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Combining farm typology and yield gap analysis to identify major variables limiting yields in the highland coffee systems of Llano Bonito, Costa Rica

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ABSTRACT

Yield variability in space and time is a well-known phenomenon in the highland coffee production systems of Costa Rica. Our objective was to systematically unravel variations and gaps in yields due to the combined effects of farm resources and major production variables in a region of premium quality highland coffee. We surveyed 40 coffee producing farms varying in size from small to large in Llano Bonito, Costa Rica to examine their diversity based on their resources. We further conducted an agronomic diagnosis and yield estimates in 97 individual measuring plots in 63 coffee fields over two cropping years (2013–2014 and 2014–2015). We categorized farm diversity through a resource endowment typology built by combining direct observation with the use of multivariate analysis and clustering techniques. This resulted in four farm types: large farms depending on external labour (Type 1, 25%), large farms with livestock (Type 2, 20%), small farms dedicated to coffee (Type 3, 38%), and small farms with an off-farm income (Type 4, 17%). We then analysed coffee yield variability and yield gaps through a boundary line approach. The mean yields for two cropping years fluctuated between 2.5 ± 0.18 and 1.6 ± 0.12 t ha^{-1} on farm types 1 and 2 respectively. Though the yields did not differ strongly across farm types, there was a weak tendency ($p = 0.10$) towards yield variability between study years.

The combined use of farm typology and yield gap analysis revealed multiple farm-specific production variables that were significantly related to gaps in attainable yields. For any intervention to improve and stabilize yields in the future, the heterogeneity of farm orientation, management practices, production geographical context and soil properties must be given proper attention and integrated into crop, shade tree and soil management practices.

1. Introduction

Traditional coffee production systems, which incorporate various strata of indigenous shade trees as major components, are systems that produce multiple goods and services (Moguel and Toledo, 1999). The introduction of intensive coffee production systems, which are characterized by the removal or reduction of the shade component and the increased application of agro-chemicals (e.g. synthetic fertilizers, pesticides and herbicides), principally targeting yield maximization, has transformed traditional systems into simplified systems on large scales in many parts of the world (Perfecto et al., 1996; Beer et al., 1997; Philpott et al., 2008; Jha et al., 2014).

Unstable coffee prices after the coffee crisis in early 2000, when coffee prices collapsed to historically low levels, exposed producers to several complex socio-economic consequences (Bacon et al., 2005; Babin, 2015). For farmers who continued producing coffee in the post-crisis context, it was essential to adopt cost-effective cropping practices and to diversify sources of income, including increased reliance on off-farm income.

Depending on farm characteristics and objectives, producers tend to allocate various farm resources to different cropping practices, causing diversity in crop and soil nutrient management (Tittonell et al., 2007) that may result in a variation in crop yields. When farm holders with different strategies produce coffee in fields with diverse biophysical

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settings (e.g. altitude, slope), it further results in variations in yield. An understanding of how coffee plots on farms with different resources are managed in diverse biophysical settings resulting in yield variation is therefore crucial in improving current coffee production systems.

Acknowledgement of farm diversity is the first step towards improving the performance of smallholder agricultural production systems (Ruben and Pender, 2004). Dividing farm diversity into typologies is one of the earliest approaches used to sum up farm diversity (Landais, 1998). Farm typologies have been used in various agricultural studies as a tool for understanding how different farmer objectives lead to farms with different characteristics and resource allocations (Tittonell, 2014), and for assessing the adoption rate of new agricultural technologies (Sabastian et al., 2014). Close to our study area, Meylan et al. (2013) developed a typology of coffee management practices for producers associated with the Llano Bonito cooperative (one of the cooperatives covered by this study) to assess their roles in erosion mitigation at plot level.

An understanding of yield gaps, the differences between actual farm yield and the maximum yield that can be achieved under the same agro-ecological conditions, can guide management recommendations and site-specific interventions to address the limiting factors and thus close the gap (van Ittersum and Cassman, 2013). Chopin and Blazy (2013) identified three approaches to yield gap analysis on a regional scale: field trial-based, on-farm agronomic diagnosis, and statistical correlation approach. We chose the on-farm agronomic diagnosis approach because of its applicability in on-farm situations, and its need for relatively fewer technological inputs. In the context of coffee, Wang et al. (2015) applied the yield gap analysis technique to evaluate yield gaps in major coffee growing regions of Uganda.

We combined farm typology and yield gap analysis techniques to understand the farm type-specific production variables that limit yields, and cause yield gaps in the highland coffee production systems of Llano Bonito, Costa Rica. Although farm typology and yield gap analyses have been applied separately to various crops in different regions worldwide, we are the first to combine these useful tools, particularly in the context of coffee in Latin America.

A practical approach to understanding a farm production system involves separating it into decision, technical and biophysical sub-systems (Le Gal et al., 2010). Coffee farming households (decision sub-systems) in Llano Bonito apply diverse crop management practices (technical sub-systems) depending on biophysical sub-systems (production geographical context and soil properties) (Fig. 1).

There are variations in each of these sub-systems. Moreover, farming households change management practices from year to year, and coffee is physiologically a crop that exhibits a high and a low yield in alternate years (or a biennial yield characteristic) (DaMatta, 2004; Bernardes et al., 2012). It is hypothesized that combinations of all these factors result in high variability in coffee yields over space and time.

Our objective was to systematically understand coffee yield variability in relation to farm resource diversity, yield limiting factors and gaps, and their links to variations in the decision, technical and biophysical sub-systems in the highland region of Llano Bonito producing premium quality coffee in Costa Rica.

2. Materials and methods

2.1. Site description

The study area, the Llano Bonito watershed, is located in the *Pirris* region in the León Cortés canton of Costa Rica (Fig. 2).

Climate in the area shows well defined dry and wet seasons with an average rainfall of 1,491 mm, concentrated between May and November. The altitude ranges between 1,180 and 2,120 m a.s.l., with variations in slope inclination and orientation (aspect). The dwarf "caturra" is the most commonly planted Arabica coffee (*Coffea arabica* L.) variety in the study area, predominantly on Ultisols (FAO) under the shade of *Erythrina* and *Musa* species, or without any shade. Capitalizing on favourable climatic conditions, farmers in the area have been successful in building a specialty market for the high quality coffee that is produced by intensive cropping systems.

2.2. Sample selection

The study involved socio-economic (farm resources and crop management) as well as biophysical (coffee field) components. Different sampling, surveying, measurement and monitoring tools and techniques were employed at various levels (Fig. 3, Table 1).

Coffee producing farms (n = 40) were selected from a list of coffee producers (if they were associated with the local cooperative), and in consultation with technicians from the cooperative and in discussions with key informants (if the producers were not associated with the cooperative). The criteria for selecting the study farms included i) diversity of coffee farm resources, objectives and management practices, and ii) variations in the local geographical context of coffee production. The study of socio-economic components consisted of surveys regarding farm resources and coffee management practices.

For the measurement of biophysical components, coffee fields belonging to the study farms were selected so that the diversity of the coffee fields was represented and well distributed over all parts of the study area. Biophysical measurements consisted in quantifying production variables, which included characterization of the production geographical context, an analysis of soil properties and the determination of shade tree and coffee plant properties in the sampled coffee fields. Lastly, coffee yields were estimated annually in permanently marked sample plots in the fields.

2.3. Surveys and measurements

The selected farmers were interviewed using structured questionnaires, the sampled fields were visited, site characteristics were recorded, and soil samples were taken. In addition, depending on within-field variation in the production geographical context, one to six measurement plots were delineated for shade tree and coffee plant characterization. Measurement plots were located towards the centre of the field to avoid edge effects. The corners of the delineated measurement plots were marked for repeated yield estimates by the quantification of yield components.

2.3.1. Farm and coffee management surveys

Farm surveys were carried out at farm level at the beginning of the study to account for farm characteristics including resource endowment and farm objectives. Initial discussions with key informants helped to identify major variables at farm level that described farm variability in terms of the local socio-economic status of households and their allocation of resources to coffee production. These variables were related to land, labour, income and livestock. In order to collect the information related to these variables, a structured questionnaire was developed, pilot-tested, fine-tuned and applied to the sample of farming households. To account for the allocation of resources to different coffee management practices, such as labour and fertilizer inputs, coffee management surveys were carried out at the end of the annual coffee harvests (2013–2014 and 2014–2015). These years had average temperatures and rainfall, so high variability in yield due to variations in climatic components was not expected.

2.3.2. Agronomic diagnosis

The general production geographical context (altitude, slope and aspect) were determined at field level. Five soil samples (depth = 0–20 cm) were taken in each coffee field using an auger in zig-zag locations and combined to form a composite sample which was sent to the CATIE laboratory for analysis. The analysed soil properties were pH in water (Bates, 1973), N by the combustion method (Nelson