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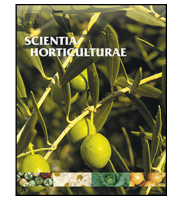

Evaluation of a non-destructive sampling method and a statistical model for predicting fruit load on individual coffee (*Coffea arabica*) trees

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ABSTRACT

Destructive sampling schemes are the most direct and accurate methods to estimate yields in agro-ecosystem studies. However, in many situations these resource-intensive schemes are not feasible and/or sustainable. The objective of this research was to develop and compare non-destructive visual censuses and analytical methods for estimating fruit loads on *Coffea arabica* var. Caturra and Catuaí trees using different components of yield.

Fruit load data were collected in coffee farms found in the Los Santos Region of Costa Rica. Two components of yield where estimated: number of productive lateral branches per tree and fruit load per lateral branch. OLS regression was used to develop empirical models relating these components of yield with total fruit load per plant.

Productive laterals at medium relative distance from the apical meristem had higher fruit loads than those found at the top or bottom of the orthotropic stem in *C. arabica* plants. In addition, by sampling eight to nine productive laterals per plant, the maximum observed error of the estimated fruit load per lateral was reduced by half. Regression coefficients of the empirical models relating total fruit load with yield components ranged between 0.73 and 0.92.

Sampling schemes which grant equal probability of selection to productive laterals at different relative distances from the apical meristem should be chosen when estimating fruit load per lateral in commonly cultivated varieties of *C. arabica* plants. Furthermore, a non-destructive sampling protocol of the key components of yield provides accurate estimates of total fruit load per tree. Additional research is required to relate fruit loads with total biomass of fresh fruit and dry biomass in this perennial crop.

1. Introduction

Field research and monitoring efforts in agro-ecosystem studies commonly require standard estimates of crop productivity. Destructive sampling schemes (i.e. harvesting fruit or plant biomass) represent a straightforward and accurate method for obtaining estimates of yield. However, under certain conditions, these schemes are inadequate or simply not feasible. In these situations, non-destructive sampling schemes such as visual censuses represent an alternative technique for estimating yields without harvesting the crop.

Coffee is a high-value crop cultivated in 56 countries throughout the tropical and subtropical regions of the world (ICO, 2013). Millions of farmers depend on revenue generated and ecosystem services provided by coffee agro-ecosystems to make up for their livelihood (Mendez et al., 2007; Jha et al., 2011). In addition, tree-diverse coffee agroecosystems provide vital refugia for biodiversity,

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especially in diminished and fragmented tropical forest ecosystems (Philpott et al., 2008; Perfecto et al., 2009). Understanding yield response of this crop to a range of management and environmental conditions is of great importance. As a consequence of the flowering and fruit phenology of this crop (Rena et al., 1994), several harvest events in a same season are required to collect all fruit from a plant. This may represent a challenge to field studies and development projects, which require working in a large number of sites and farms. In addition, destructive sampling schemes may be controversial when studying commercial coffee farms, especially those belonging to smallholders who depend on this crop.

Consequently, various non-destructive methods for estimating fruit productivity in *Coffea arabica* have been developed and used. Examples of this include attempts to determine how coffee yields vary with different varieties (Upreti et al., 1991; Kufa and Burkhardt, 2007), planting densities (Gathaara and Kiara, 1985; Arias-Basulto et al., 2003) and fertilizer management (de Carvalho et al., 2007). Field research documenting the effect of shade tree canopy composition and structure on the productivity of coffee plants has also relied on non-destructive yield estimation methods (Soto-Pinto et al., 2000; Peeters et al., 2003; Kimemia, 2005).

Non-destructive methods require sampling schemes and analytical techniques that produce good estimates of the different components of yield (Gundersheim and Pritts, 1991). Upreti et al. (1991) developed a sampling scheme in which a pole placed perpendicular to the ground is used to divide the coffee plant into four quadrants. In one of these quadrants, the total number of fruiting nodes and the average number of fruit per node is estimated through visual census. Once these figures have been projected to the whole tree, the total fruit load can be estimated as the product of the mean number of fruit per node, the number of fruiting nodes per tree and the mean mass of a fruit.

Furthermore, Upreti et al. (1991) determined that total harvested fruit biomass was correlated to the components of yield estimated in the field. Although highly accurate, a disadvantage with the quadrat method is that it is time consuming. In addition, challenging field conditions such as steep, muddy slopes may render this method impractical. We present here an alternate approach that provides an optimal tradeoff between sampling effort and accuracy.

Recent studies have explored methods that sample the subset of productive laterals and estimate the total fruit load on them (Soto-Pinto et al., 2000; Peeters et al., 2003). In these schemes, laterals within a coffee tree or stem not bearing fruit were excluded from the sample. Random sampling was used to estimate the expected number of fruit in the population of productive laterals. For these studies, sampling effort ranged between 3 and 10 productive laterals per tree. The total fruit load of a plant was calculated as a product of the total number of productive laterals and the mean number of fruit per lateral on a tree. This can then be multiplied with an estimate of individual fruit mass to predict yield. Arcila-Pulgarin (2007b) identifies the number of fruit bearing branches, average number of fruit bearing nodes per branch, the average number of fruit per node, and the average mass per fruit as the most important components of yield in *C. arabica*.

This approach is more suitable to many field conditions. Given that the mean number of fruit per lateral is used as the estimation of the expected value, this variable should be normally distributed to get adequate results. This method also assumes that laterals within a coffee tree are equivalent and independent from each other.

Finally, there are methods which correlate vegetative structure growth and characteristics and harvested yield (Srinivasan, 1980; Sadananda and Azizuddin, 1996; Agwanda et al., 1999; Kufa and Burkhardt, 2007). A drawback of this approach is that environmental gradients may determine the relationship between vegetative growth characteristics and yield (Kufa and Burkhardt, 2007), making empirical models developed with these variables region specific with limited applicability in the wrong context.

Our study explores and compares sampling and analytical methods for estimating fruit load per individual coffee plant. We consider that field estimates of yield components provide a starting point to develop predictive models of fruit loads on individual *C. arabica* trees. Specifically, to determine how the architecture and phenology of the coffee plant may affect field estimates of yield components we ask the following question: does the position of the lateral with respect to the apical meristem of the orthotropic axle influence the number of fruit per lateral?

In order to develop quantitative methods using field estimates of the components of yields to predict total fruit loads, we specifically ask the following questions: In coffee plants and stems, what is the best distribution model to represent the number of fruit per lateral? What is the error of the estimated mean number of fruit per lateral when calculated with differing sampling intensity? And, is the total fruit load of a coffee plant proportional to the expected number of fruit per lateral and the number of productive laterals? We consider that this information will inform the development of non-destructive sampling schemes for determining the yields of individual coffee plants during different growth stages.

2. Materials and methods

2.1. Analytical approach

Across Costa Rica and many Central American countries, farmers cultivate Caturra, Catuaí, and other varieties of *C. arabica* with a similar growth-form. These varieties are characterized by having one or more orthotropic stems perpendicular to the ground (Fig. 1). Although the orthotropic stems are generally cultivated to have one apical meristem, more than one may form as a result of damage or pruning (Ramirez, 1994). Under intensive agronomic management, *C. arabica* plants can have more than one orthotropic stem and these are regularly pruned at the bottom when they are 5–10 years old (Ramirez, 1996). Dimorphic development, where two plagiotropic branches (laterals) occur at each node of the orthotropic stem opposite to each other, is observed in *C. arabica* plants (Willson, 1999). Flowers and later fruits are clustered in the nodes found in laterals.

We can therefore describe the total fruit load per tree (B) in a coffee plant at a given moment as the total number of fruit (α) in all productive laterals (l), where l is the subset of branches that contain at least one fruit (Fig. 1):

$$B = \sum_{l=1}^{n} \alpha_l \quad (1)$$

We can treat α within a coffee plant or stem as a random variable. Three potential probability distributions which can be used to describe this variable are the normal, log-normal (Limpert et al., 2001) and the Poisson distribution. Once we know the properties of the distribution, we can accurately represent the distribution with a reduced number of parameters, which could be measured from a non-destructive visual census. For example, for the normal and log-normal distribution, the mean number of fruits on the sample of productive laterals (b) can be an accurate representation of the expected value, while the standard deviation can be useful for describing the variance.

When selecting our sample however, we need to consider that laterals closer to the apical meristem correspond to vegetative growth produced in the most recent rainy season (Ramirez, 1996). Laterals found at the bottom tend to be the oldest within the orthotropic stem. These and other factors could affect the fruit loads found in a given lateral. If this were true, focusing on any specific strata of the coffee plant would most likely introduce a sampling