: *family labor* (compensated from farm returns), *temporary hired labor* (with a wage of 50,000 pesos per day), and *permanent hired labor* (with a salary of 15 million pesos per year). These wages represent the cost to farmer including all Colombian labor regulations. The monthly wage is the daily wage times 24 business days. Sources of labor are treated as perfect substitutes. Family and existing permanent labor are treated as fixed and therefore sunk cost (firing is not permitted). Permanent labor is hired for twelve months, while temporary labor is hired as needed. Labor cost is deducted from the monthly-retained earnings of the farm to ensure liquidity to cover monthly expenses. Net earnings before labor cost, and labor requirement per enterprise are included in **Table 2** (for more details see online Appendix III and IV). Due to the limited availability of workers in the region, the model constrains labor hiring to a maximum of 300 permanent laborers in a year, and up to 600 person-days of temporary labor per month.

Enterprise		Earnings before payments to labor (Thousand pesos/ha/year)	Labor requirement (Person days/ha/ year)*	Cash requirement (Thousand pesos/ha/year)
Conventional	Corn-Soybeans	1,250.89	2.01	7,869.28
	Rice-Soybeans	1,414.23	1.99	6,690.98
	Oil Palm	3,008.74	30.26	2,555.13
	Rubber	3,198.24	75.06	1,519.06
	Traditional Cattle	65.33	0.96	7.47
	Cow-Calf	207.26	1.10	560.34
	Beef Fattening	617.59	1.41	2,799.54
	Beef Pasture + Silage	1,074.11	2.85	1,230.60
	Beef Crop-Pasture	1,320.86	1.94	6,017.22
Promising	Integrated Hog	22,157.89	29.64	13,115.98
	Cacay	11,124.97	40.77	1,986.03
	Cashew	2,444.39	9.84	235.61

Table 2 Annual Labor, cash flow requirement, and net return by enterprise

* The temporary hired labor wage is 50 thousand pesos/day.

2.2.3. Output prices

Commodity prices received by farmers in the local market during 2017 are displayed in **Table 3.** Note that, commodity prices are indicated independent of the farming system.

Commodity	Price per unit* (Thousand Pesos/Unit)	Production Units
Rice	1,050	ton
Soybeans	1,300	ton
Corn	820	ton
Oil palm fruit (FFB)	320	ton
Steer fattened	4.5	kg
Rubber	3.5	ton
Cacay	700	ton
Heifer	4.1	kg
Cow	3.9	kg
Steer	4.8	kg
Silage	300	ton
Pork	5.3	kg
Cashew	2,680	ton

Table 3 Sales prices of commodities in 2017

2.3. The Orinoquía-LP model

In this study, a farm-based model designed for the Orinoquía (Orinoquía-LP) was adapted to assess prospects for agricultural development in the Altillanura. This model is written in the GAMS language (for model equations and code, see online Appendix I and II).

2.3.1. The steady-state principle

Orinoquía-LP is a one-year, deterministic model that can compare both short- and long-term (perennial) enterprises by using a *steady-state* principle. This assumption permits the representation of a multi-year crop as an equal-area rotation of the same crop at different stages of the lifecycle. For example, 1 hectare of a three-year crop would be modeled as: one-third hectare each of the first, second, and third year crop, respectively. As such, it is not well-suited for planning for transitions from one cropping system to another, but rather for identifying the cropping system that maximizes the return to fixed resources in the medium to long run as a steady-state.

2.3.2. Framework of the model

Orinoquía-LP model is formulated to maximize the net revenue of a representative farmer in the Altillanura by choosing the optimal portfolio of enterprises limited by input endowments of land, labor, and capital. It also tracked inventories of commodities, allowing uses of intermediate inputs (e.g. crops produced on farm can be used as livestock feed). Model parameters reflected the input requirements and output levels of each enterprise on a monthly basis. The model also allowed borrowing cash, hiring additional labor, saving money, and commodities storage. Commodity storage only became active when monthly commodity price variations are included in the model, which is not incorporated in the base case. Monthly farm expenditure obligations were also reflected in the model as exogenous cash outflows in the constraint tracking the sources and uses of working capital. Enterprises and commodities considered in the Altillanura model are listed in **Table 4**. Resource constraints include land (non-irrigated), labor (family, permanent hired, temporary hired), and cash. Loans from month to month are available at a monthly interest rate of 1.5%.

Enterprise	Commodities
Oil Palm	Fresh Fruit Bunches
Rice-Soybeans	Rice, Soybeans
Corn-Soybeans	Corn, Soybeans
Rubber	Rubber
Traditional Cattle	Heifer, Cow, Steer
Cow-Calf	Heifer, Cow, Steer
Beef Fattening	Fed Cattle
Pasture + Silage	Heifer, Cow, Fed Cattle and Silage
Beef Crop-Pasture	Rice, Soybeans, Corn and Fed Cattle
Integrated Hog	Hog and Soybeans
Cashew	Cashew
Cacay	Cacay

Table 4 Commodities produced by enterprise

2.4. Description of farming scenarios and the situation in the Altillanura

The *Orinoquía-LP* model is flexible in structure and can be modified to reflect policies such as improved credit access, taxes or subsidies to reflect environmental goals (Preckel et al., 2019). The model in this study was used to provide policy makers and farmers with research methods for assessing the economic outcomes of the agricultural alternatives in the Altillanura, anticipating the effect of labor shortages, a problem that eventually must be addressed in this region. By identifying promising agricultural opportunities for the region, this study was aligned with the enhancing of socioeconomic and rural development in the Altillanura, an important component of the government-FARC peace agreement. This is particularly useful for the region considering current challenges: (1) lack of infrastructure and weak capacity of government agencies at the local level, (2) post-traumatic fear associated with violence during the 50 years of conflict between the Colombian government and FARC, (3) limited experience of farmers with crop production, and (4) a lack of training on how to manage multiple enterprises simultaneously. This model takes into account the farm-level limitations in endowments including labor, capital, and land.

For the analysis of the agricultural potential of the region, the following scenarios were considered (see **Figure 1**):

- *Cattle production systems* (*Only-Cattle* scenario). The first scenario focused on the specialized cattle farmer. Cattle production systems based on improved pasture with no crop rotation and the traditional extensive system on native savannas are considered.
- *Perennial crops and Cattle* (*Perennial + Cattle* scenario). This scenario compared perennial crops (palm and rubber) with cattle farming to analyze which combination of these enterprises may improve farms' profitability.
- *Crop and cattle rotation* (*Rotation + Cattle* scenario). This scenario illustrated how farmers could enhance net revenue using a rotation of crops and cattle with improved pasture.
- *Conventional farming systems* (*Conventional* scenario). This scenario illustrated how farmers could enhance net revenue using current resources under an optimal crops-cattle production mix. Three seasonal-rotational crop enterprises (*corn-soybean*, *rice-soybean* and *crop-pasture*) were included.
- *Promising enterprises* (*Promising* scenario). This scenario added attractive newer enterprises for the region (cashew, integrated hog production and cacay) to the *Conventional* scenario.

The goal is to evaluate how profitability may vary if new alternative enterprises are taken into consideration.

- *Labor sensitivity* (*Labor-S* scenario). Given that this region has a relatively low population density, and that labor shortages may occur, it is of interest to know to what extent increases in labor cost may affect profitability for the agricultural systems. For this scenario, which was based on the *Promising* scenario, labor costs (wages plus benefits such as health insurance, retirement plan, meals, housing, and transportation, among others) were increased from 10% to 100% from their original level (in increments of 10%).

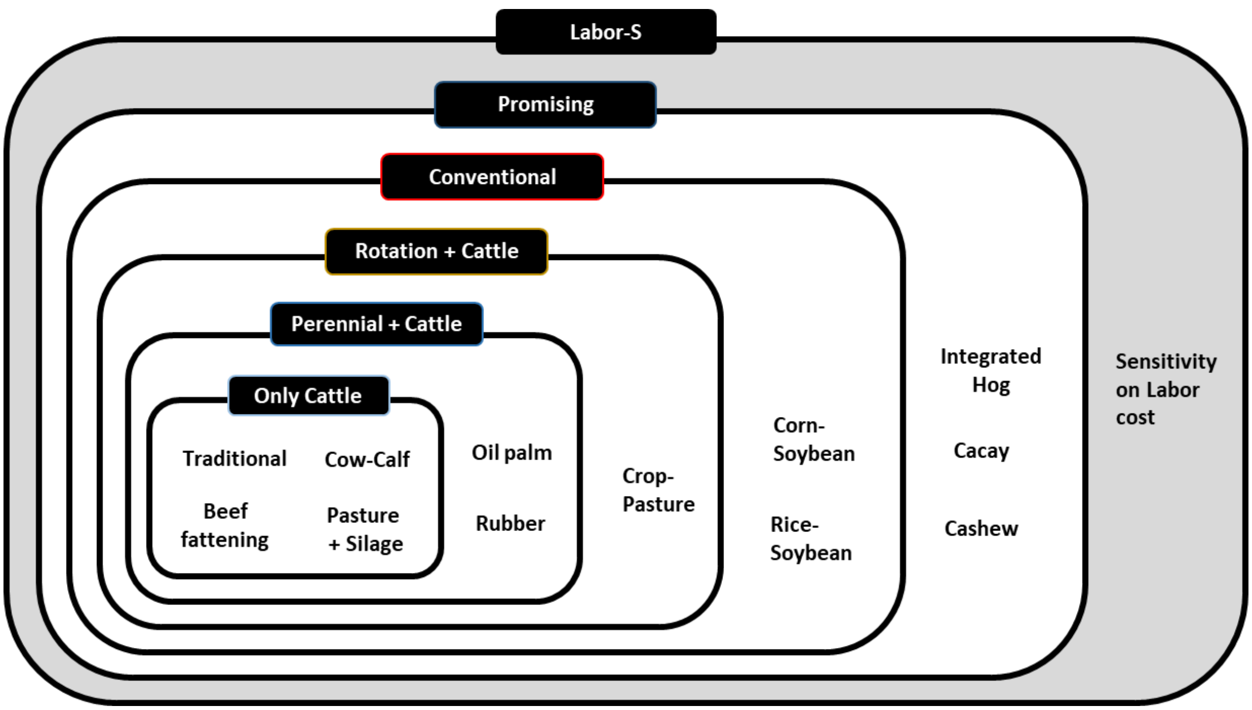

Figure 1 Enterprises available by scenario*

* The figure indicates the nesting of available enterprises by scenario. Only Cattle includes traditional cattle production on native savannas plus three other cattle production alternatives that involve improved pastures: cow-calf, beef fattening and pastures + silage (which is all stages on the cattle production cycle). Perennial + Cattle includes the Only Cattle enterprises plus Oil Palm and Rubber. Rotation + Cattle adds a crop-pasture rotation, to the Perennial + Cattle enterprises, and so on. Labor-S is used to illustrate the impact of wage increases on the most inclusive scenario, Promising.

The hypotheses to be tested from the scenarios were: (I) cattle productions systems based on improved pastures are more profitable than traditional extensive systems; (II) new promising enterprises may improve net revenue; and (III) labor availability is a major constraint to agricultural development in the Altillanura.

3. Results

The Orinoquía-LP for the Altillanura showed the impact of prices, costs and resource availability on the profit maximizing options for this frontier region. This section presents the key results to highlight the differences in enterprises chosen, changes in net revenue, and the implications of changes in labor cost for farming profitability.

3.1. Only-Cattle: Traditional cattle production vs cattle with improved pasture systems

Traditional cattle production on native savannas is the most common agricultural activity in the Altillanura in terms of land use (Galvis, et al., 2007). However, net returns to resource endowments are quite low (see **Table 2**). As a result, when optimizing resources using the *Orinoquía-LP* model, this system is not selected as farmers barely make any net return (i.e. only 17,000 pesos – or 5.8 USD – per hectares seen in **Table 2**).

The adoption of the production of cattle on improved pastures has been more successful for other departments of the Orinoquía than Vichada, such as in Meta. Among the three cattle production systems on improved pastures considered in this study, the most attractive possibility is the *pasture + silage* enterprise, resulting in annual net revenue of about 1.02 million pesos per hectare. Model solutions suggested that the entire 2,000 hectares should be solely devoted to this enterprise (see **Table 5**), which generates a net annual return of 2,042 million pesos (see **Table 6**), driven by cattle yields that are larger than the traditional system and the sale of a surplus of 3,000 tons of silage to the local market. A small loan is incurred during the months of April-May, which coincides with the time that corn is planted for silage. Net revenue is also affected by the employment of 19 permanent workers and hiring temporary workers in the periods of April-July and November-December (**Figure 2**). Note that during July in particular, temporary workers are at the maximum (600-man days), forcing the hiring of permanent labor.

Enterprise	Only Cattle	Perennial + Cattle	Rotation + Cattle	Conventional	Promising
	Land devoted (hectares)				
Traditional Cattle					
Beef Fattening					
Cow-Calf					
Beef (Pasture + Silage)	2,000	1,916.4			
Oil Palm		83.6	70.5		
Rubber					560.3
Rotation (Crop+Cattle)			1,929.5		
Corn-Soybeans					
Rice-Soybeans				2,000	
Integrated (Crop+ Hog)					200.0
Cacay					419.9
Cashew					819.8

Table 5 Optimal land allocation to each enterprise for each scenario

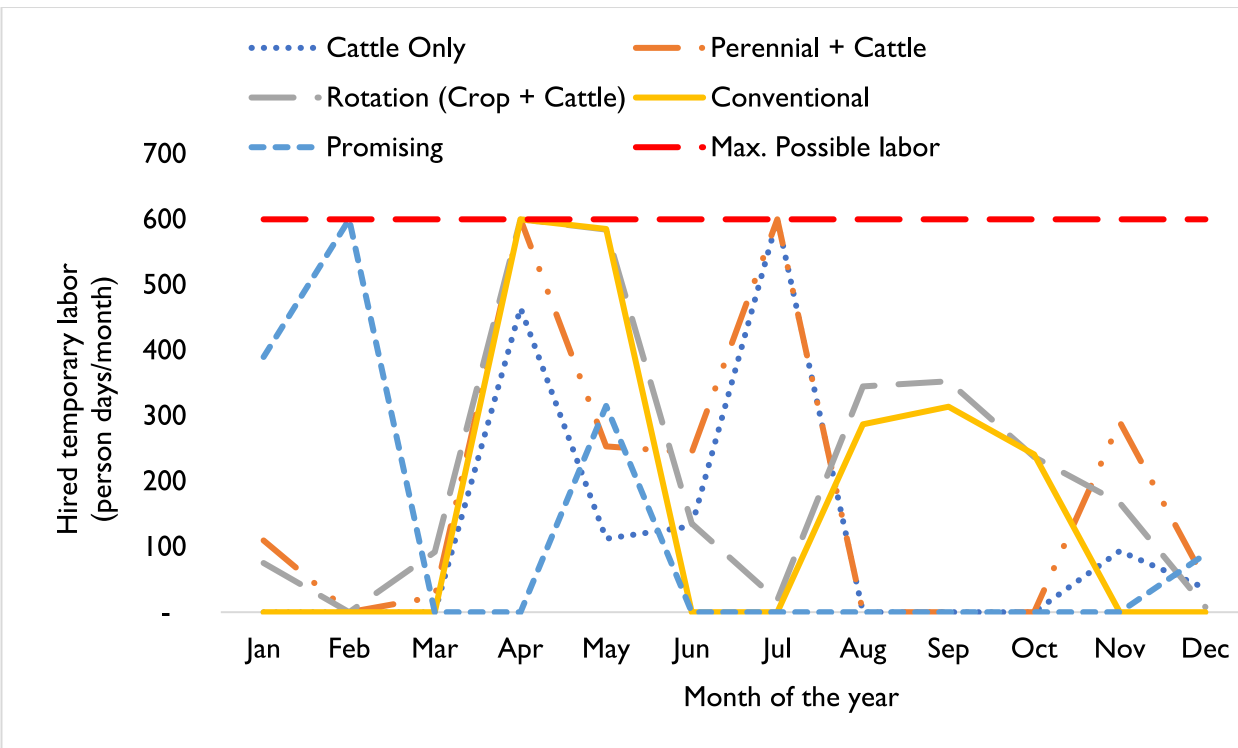

Figure 2 Temporary labor by scenario*

*The figure indicates hiring of temporary labor during the year.

Enterprise	Revenue before labor (Million pesos) Only Cattle	Perennial + Cattle	Rotation + Cattle	Conventional	Promising
Traditional Cattle					
Beef Fattening					
Cow-Calf					
Beef (Pasture + Silage)	2,402.8	2,302.4			
Oil Palm		251.4	212.1		
Rubber					1,792.0
Rotation (Crop+Cattle)			2,548.2		
Corn-Soybeans					
Rice-Soybeans				2,828.0	
Integrated (Crop+ Hog)					2,596.0
Cacay					4,671.7
Cashew					2,003.8
Permanent Labor (workers)	**18.9**	**24.0**	**12.7**	**14.7**	**300.0**
Temporary labor (person days)	**1,437.9**	**2,168.6**	**2,614.7**	**2,027.1**	**1,393.7**
Interest (million pesos)	**4.0**	**0.0**	**3.7**	**17.5**	**0.0**
Net Revenue (million pesos)	**2,042.9**	**2,084.8**	**2,435.2**	**2,489.4**	**6,493.9**

Table 6 Optimal net revenue generated in each scenario

3.2. Perennial-Cattle: Perennial crops vs. Cattle production

This scenario includes the most commonly planted perennial crops in Altillanura, palm and rubber trees in addition to the cattle enterprises. Considering all enterprises of this scenario, the optimal portfolio is a mix of the *pasture + silage* system (1,916 ha) and *oil palm* production (84 ha). This combination provides a net revenue of 2,084 million pesos, which means that profits increase by 42 million pesos with the inclusion of this perennial crop relative to a pure pasture + silage system. Note that, although palm provides larger net earnings than cattle production, it requires twice the working capital and substantially more workers. This makes labor a limiting factor, particularly in April and July. Likewise, shadow prices for both months are higher than the daily wage of 50 thousand pesos, which suggests that it could be profitable to find alternative sources of temporary labor.

3.3. Rotation + Cattle system: A crop-pasture rotation for a cattle farmer

A scenario was developed to evaluate the situation for farmers whose main agricultural activity is cattle production and who would be challenged to abandon this source of income. Thus, to avoid drastically changing management and operational activities, this section introduced a *crop-pasture* rotation into the alternatives. This enterprise offers a higher net return per hectare than other ruminant systems originated from crops (rice, soybeans and corn) and cattle (fed cattle). The results indicate that the optimal combination is to devote most of the resources to the *crop-pasture* alternative (1,930 ha) with a modest complement of palm production (70 ha), for which sales are distributed throughout the year. The resulting net revenue increased to 2,435 million pesos, which is 392 million pesos higher (or +19%) than the profits generated by *pasture* + *silage*.

3.4. Conventional farming: Seasonal rotation, perennial crops, and cattle production

To assess the potential for crop farming based on seasonal rotations, an additional scenario was developed, involving two seasonal crop rotations (*corn-soybean* and *rice-soybean*), in addition to the previous menu of potential enterprises. The results show that the rotation *rice-soybean* enterprise should be the exclusive choice (**Table 5**). Net returns for the farm become 2,489 million pesos (19% higher than the *Perennial* + *Cattle* case). This is because seasonal crops can exploit mechanization, reducing the need for hired labor. Thus, only 15 permanent workers were hired in the solution, and temporary labor would be only needed during April-May and August-October to assist with sowing and harvesting (see **Figure 2**). However, these rotations do not provide year-round production and farmers must borrow money for working capital – 432 million pesos in May and 733 million pesos in June. During the August-October period, there is no need for loans because the revenue from the first crop in the rotation covers the expenses.

3.5. Promising agricultural enterprises for the Altillanura

In addition to the conventional enterprises considered in the scenarios thus far, another scenario adds three alternatives that appear to have good potential for Altillanura: *integrated hog*, *cashew*, and *cacay*. To reflect the limited ability of individual producers to dominate the pork supply, a limit of 200 ha was imposed for the integrated pork enterprise. This would be equivalent to about 1% of the current total regional pork production in the central region of Colombia (which comprises Meta, Bogota, and Cundinamarca).

Given these restrictions, the optimal enterprise mix is a combination of the three promising enterprises and *rubber*. The potential net revenue is 6,493 million pesos, which means that profits more than double the previous scenario. The diversity of enterprises is attributed to the complementarity in the labor use between cacay, rubber, and cashew. Rubber is labor-intensive during March-December, while cashew and cacay labor use peaks in January and February. Consequently, the model reaches full employment of annual permanent workers (see **Table 6**), and full use of temporary workers during February (see **Figure 2**). Note that if one additional temporary employee could be hired during February, net returns could improve by about 500 thousand pesos. Likewise, the marginal value of one extra permanent worker was 2.26 million pesos. Interestingly, there is no need to borrow cash throughout the year because the portfolio of selected enterprises produces income throughout much of the year.

3.6. Labor S: Effect of labor costs on the optimal portfolio

To reflect the likelihood that the dramatic increases in farm-level labor use would have an impact on regional wages, a sensitivity analysis was designed to assess the impact of increased labor costs on the portfolio of enterprises. Here, the percent labor cost increase is applied for both permanent and temporary employees. The sensitivity analysis was based on the *Promising* scenario to observe changes in land distribution across enterprises (**Figure 3**), labor hiring (**Figure 4**), and net returns (**Figure 5**).

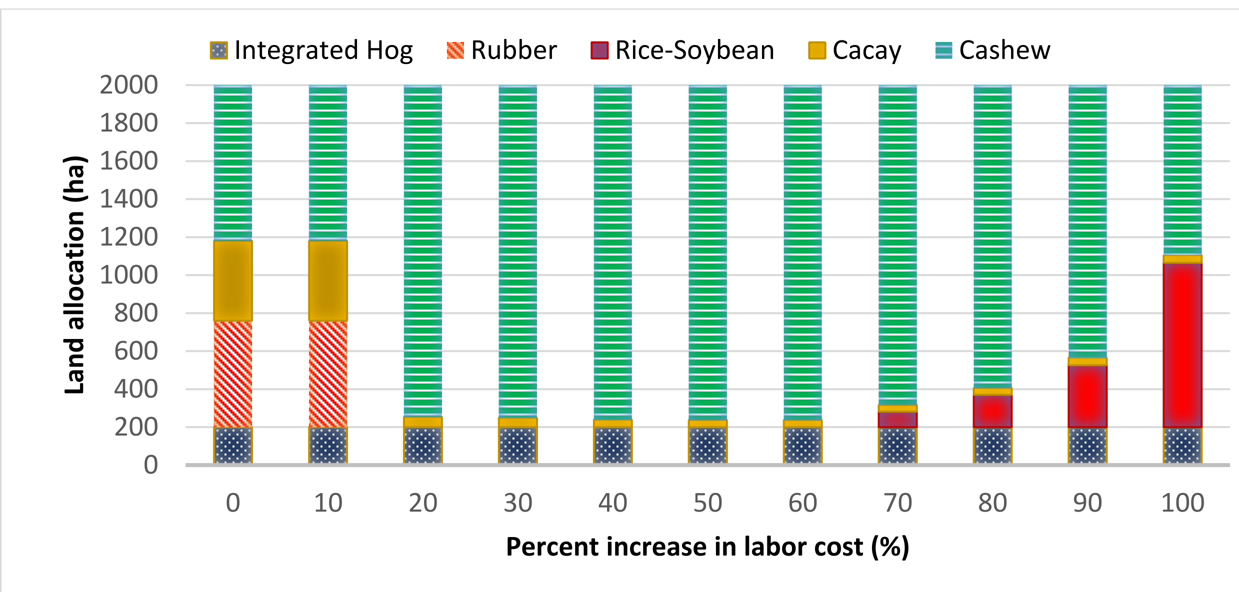

Figure 3 Enterprise allocation in the *Promising* scenario given changes in labor cost (in %)

The sensitivity analysis started with the labor cost in the base model. The optimal enterprise combination for the *Promising* scenario was a mix of *rubber* (560 ha), *integrated hog* (200 ha), *cacay* (420 ha) and *cashew* (820 ha). This portfolio remained optimal under moderate changes of wages in the 0-10% range (see **Figure 3** and **Figure 4**); however, the decrease in net return was 45.7 million pesos for each 1% increase in labor cost (see **Figure 5**). Up to a 10% cost increase, permanent workers were hired at maximum capacity, mainly driven by the labor intensive rubber enterprise during harvesting season.

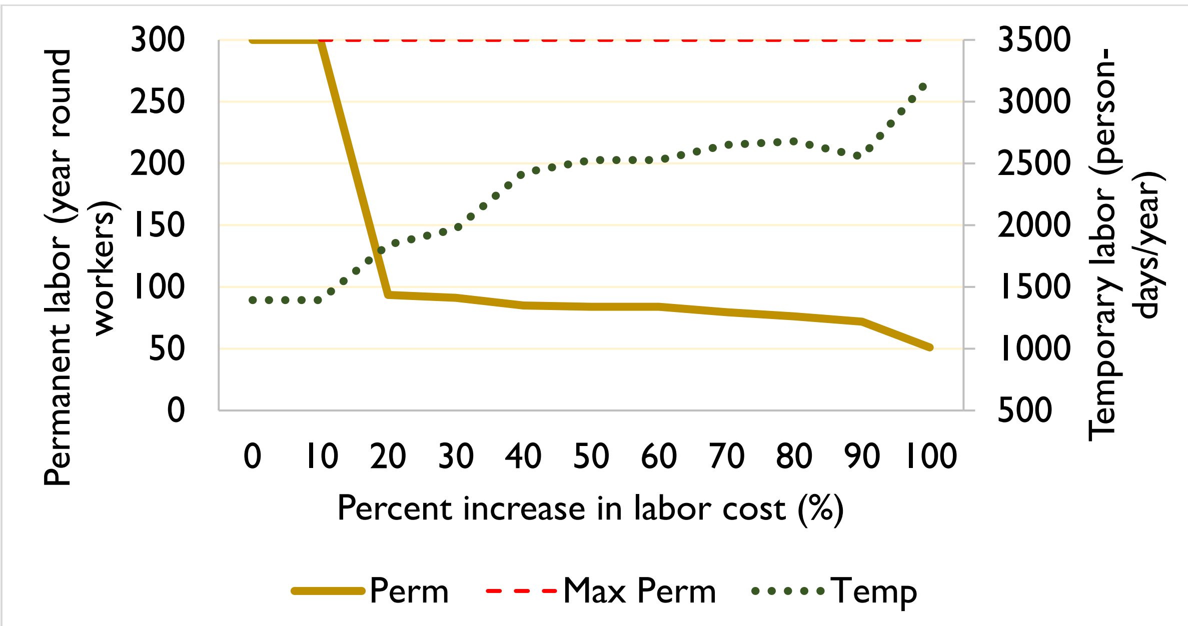

Figure 4 Effect of labor cost on hired labor*

*Permanent labor (left axis –solid line) and temporary labor (right axis – dotted line) hired due to changes in labor cost (in %) for the promising scenario

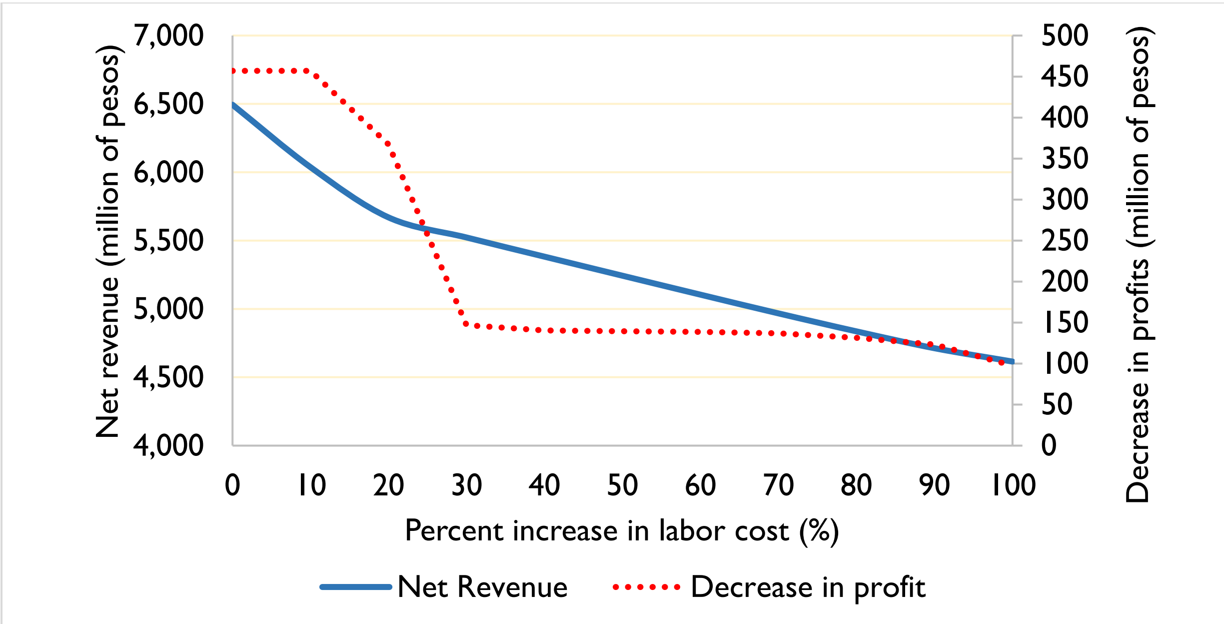

Figure 5 Effect of labor cost on profitability*

*Net revenue (left axis –solid line) and decrease in profitability (right axis – dotted line) due to changes in labor cost (in %) for the promising scenario

As hired labor became costlier, changes in the optimal crop-mix became substantial. When cost increased from 20% to 60% for both temporary and permanent labor, the optimal portfolio involved only *cashew*, *cacay* and small allocation to the *integrated hog* system. Land allocation to labor intensive crops fell, and the complementarity use of permanent labor over time for *cacay* and *rubber* was no longer attractive. Results indicated that farmers with higher labor costs would opt to hire more temporary labor, drastically decreasing the number of permanent workers. Although, net revenue continued to decline, it did so at a decreasing rate.

With even larger labor cost increases (70% or more), the optimal portfolio abruptly changed, shifting to the *rice-soybean* rotation, a less labor-intensive enterprise. This resulted in a further decrease in permanent workers and more frequent hiring of temporary labor. The higher the cost of labor, the larger the substitution of crops in favor to a *rice-soybean* rotation and away from *cashew* (see **Figure 3**).

4. Discussion

Agricultural modelling has been widely studied by authors motivated to promote the scientific understanding of agricultural systems and to support decision-making and agricultural policy (Jones et al., 2017). Models that address the design of agricultural production systems allow farmers to face environmental, technical and economic challenges more efficiently (Le Gal et al., 2011). Linear programming models have been particularly useful for optimizing farm resource allocation, including the use of intermediate inputs in a crop/livestock production context (Ngambeki et al., 1992), and analysis of price volatility (Cai et al., 2013). Such models have contributed to enhancing decision making and agricultural planning by the integration of research, extension, and commercial production. This is the case of a series of LP models developed at Purdue University that were used extensively in extension programs beginning from the 1970s (Brink and McCarl, 1979, 1978; Dobbins et al., 1990; McCarl et al., 1977; Ngambeki et al., 1992). The objective of these models was to select a cropping plan that maximizes the net income for a Midwest commercial farm. The output of those models represented a static equilibrium cropping plan that can be repeated every year assuming no major changes in prices or productivity occur.

Jones (1973) was among the first to study crop allocation models in Latin America. He developed a LP to describe regional agricultural land use for the state of Portuguesa (Venezuela) to help identify policies that improve efficiency by relaxing restrictions on resources. Results suggested that policies should focus on increasing access to capital rather than extending acreage. Nicholson et al. (1994) developed an LP model for a dual purpose (milk-beef) cattle production system for the region of Sur del Lago (Venezuela), in which the objective function was to maximize the discounted herd net margin (revenues less variable cost) subject to some constraints on nutritional factors, feed sources, and herd composition constraints. This model simultaneously allocated farm forage and purchased feed resources among the animals of the herd, and determined the optimal inventory and sales of cows within the herd. Using this model, the authors evaluated how farmers would respond to price incentives, alternative feed ingredients (molasses, urea, and cassava), and labor constraints. Val-Arreola et al. (2004) used LP and partial budgeting to optimize land use for forage production and nutrient availability in Mexican dairy systems. They assessed five forage production strategies and identified alternatives to achieve the highest seasonal stocking rates to maximize returns.

In Colombia, Arcia and Sanders (1980) performed an ex-ante evaluation of a new technology for field beans production (*Phaseolus vulgaris*) in southern Huila (a Colombian department). Their LP model used a profit maximization objective, and constraints included the size of the farm, soil fertility, and diversification. Small farms were classified as either fairly diversified (raising coffee-plantain, corn-beans, pastures, and other crop foods) and less diversified (raising only tomatoes and onions). Land, credit, and labor were constrained, and the decision variables were the land allocations to the crop alternatives, including the new bean technology. Results emphasized the importance of labor and credit availability for adoption of the technology. Recently, Casas Moreno (2018) developed a multi-objective LP model at the farm level in Valle del Cauca, Colombia, to analyze the combination of agricultural activities among sugar cane, passion fruit, cattle, and table grapes (Isabella cultivar) that maximized annual net revenue, or minimized the economic risk (gross income) at the farm, while increasing the efficiency of labor.

The work presented in this article continues this vein of research, focusing on a frontier region of Colombia. Even though linear programming models have been widely applied for farm resource allocation and crop planning, this study is one of the first targeting Colombia and specifically the Altillanura, and results shed light on prospects for agricultural development on the frontier. Details regarding the objective and constraints are provided in Appendix I.

Although traditional cattle production on native savannas is the most common agricultural activity in the Altillanura in terms of land use (Galvis et al., 2007), native grasses provide low-quality feed, resulting in low yields for cattle production with an average annual gain per hectare of only 3-27 kilos (Bernal et al., 2014). In Vichada, alone, more than 4.2 million hectares are used for grazing cattle, and around 95% of this land has native savanna land cover (DANE, 2016). Locals produce cattle under these conditions because investment is minimal; another reason is perhaps land speculation (OXFAM, 2010).

Production of cattle on improved pastures has been more successful in the Meta region of the Orinoquía. CIAT estimated that at least 55% of grass land had transitioned from native grasses in that Department (Gómez Naranjo, 2011). The *pasture + silage* enterprise offers three cattle products (heifers, cows and fed cattle) and corn silage, which is used to complement the pasture diet of the animals during the dry season. Nevertheless, the additional corn cultivation increases labor use and cash requirement; thus, *pasture + silage* requires at least twice the labor of the other alternatives, and a relatively high cash investment (see **Table 2**). The relatively high net returns to this production system are driven by cattle yields that are higher than the traditional system and the sale of a surplus silage to the local market. However, labor requirements are nearly triple the level of the traditional system.

Perennial crops commonly planted in Altillanura are palm and rubber trees, which require nearby processing facilities and include labor intensive activities such as harvesting and tapping. As these field activities need to be performed regularly on the same plot, managers are likely to offer long-term employment, which helps to prevent labor-shortages, especially during peak harvest. The recommendation of combining oil palm and cattle production, however, must be taken with extreme caution because the grasses host *Haplaxius crudus*, an insect associated with the lethal wilt, one of the most harmful diseases for oil palm in the region.

A transition to substantially more complex production systems, some of which may include processing onsite, leads to the consideration of systems involving a rotation of crops and pasture. The *crop-pasture* enterprise yields higher net returns per hectare than other cattle systems, with a more diversified income stream. Working capital requirements are higher (about 6 million pesos/ha), but labor use is less intensive than the *pasture* + *silage* system. However, this alternative might be challenging for ranchers as the core crop activities require a rigorous schedule.

Farmers in the Altillanura have achieved relatively higher yields in their annual crops by managing soils, including application of lime and inorganic fertilizer. Seasonal crop rotations have potential for increasing net returns provided that farmers invest in these soil improvements. However, these rotations do not provide year-round production, and farmers will need to make greater use of operating loans during critical periods in spring and summer.

Additional enterprises that appear to have potential for Altillanura are *integrated hog*, *cashew*, and *cacay*. An important constraint, however, is the amount of integrated hog/soybean output that may be produced. Because the Colombian pork supply in 2017 was 410 thousand tons (PORKCOLOMBIA, 2017). The share of the Pork Slaughter industry for the Central Region of Colombia (including Meta, Bogotá, and Cundinamarca) was 23.1% and 23.7% for the years 2017 and 2018, respectively. Unless a farmer is well connected to the entire pork supply chain in Colombia, it would be difficult to capture a large portion of the existing pork market. This motivates the model constraint limiting area in the integrated pork enterprise to 200 ha, which would limit hog production to 1% of the central region total. Even with this restriction, the potential for these promising enterprises is substantial with much higher net returns. A key to achieving these higher returns is being able to hire 10 to 20 times as much permanent labor as under the other scenarios.

Labor supply in Altillanura is constrained by low population density, i.e. one person every 118.3 hectares (UPRA - Rural Agricultural Planning Unit, n.d.). Given the exceedingly high labor use in the scenario including the promising alternatives, a sensitivity analysis was designed to assess the impact of labor cost increases in the form of wages and employee benefits that would likely be needed to attract labor from outside of the region. Moderate labor costs on the order of 10-20% were sufficient to cause substantial shifts away from high labor intensity enterprises such as rubber and cacay, and toward relatively low labor intensity cashew. The integrated hog enterprise was not sensitive. When labor costs increased very substantially (70-100%), cashew started to be displaced by the more mechanized rice-soybean seasonal rotation.

The results indicated that producers have several opportunities to increase the returns to endowed factors by switching from the most common use of land in Vichada – cattle raised on pastures with native grasses – to other technologies for cattle production. Hypothesis 1 (cattle productions systems based on improved pastures are more profitable than traditional extensive systems) was supported. Cattle producers were able to further improve their net returns if they included silage production to feed their animals during the dry season and were able to sell excess silage in the market.

Given sufficient labor availability, the oil palm enterprise was a better alternative than cow-calf production even when improved pastures were used. Oil palm, however, is highly labor intensive, potentially limiting the allocation of land to this enterprise. If the farm specialized in only oil palm, 271 hectares out of 2,000 would remain idle given the model limitations on hiring of permanent workers and temporary labor. In fact, the maximum amount of land in oil palm that could be supported if the entire population of Altillanura (115.2 thousand habitants) chose to work on that enterprise would be 603.6 thousand hectares out of the 2.04 million hectares suitable for agriculture.

Hypothesis 2 (new promising enterprises may improve net revenue) was also supported because the integrated hog enterprise, as well as cacay and cashew can provide a more profitable use of land, labor and other resources than cattle-based production systems. The integration of hog production and crops as a strategy to feed the animals with farm produced feed offers substantial potential returns to the farmer. Because pork production on a 2,000 ha farm would strain the modest size of the Colombian pork market, pork production is likely to be constrained by access to processing and marketing. High productivity per unit of area is expected, so determining the optimal scale of operation for this enterprise would be essential

Cacay and cashew also show promise for the region, especially for rubber producers that have been experiencing the effects of low prices of latex during the past 3 years. In addition to the high prices for the two nut crops, their complementary use of labor across time and in combination with the rubber enterprise provides a potentially highly profitable portfolio of enterprises.

Hypothesis 3 (labor availability is a major constraint to agricultural development in the Altillanura) is less well supported. Sensitivity analysis to wages and salaries showed substantial impacts on the portfolio of optimal enterprises. For some labor intensive enterprises like oil palm and rubber, labor availability and costs can limit expansion of enterprises. For high value, relatively low labor, activities like cacay and cashew, labor was much less of a concern. In all these cases, cooperation or contract farming arrangements between small and large farmer producers could provide incentives to attract labor and could help to alleviate labor shortages; however, further study is needed to support this recommendation.

5. Conclusions

The Colombian frontier of the Altillanura represents a substantial opportunity for agricultural and economic development. A variety of enterprises appear to be compatible with the resource base available to farms in the region, and present a number of alternatives for increasing net returns to farms. This paper does not attempt to define one crop-pasture system for the entire region, but to modelling agricultural alternatives that fit to some specific characteristics that are representative of the Altillanura.

A representative farm linear program was used to assess current and potential agricultural alternatives at the agricultural frontier in the Altillanura and to identify the portfolio that maximizes the net return to the farm´s endowment of fixed resources in the medium and long term. Even though this model was applied to the case of the Altillanura, it is adaptable to other agricultural frontiers. This model relied on a steady-state framework that allowed for the analysis of annual and perennial enterprises. The optimal solutions in this study generally differ from existing practices in the region and could boost the regional rural economy. That is, this study has shown extensive cattle ranching on native savannas is a less attractive enterprise for the Altillanura. Other cattle production methods based on the CIAT-ICA technologies involving improved pastures offer large net returns despite their relatively high investments in soil management and improved pastures. In addition, the study shows that a portfolio of enterprises performs better from a net return at the farm level when compared with the sole cattle production alternative.

Although this paper does not target some of the main challenges of the Altillanura, such as the lack of infrastructure development and the absence of confidence for investment associated with the violence of illegal armed groups that have presence in the region, the model facilitates analysis and evaluation of policy interventions that eventually may be implemented by the government. That said, this model permits assessment of the impact at the farm level of any intervention that affects yields, input or output prices, as well as labor, land, and credit constraints, such as the labor cost scenario that was presented in the results.

It is important to recall that this model assumes that local producers in this context are price takers and don’t have the ability to alter prices. However, a further extension of this research should address the volatility of market prices for inputs and outputs, and consider a potential price collapse if public intervention pushes for overspecialization of activities. In this context, market-level issues both for enterprise outputs and for scarce labor inputs, are important and may need further assessment, especially for those promising alternatives that have been relatively less exploited in the region.

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8. Appendices (Online supplement)

I. Model equations

Orinoquía-LP is composed by five equations, four structural constraints (*land*, *labor*, *intermediate use*, and *cash use*) and an objective function (*net return*). These equations represent the typical activity of a Colombian farm (Preckel et al., 2019).

The land equation is:

$$\sum_{e \in E} X_{l,e} \leq \overline{M_l}$$

the left-hand side (LHS) represents land needed for each enterprise e (in **Table 4**) if planted ($e \in E$) where $X_{l,e,t}$ is area planted of enterprise e on land type l (irrigated or non-irrigated). The right-hand side $\overline{M_l}$ reflects the endowment of land type l.

The labor constraint has the form:

$$\sum_{e} \sum_{l} A_{l,e,t} X_{l,e} \leq (\overline{L_F} + \overline{L_P}) g_t + H_t.$$

This relation establishes that labor needed which is labor needed per hectare $A_{l,e,t}$ at month t times area planted $X_{l,e,t}$cannot exceed the monthly labor endowment which is composed by family-labor $\overline{L_F}$ and permanent labor $\overline{L_P}$ who work g_t days during month t, and hired temporary labor H_t.

The third restriction permits intermediate use of products:

$$Q_{c,t} + \sum_{e} \sum_{l} B_{l,e,c,t} X_{l,e} \leq \sum_{e} \sum_{l} Y_{l,e,c,t} X_{l,e}.$$

The LHS is the monthly use of the commodity c, either as final product $Q_{c,t}$ or as intermediate input $B_{l,e,c,t}$ used in the planted area $X_{l,e}$ of enterprise e. The RHS is the total production of the commodity, where $Y_{l,e,c,t}$ is the monthly yield per hectare times the area $X_{l,e}$

The fourth restriction models cash use depending if it is the beginning ($t = 1$ or first month), intermediate ($1 < t < 12$) or final stage of the annual cycle ($t = 12$)

$$
\begin{cases}
\sum_e \sum_l K_{l,e,t} X_{l,e} + \overline{L_P}\left(\frac{w_P}{12}\right) + H_t w + \pi_t \leq V_t + \sum_c P_c Q_{c,t} + \delta_t & \text{if } t = 1 \\
\sum_e \sum_l K_{l,e,t} X_{l,e} + \overline{L_P}\left(\frac{w_P}{12}\right) + H_t w + \pi_t + \delta_{t-1}(1+r) \leq \sum_c P_c Q_{c,t} + \pi_{t-1} + \delta_t & \text{if } 1 < t < 12 \\
\sum_e \sum_l K_{l,e,t} X_{l,e} + \overline{L_P}\left(\frac{w_P}{12}\right) + H_t w + \pi_t + \delta_{t-1}(1+r) + V_t \leq + \sum_c P_c Q_{c,t} + \pi_{t-1} & \text{if } t = 12.
\end{cases}
$$

For the intermediate cycle, the LHS is the cash used to (i) pay for non-labor variable cost $K_{l,e,t}$ per hectare times the area planted $X_{l,e}$ of the enterprise, to (ii) cover the expense of permanent labor $\overline{L_P}$ with monthly salary of $(w_P/12)$ and (iii) hiring temporary workers H_t at monthly wage of w. Cash can also be saved (π_t) but loans from previous period δ_{t-1} must be paid including interest r. The RHS represents the sources of cash: the sale of product $Q_{c,t}$ at a price of P_c, previous savings (π_{t-1}), and money borrowed from the bank in the current period δ_t.

At the beginning of the annual farm cycle, working capital V_t is used to start operations which is exhausted at the end of the year (at $t = 12$). Likewise, final savings π_t are collected from all the operation when the year ends. Thus, the objective *net return* function Z is:

$$Max\ Z = \pi_{t \epsilon T_f}$$

to maximize the net savings at the end of the project ($t \epsilon T_f$, where T_f is final period or $t = 12$)

II. GAMS CODE

```
$call copy AltillanuraL20190613.xlsx Orinoquía_Tables.xlsx
* If you would like to see the equations, increase limrow in the line below.
* If you would like to see the activities, increase limcol in the line below.
Option limrow=0,limcol=0 ;
* Note all of the data are read from the spreadsheet; so not data appears in
* this program.
Sets
 t(*)       Time periods
 e(*)       Enterprises
 c(*)       Commodities
 l(*)       Land type ;
Scalars
```

```
 flab           Family labor available (no. of workers)
 plab            Permanent labor available already employed (no. of workers)
 thlab          Maximum hired temporary labor in each period (person-days)
 phlab           Maximum additional permanent labor hired (man years)
 twlab          Temporary wage (000 pesos per 8 hour person-day)
 pwlab           Permanent worker wage (000 pesos per man year)
 initcash       Initial cash available (000 pesos)
 intrst         Monthly interest rate
 mxborrow       Borrowing constraint in 000 Pesos ;
* The following does imports of data from Gams_Tables.xlsx.
$onecho > tasks.txt
set=t rng=Scalars_and_Parameters_(R)!f4 dim=1 rdim=1
set=e rng=Labor_use_(R)!b2 dim=1 rdim=1 maxdupeerrors=50
set=c rng=Commodity_produced_(R)!c2 dim=1 rdim=1 maxdupeerrors=50
set=l rng=Commodity_produced_(R)!a2 dim=1 rdim=1 maxdupeerrors=50
par=flab rng=Scalars_and_Parameters_(R)!c3 rdim=0 cdim=0
par=plab rng=Scalars_and_Parameters_(R)!c4 rdim=0 cdim=0
par=thlab rng=Scalars_and_Parameters_(R)!c5 rdim=0 cdim=0
par=phlab rng=Scalars_and_Parameters_(R)!c6 rdim=0 cdim=0
par=initcash rng=Scalars_and_Parameters_(R)!c7 rdim=0 cdim=0
par=intrst rng=Scalars_and_Parameters_(R)!c8 rdim=0 cdim=0
par=mxborrow rng=Scalars_and_Parameters_(R)!c9 rdim=0 cdim=0
par=twlab rng=Scalars_and_Parameters_(R)!c10 rdim=0 cdim=0
par=pwlab rng=Scalars_and_Parameters_(R)!c11 rdim=0 cdim=0
$offecho
$call GDXXRW Orinoquía_Tables.xlsx  trace=3 @tasks.txt
$GDXIN Orinoquía_Tables.gdx
$LOADDC t,e,c,l,flab,plab,thlab,phlab,initcash,intrst,mxborrow,twlab,pwlab
$GDXIN
Set
 fnt(t)         Final time period ;
fnt(t) = Yes$(ord(t) eq card(t)) ;
* Display those sets and scalar values in case we need to verify the data got
* read in all right.
```

```
Display t,fnt,e,c,l,flab,plab,thlab,phlab,initcash,intrst,mxborrow,twlab,pwlab;
* Declare the parameters whose values will also be read from the spreadsheet.
Parameters
 lnd(l)          Land of type l available (ha)
 gfd(t)          Good field days available in period t (days per period)
 wu(l,e,t)       Labor use of enterprises by period
 cu(l,e,t)       Cash use for enterprises by period
 lu(l,e,t)       Land use of enterprises by period (ha per period)
 entcom(l,e,c,t) Quantity commodity c produced per unit of enterprise e on land l
 fu(l,e,c,t)     Commodity use of enterprises by period (intermediate inputs)
 sprc(c)         Selling prices for commodities (000 pesos per unit)
 lobd(l,e)       Lower bounds on commodities by enterprise (ha)
 upbd(l,e)       Upper bounds on commodities by enterprise (ha) ;
* Import parameter values.
$onecho > tasks.txt
par=lnd rng=Scalars_and_Parameters_(R)!b16 dim=1 rdim=1
par=gfd rng=Scalars_and_Parameters_(R)!f4 dim=1 rdim=1
par=sprc rng=Scalars_and_Parameters_(R)!j4 dim=1 rdim=1
par=wu rng=Labor_use_(R)!a1 rdim=2 cdim=1
par=cu rng=Cash_use_(R)!a1 rdim=2 cdim=1
par=entcom rng=Commodity_produced_(R)!a1 rdim=3 cdim=1
par=lu rng=Land_use_(R)!a1 rdim=2 cdim=1
par=fu rng=Commodity_use_(R)!a1 rdim=3 cdim=1
par=lobd rng=Scalars_and_Parameters_(R)!n4 dim=2 rdim=2
par=upbd rng=Scalars_and_Parameters_(R)!s4 dim=2 rdim=2
$offecho
$call GDXXRW Orinoquía_Tables.xlsx o=Orinoquía_Tables_par.gdx trace=3 @tasks.txt
$GDXIN Orinoquía_Tables_par.gdx
$LOADDC lnd,gfd,sprc,wu,cu,entcom,lu,fu,lobd,upbd
$GDXIN
* Display those parameter values in case we need to verify the data got
* read in all right.
Display lnd,gfd,sprc,wu,cu,entcom,lu,fu,lobd,upbd ;
* Set the enterprise-land type mapping based on whether the enterprise
```

```
* produces any commodity in any time period on the specific land type.
* If it doesn't produce anything, it gets supressed.
Set
 el(e,l)        Enterprise-land type included if enterprise has output on land l ;
el(e,l) = Yes$(sum((c,t),entcom(l,e,c,t)) gt 0) ;
el(e,l)$(lnd(l) eq 0) = No ;
Display el ;
Positive Variables
 produce(l,e)    Produce enterprise e on land type l (ha)
 sell(c,t)       Sell commodity c in period t (commodity units)
 phire           Permanent labor hired (man years)
 thire(t)        Temporary labor hired in period t (person-days)
 save(t)         Cash stored from period t to t+1 (000 pesos)
 borrow(t)       Cash borrowed in period t and repaid in period t+1 (000 pesos) ;
Variables
 netret          Net return to the farm (000 pesos) ;
Equations
 land(l,t)       Limit on land use for land of type l in period t (ha)
 labor(t)        Define amount of labor to hire in period t (person-days)
 comuse(c,t)     Sources and uses for commodity c in period t (commodity units)
 cash(t)         Sources and uses of cash in period t (000 pesos)
 nrobj           Net return objective ;
land(l,t) ..
sum(e$el(e,l),lu(l,e,t)*produce(l,e)) =l= lnd(l) ;
labor(t)  ..
 sum(el(e,l),wu(l,e,t)*produce(l,e)) =l=
 (flab+phire)*gfd(t) + thire(t) ;
comuse(c,t) ..
 sell(c,t)
 + sum(el(e,l),fu(l,e,c,t)*produce(l,e)) =l=
 sum(el(e,l),entcom(l,e,c,t)*produce(l,e)) ;
cash(t) ..
 sum(el(e,l),cu(l,e,t)*produce(l,e))
 + phire*pwlab/card(t)
```

```
 + thire(t)*twlab + save(t)
 + borrow(t-1)*(1+intrst)
 + initcash$fnt(t) =l=
 initcash$(ord(t) eq 1) + sum(c,sprc(c)*sell(c,t))
 + save(t-1) + borrow(t)$(not fnt(t)) ;
nrobj ..
netret =e= sum(fnt,save(fnt)) ;
* Set bounds on individual variables.
produce.lo(l,e) = lobd(l,e) ;
produce.up(l,e) = upbd(l,e) ;
thire.up(t) = thlab ;
phire.lo    = plab ;
phire.up    = plab + phlab ;
borrow.up(t)= mxborrow ;
Model finca / land,labor,comuse,cash,nrobj / ;
option lp=cplex ;
finca.optfile=1 ;
Solve finca using lp maximizing Netret ;
```

III. Cash use by crop (in thousand pesos per hectare)

Land type	Enterprise	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total cash per year per hectare
NoIr	Rice-Soybean	315.0	0.0	80.0	1198.8	736.9	138.0	237.5	1192.9	621.9	427.8	1492.1	250.0	6691.0
NoIr	Corn-Soybean	315.0	0.0	80.0	2044.4	1191.7	156.0	0.0	1360.4	1026.9	427.8	1017.0	250.0	7869.3
NoIr	Crop-Beef	299.6	119.6	261.7	1188.0	716.6	204.2	187.4	849.1	590.7	409.4	882.4	308.4	6017.2
NoIr	Oil Palm	95.7	164.0	175.6	482.0	90.7	397.3	81.4	395.8	89.3	87.3	407.1	88.8	2555.1
NoIr	Rubber	28.4	28.4	45.4	405.3	135.2	171.7	45.4	45.4	135.2	135.2	171.7	171.7	1519.1
NoIr	Cacay	94.1	172.0	148.7	42.5	75.5	66.9	40.6	46.0	129.6	113.2	981.4	75.4	1986.0
NoIr	Cow-Calf	8.9	8.9	233.9	233.9	9.8	9.8	8.9	8.9	8.9	8.9	9.8	9.8	560.3
NoIr	Beef-Fattening	169.0	169.0	394.1	457.5	233.4	169.9	169.0	169.0	169.1	232.5	233.4	233.4	2799.5
NoIr	Pasture + Silage	26.1	21.5	546.6	558.4	26.1	26.1	36.3	21.5	21.6	21.5	26.1	26.1	1230.6
NoIr	Beef-Traditional	0.6	0.6	0.6	0.6	0.7	0.7	0.6	0.6	0.6	0.6	0.7	0.7	7.5
NoIr	Integrated	660.3	743.2	822.6	2322.1	2546.6	898.0	1728.7	2387.2	1034.3	804.1	2675.1	677.4	17299.6
NoIr	Cashew	2.2	0.0	0.0	42.9	0.8	0.8	0.8	0.8	0.8	0.8	125.3	60.3	235.6

IV. Labor use by crop (person-days per hectare)

Land type	Enterprise	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total person-days/ha-year
NoIr	Rice-Soybean	0.05	0.01	0.01	0.43	0.43	0.04	0.04	0.30	0.32	0.28	0.02	0.04	1.99
NoIr	Corn-Soybean	0.04	0.01	0.01	0.44	0.44	0.04	0.01	0.32	0.34	0.28	0.02	0.04	2.01
NoIr	Crop-Beef	0.09	0.07	0.07	0.32	0.32	0.09	0.08	0.24	0.26	0.23	0.08	0.09	1.94
NoIr	Oil Palm	3.09	2.30	3.61	3.12	3.08	2.68	1.71	2.00	1.97	1.09	3.82	1.78	30.26
NoIr	Rubber	0.65	0.65	6.84	8.48	8.09	6.84	6.84	6.84	8.09	8.09	6.84	6.84	75.06
NoIr	Cacay	15.26	15.06	0.26	0.31	1.12	0.02	0.02	0.06	1.11	1.03	1.86	4.67	40.77
NoIr	Cow-Calf	0.11	0.07	0.07	0.11	0.11	0.11	0.07	0.07	0.07	0.07	0.11	0.11	1.10
NoIr	Beef-Fattening	0.14	0.09	0.09	0.14	0.14	0.14	0.09	0.09	0.09	0.09	0.14	0.14	1.41
NoIr	Pasture + Silage	0.24	0.16	0.16	0.40	0.24	0.24	0.49	0.16	0.16	0.16	0.24	0.24	2.85
NoIr	Beef-Traditional	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.96
NoIr	Integrated	1.55	1.52	1.52	1.95	1.95	1.55	1.52	1.83	1.85	1.79	1.53	1.55	20.14
NoIr	Cashew	0.99	0.99	0.98	0.16	0.76	0.76	0.76	0.76	0.76	0.76	1.08	1.08	9.84

V. Enterprise Yields

Enterprise	Commodity	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Units/ha-year	Units
Oil Palm	FFB	2.92	3.21	3.80	2.63	1.75	0.73	0.58	0.73	1.02	1.17	1.02	1.17	20.7	ton
Rice-Soybean	Rice	0.00	0.00	0.00	0.00	0.00	0.00	2.25	2.25	0.00	0.00	0.00	0.00	4.5	ton
Rice-Soybean	Soybeans	1.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.30	2.6	ton
Corn-Soybean	Corn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.50	3.50	0.00	0.00	0.00	7.0	ton
Corn-Soybean	Soybeans	1.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.30	2.6	ton
Oil Palm	FFB	2.45	2.69	3.18	2.20	1.47	0.61	0.49	0.61	0.86	0.98	0.86	0.98	17.4	ton
Crop-Beef	Rice	0.00	0.00	0.00	0.00	0.00	0.00	0.64	0.64	0.00	0.00	0.00	0.00	1.3	ton
Crop-Beef	Soybeans	0.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.74	1.5	ton
Crop-Beef	Corn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.00	2.0	ton
Crop-Beef	Fed Cattle	53.70	38.36	38.36	38.36	53.70	53.70	38.36	38.36	38.36	38.36	53.70	53.70	537.0	kg
Rubber	Rubber	0.00	0.00	134.78	134.78	134.78	134.78	134.78	134.78	134.78	134.78	134.78	134.78	1347.8	kg
Cacay	Cacay	9.37	9.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.7	ton
Cow-Calf	Heifer	0.09	0.09	0.09	0.09	0.09	0.43	0.43	0.43	0.09	0.09	0.09	0.09	2.1	kg
Cow-Calf	Cow	4.12	4.12	4.12	4.12	4.12	18.53	18.53	18.53	4.12	4.12	4.12	4.12	92.7	kg
Cow-Calf	Steer	3.68	3.68	3.68	3.68	3.68	16.56	16.56	16.56	3.68	3.68	3.68	3.68	82.8	kg
Beef-Fattening	Fed Cattle	75.94	54.24	54.24	54.24	75.94	75.94	54.24	54.24	54.24	54.24	75.94	75.94	759.4	kg

Pasture + Silage	Heifer	0.20	0.20	0.20	0.20	0.20	0.88	0.88	0.88	0.20	0.20	0.20	0.20	4.4	kg
Pasture + Silage	Cow	9.04	9.04	9.04	9.04	9.04	40.70	40.70	40.70	9.04	9.04	9.04	9.04	203.5	kg
Pasture + Silage	Fed Cattle	11.56	11.56	11.56	11.56	11.56	52.04	52.04	52.04	11.56	11.56	11.56	11.56	260.2	kg
Pasture + Silage	Silage	0.30	0.30	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.30	1.5	ton
Beef-Traditional	Heifer	0.01	0.01	0.01	0.01	0.01	0.04	0.04	0.04	0.01	0.01	0.01	0.01	0.2	kg
Beef-Traditional	Cow	0.44	0.44	0.44	0.44	0.44	1.98	1.98	1.98	0.44	0.44	0.44	0.44	9.9	kg
Beef-Traditional	Steer	0.31	0.31	0.31	0.31	0.31	1.38	1.38	1.38	0.31	0.31	0.31	0.31	6.9	kg
Integrated	Pork	419.43	419.43	419.43	419.43	419.43	419.43	419.43	419.43	419.43	419.43	419.43	419.43	5033.10	kg
Integrated	Soybeans	1.295	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.295	2.59	ton
Cashew	Cashew	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	ton