Designing new management sequences for pineapple production using the SIMPIÑA model

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A B S T R A C T

The pineapple Victoria (‘Queen’) is grown on Reunion Island under a large range of weather conditions where the elevation ranges from 50 to 900 m a.s.l. and annual temperatures ranges from 19 °C to 25 °C in both humid and dry areas, resulting in variable fruit size, fruit quality, selling prices of products and N leaching. Our objective was to use a crop model to improve pineapple management practices according to the diversity of conditions on Reunion Island. Farm surveys resulted in the definition of eleven criteria describing the diversity of pineapple practices to characterize pineapple farm-type: ridges, tillage, planting density, level of N fertilization and number of N application, harvest date, irrigation, farm diversification, elevation, weather and location. Three types were then identified: 1) pineapples with sugarcane the main crop located at low elevation; 2) pineapples only located at high elevation; 3) diversified farms including pineapples located at low elevation. The SIMPIÑA model was used to identify a set of best practices for each farm-type, based on fruit quality (TSS/TA), agronomic (yield), economic (income at selling), and environmental criteria (N leaching). Producing large fruits seems to be the condition to increase agronomic and economic criteria, regardless pineapple farm-type because prices of products is higher for large fruit on local market. As a result, promising management sequences selected with the model underestimated the importance of selling small fruits at local market. Overall, a decrease of level of N fertilization could reduce N leaching without reducing yield and fruit quality. This study demonstrates that multi-criteria crop simulation models used with an optimization approach provide a framework suitable for designing new management strategies of pineapple production, while taking the type of pineapple farms into account.

1. Introduction

Pineapple Victoria (‘Queen’) is the first fruit produced on Reunion Island, where sugarcane was once the dominant crop. With 16,000 tons produced on 360 ha, pineapple is considered as a diversification crop and represents 75% of the fruits exported from the country toward the international markets (Soler and Dorey, 2017). The marketing of fruit takes place in three markets: export, local market and transformation (corresponds to processing for pineapple juice and canned fruit) whose selling prices could be very variable because it depends on harvest season and fruit weight and quality at harvest. Pineapple grown under a wide range of conditions on the island, the elevation ranges from 50 to 900 m a.s.l., with average annual temperatures varying from 19 to 25 °C, and annual rainfall ranges from 500 mm in the west to 5000 mm in the east. Irrigation is only used on the south of the island. When cultivated away from the humid tropics or equatorial conditions, the pineapple growth rate, determined by temperature, decreasing and growing cycles get longer (Py et al., 1984). Moreover, through the use of ethylene forcing, flowering can be induced in pineapple throughout the year. This induced that harvests could occur from January to December. As variation in fruit size at harvest is determined in large part by plant size at forcing (Py and Lossois, 1962; Malezieux, 1988), forcing of ‘Queen’ pineapple is usually done at 11 or 12 months after planting at 750 m above the sea level, instead of 6 months under tropical conditions at sea level (Dubois et al., 2011). Consequently, a great variability in fruit size, fruit quality and price of selling were observed on the island.

Several studies have demonstrated the effects of seasonality on...
pineapple fruit size and quality (Py et al., 1984; Bartholomew and Paull, 1986; Bartolome et al., 1995; Dorey et al., 2016a, 2016b). However, although the pineapple growth rate varies with elevation and season due to variations in temperature and photoperiod, it is possible to obtain larger fruits by increasing the plant size at forcing with cultural practices. Increasing the size of planting material, mainly suckers for "Queen" pineapple (Fournier et al., 2010; Dubois et al., 2011; Dorey et al., 2015), and reducing planting density (Hepton, 2003) would achieve larger plants at forcing. Water supply and N and K fertilization are also recommended to satisfy pineapple requirement and prevent growth reduction (Malezieux et al., 2003). Thus, smaller fruit can be obtained by forcing earlier. Regardless of the area of production on the island, the recommended fertilization rates are 300 kg of N ha⁻¹ and 450 kg of potassium ha⁻¹ in seven applications according to Fournier (2011), but recent surveys demonstrated that the actual fertilization rate varies greatly. Nevertheless, fruit quality is equally affected by season and fruit development conditions and variation in sugar and acids contents can be significant; for example, acid levels are higher during cool season and sugars are lower in mainly areas of production (Paull and Chen, 2003). The diversity of conditions for pineapple production on the island makes the prediction of yield and fruit quality very complex. However, there is a need to optimize practices in order to perform in yield and fruit quality elaboration and to ensure the best prices of product at selling.

Simulation model are useful for exploring and selecting cropping system under a wide range of conditions (Sterk et al., 2007; Semenov et al., 2009). It could be used for ex-ante assessment, as demonstrated by the use of the BANAD farm model to assess agro-ecological innovations on banana farms in Guadeloupe (Blazy et al., 2010). In agronomic sciences, biotechnical models integrated the effects of cultural practices such as irrigation and fertilization for optimizing practices like planting date or fertilization rates to perform crop management (Boote et al., 1996). But in most cases, these models concern annual crops and focus on yield. Concerning fruit, models range from simple equations that estimate fruit size and yield to a complex representation of respiration, photosynthesis, and assimilation of nutrients with the goal of predicting seasonal changes in concentrations of compounds involved in quality (Vasquez-Cruz et al., 2010). Although the latter ecophysiological models simulate how environment and plant metabolism affect fruit mass, fruit volume, and sugar content, they seldom consider how water and nitrogen (N) balances affect vegetative growth and fruit quality, except models on kiwifruit (Lescourret et al., 1999) and the recent Qualitree model on peach (Lescourret and Génard, 2005; Lescourret et al., 2011). The SIMPIÑA model was recently developed to simulate the growth and fruit quality of pineapple Victoria ("Queen") on Reunion Island. Model inputs include weather and practices (planting density, sucker weight at planting, level of N fertilization, irrigation). The model simulates fruit weight at harvest, N leaching, and total soluble solids (TSS);titratable acidity (TA) ratio (Dorey et al., 2015; Dorey et al., 2016a, 2016b). An economic indicator was simulated according to harvest date, fruit weight and targeted market to estimate the income at selling of products (Pissonier et al., 2015).

The objective of this study was to improve pineapple management sequences according the diversity of conditions and practices used to produce pineapple Victoria ("Queen") on Reunion Island. The SIMPIÑA model was used to optimize pineapple management sequences and evaluate them for several farm-types with multi-criteria approach defined on the base of results of surveys. After presenting the results issued from surveys to characterize pineapple farm-types with common practices, we present the results of simulations of current and promising indicators (agronomic, economic, environmental and fruit quality). The range of promising practices are then discussed for each types.

2. Materials and methods

2.1. The SIMPIÑA model

The SIMPIÑA model is a pineapple crop model developed for the Victoria ‘Queen’ on Reunion Island. In this model, plant growth and soil modules simulate harvest date, fruit weight, yield, and N leaching according to weather (global radiation, temperature, PET, and rainfall) and practices (planting date, irrigation, fertilization N, sucker weight at planting, planting density, and date of forcing) (Dorey et al., 2015). Quality sub-modules calculate total soluble solids (TSS) and titratable acidity (TA) of fruit at harvest (Dorey et al., 2016a, 2016b). Fruit weight and harvest date determine the targeted market (local, export, local transformation of products (Table 1) and also the selling price of products (Pissonier et al., 2015) that is used as economic indicator (Table 2). A general description of the model is presented in Fig. 1.

2.2. Characterization of practices of pineapple farmers on Reunion Island

We use the method proposed by Girard et al. (2001, 2008) and adapted by Michels et al. (2009) to characterize the diversity of practices of pineapple growers on the island based on surveys conducted in 2013 at 39 farms. One representative farm field was analysed for each

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<table>
<thead>
<tr>
<th>Months of harvest</th>
<th>Range of fruit weight (g)</th>
<th>Export (%)</th>
<th>Transformation (%)</th>
<th>Local (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>December, March, April</td>
<td>&lt; 600</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>600-1000</td>
<td>80</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>&gt; 1000</td>
<td>0</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>October–November–January–February</td>
<td>&lt; 600</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>600-1000</td>
<td>50</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>&gt; 1000</td>
<td>0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>May–June–July–August–September</td>
<td>&lt; 600</td>
<td>10</td>
<td>0</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>600-1000</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>&gt; 1000</td>
<td>10</td>
<td>90</td>
<td>0</td>
</tr>
</tbody>
</table>

* Transformation corresponds to processing for pineapple juice and canned fruit.

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Table 1: Distribution of harvested fruits (%) across the targeted markets (export, transformation, and local) according to the month of harvest and the range of fruit weight in 2014 (from Pissonier et al., 2015).

Table 2: Selling prices of pineapple fruit (€ kg⁻¹) for targeted markets in 2014 (from Pissonier et al., 2015).
farm (Fig. S1). Farm advisors, researchers, and farmers met to define 11 relevant criteria that establish types with common practices. These criteria concern: (i) initial conditions (elevation, weather, and location); (ii) farm field establishment (ridge elevation, tillage, and plant density); (iii) farm field management (including the level of N and the number of N applications); and (iv) crop cycle management (harvest dates, irrigation, and diversification). Each criterion was divided into two to four modalities, described in Table 3. A multiple correspondence analysis (‘ade4’ package, Dray and Dufour, 2007) followed by a descendent hierarchical cluster analysis (‘cluster’ package, Mächler et al., 2014) made it possible to identify three types with common practices: 1) pineapples with sugarcane the main crop located at low elevation; 2) pineapples only located at high elevation; 3) diversified farms including pineapples located at low elevation. As indicated in Fig. 2, the main criteria that defined the three types of farms were their location on the island and the associated climatic conditions.

2.3. Generating, assessing, and selected crop management sequences

In a first stage, we defined the range of each practice used as inputs in the SIMPIÑA model. The ranges explored with the model varied according to the location of the three types defined (Table 3). Planting months were restricted to the three first months of the year for type 1 to allow farmers to make planting and all N fertilization applications before the beginning of the sugar cane harvesting season. Irrigation practice was only simulated for type 3. We used weather representative of the production area for each type, including the daily values of rainfall, temperature, total radiation, and PET averaged over 5 years as weather inputs. Pineapple management sequences were assessed on a set of performance criteria simulated with the model de

<table>
<thead>
<tr>
<th>No</th>
<th>Criterion</th>
<th>Practice modalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ridges</td>
<td>Elevated ridges to prevent disease and erosion and to facilitate rooting</td>
</tr>
<tr>
<td>2</td>
<td>Tillage</td>
<td>Major tillage to loosen and prevent erosion</td>
</tr>
<tr>
<td>3</td>
<td>Planting density</td>
<td>Low planting density (&lt;70,000 plants ha⁻¹)</td>
</tr>
<tr>
<td>4</td>
<td>Level of N</td>
<td>High planting density (&gt;90,000 plants ha⁻¹)</td>
</tr>
<tr>
<td>5</td>
<td>Number of N applications</td>
<td>High number of N applications (&gt;7)</td>
</tr>
<tr>
<td>6</td>
<td>Harvest period</td>
<td>Harvest in high season (March, April, December) to export harvests</td>
</tr>
<tr>
<td>7</td>
<td>Access to irrigation</td>
<td>No irrigation (no irrigation required in humid areas)</td>
</tr>
<tr>
<td>8</td>
<td>Diversification</td>
<td>Dry location without water access</td>
</tr>
<tr>
<td>9</td>
<td>Elevation</td>
<td>Low elevation (&lt;200 m) leads to short production cycle</td>
</tr>
<tr>
<td>10</td>
<td>Weather</td>
<td>Mostly dry with rainfall &lt;1000 mm per year</td>
</tr>
<tr>
<td>11</td>
<td>Location</td>
<td>North, traditional area of pineapple production</td>
</tr>
</tbody>
</table>
of current values for agronomic, environmental and economic criteria. The method differed for fruit quality criteria where we selected promising management sequences with values of TSS/TA ranged from 1.0 to 1.2, defined as optimal for pineapple fruit quality in Soler (1992). The values of criteria for current and promising pineapple management practices as well as the values for selecting these latter are presented in Fig. 3. The current and promising ranges of practices were analysed in Fig. 4.

3. Results and discussion

According to the results of surveys, three types of pineapple farms were defined: 1) pineapples with sugarcane the main crop located at low elevation; 2) pineapples only located at high elevation; 3) diversified farms including pineapples located at low elevation. The definition and characteristics of types were presented in Table 4. As observed in Fig. 2, the three types with common practices were located in three areas of production with distinct climatic conditions. The study shows that management sequences differ between the types and thus have different impact on indicators simulated with the SIMPINA model. The indicators of current and promising management sequences were presented in Fig. 3 and the ranges of practices associated Fig. 4. We found that the yields and fruit sizes produced with promising management sequences were within the ranges of yields and sizes produced with current systems but were always greater than the median, suggesting a high potential for the improvement of current management sequences.

The Type 1 “pineapples with sugarcane the main crop located at low elevation” is located at the east of the island with an elevation < 200 m, in humid areas with rainfall > 3500 mm per year, and with average annual temperature of 22 °C. These conditions lead to a short production season. The main crop of these farms is sugarcane, harvested from June to December. In this area soil preparation required heavy tillage due to the humid condition to elevate ridges in order to prevent erosion and diseases. With sucker preparation and planting, soil preparation are the most demanding technical and labor-intensive operations for pineapple production. That’s why current planting months were restricted at the beginning of the year to allow farmers to put the plots of pineapple in place before harvesting sugarcane. The current planting density had intermediate value with 80,000 plants ha⁻¹ whereas ranged from about 50,000 to 100,000 plants ha⁻¹ on the island. We could noticed that current level of N fertilization was inferior or equal to 300 kgN ha⁻¹, and was within the recommended range defined in Fournier (2011) for pineapple Victoria (Queen). The Type 2 “pineapples only located at high elevation,” was located at a high elevation > 400 m, in the north and south of the island, with levels of rainfall < and an average annual temperature of 18 °C. Pineapple is the only crop of these farms because other crops cannot be grown at the high elevations. It represent the traditional areas of pineapple production. Low temperatures at high elevation induce long production cycle...
(> 18 months) and leads to fruit weight < 1000 g (Fig. 5). Thus agronomic criteria were lowest for current and promising management sequences for type 2 whereas economic criteria were high because the promising peak harvests occurs at months where pineapple were sold on the export market that is the most profitable market with a price of selling of 1.2 euros kg\(^{-1}\) (Tables 1 and 2). Moreover planting density was extended to 90,000 plants ha\(^{-1}\) to increase the volume of production and obtain high yield. Concerning sucker weight at planting, plant growth could be enhanced by planting large suckers > 300 g but pineapple farms located at high elevation were sensitive to natural flowering triggered once a minimum plant weight was reached and when photoperiod decreased (Bartholomew et al., 2003) so natural flowering could seriously reduce yield because it results in small fruits. The Type 3 "diversified farms including pineapples located at low elevation" was located in a dry area in the southwest of the island; this

![Fig. 4. Representation of range of cultural practices for current pineapple systems (white) and promising pineapple systems (gray) for the three farm types. *For planting months, the numbers correspond to the months of year, e.g., 1 = January.](image)

Table 4
Three types of pineapple farms on Reunion Island. Each type is based on the criteria described in Table 3. The information on practices was obtained by interviewing farmers.

<table>
<thead>
<tr>
<th>Type</th>
<th>Current practices and specific characteristics</th>
</tr>
</thead>
</table>
| Pineapples with sugarcane the main crop located at low elevation | - The main production in the farm is the sugar cane  
- Farms are located in humid areas with rainfall > 3500 mm per year  
- Planting periods limited to the beginning of the year due to the management of sugar cane the latest six months of the year  
- Heavy tillage to prevent erosion and diseases with elevated ridges due to the location in a humid area  
- N Fertilization within the recommended range (200 to 300 kg N ha\(^{-1}\))  
- Low elevation < 200 m leads to short-season of production  
- Low planting density (≤ 70,000 plants ha\(^{-1}\)) |
| Pineapples only located at high elevation | - Pineapple crop is the only crop on the farm because other crops cannot be grown at the high elevations  
- Harvest at the end of December (peak harvest) and also in April  
- Unfavorable environmental conditions: dry location without the possibility of irrigation, high elevations (> 400 m), in the north and south of Reunion Island, the traditional areas of pineapple production  
- Superficial tillage and no ridge  
- High planting density (> 90,000 plants ha\(^{-1}\)) |
| Diversified farms including pineapples located at low elevation | - Crops other than pineapple are grown on the farm  
- Harvest occurs throughout the year due to the favorable environmental conditions: dry location with the possibility of irrigation; the low elevation (< 200 m) results in a short production cycle  
- Superficial tillage  
- Intensive fertilization with high N level (> 300 kg N ha\(^{-1}\)) and high number of N applications (> 7) |

Table 5
Combination of practices simulated with the SIMPIÑA model for each type of pineapple farm.

<table>
<thead>
<tr>
<th>Practice</th>
<th>Type 1</th>
<th>Type 2</th>
<th>Type 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planting months(^a)</td>
<td>1, 2, 3</td>
<td>1 to 12</td>
<td>1 to 12</td>
</tr>
<tr>
<td>Irrigation</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Planting density</td>
<td>From 50,000 to 100,000 plants ha(^{-1}) at 10,000 plants ha(^{-1}) intervals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flowering induction</td>
<td>From 150 to 300 days after planting at 30 day intervals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of N applications</td>
<td>1, 4, and 8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Level of N</td>
<td>From 0 to 400 kg N ha(^{-1}) at 50 kg N ha(^{-1}) intervals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sucker weight</td>
<td>200, 300, and 400 g</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of simulations</td>
<td>8748</td>
<td>34,992</td>
<td>69,984</td>
</tr>
</tbody>
</table>

\(^a\) The number corresponds to the month of the year, e.g., 1 = January.
area has a low elevation < 200 m, an average annual rainfall < 1000 mm, and an average annual temperature of 24 °C. Crops other than pineapple are grown on the farms. The low elevation with high temperatures results in short production cycle. It is the only area with irrigated crops and promising management sequences were irrigated, confirming that water plays a major role in pineapple growth (Py, 1960; Combres, 1983; Malezieux, 1988). The level of N fertilization is high (> 300 kg ha$^{-1}$) and seems to intensify the production to obtain larger fruits (> 700 g) in short time (Fig. 5). However, environmental criteria calculated on N leaching showed the best potential of reduction compared to others types because type 3 is located in dry areas where the soil is rarely saturated. We hypothesize that promising sucker weight could be reduced to 200 g because type 3 can adjust irrigation when rainfall is not sufficient.

Producing larger fruits seemed to be central to improving agronomic and economic criteria. It is important, however, that an increase in fruit size does not depend on an increase in N fertilization and therefore in N leaching. As mentioned in introduction, the only way to obtain larger fruits is to force larger plants or reduce planting density but forcing larger plant require greater amounts of N (g plant$^{-1}$). Our results suggest that, in most cases, the level of N fertilization could probably be decreased so as to decrease N leaching while maintaining high yields. Moreover, increasing planting density to 100,000 plants ha$^{-1}$ made it possible to harvest more fruits with little impact on fruit weight. This is consistent with the study of Norman (1978) on the ‘Queen’ cultivar in Ghana where weight per fruit decreased by only 90 g with each increase of 10,000 plants per ha up to 100,000 plants ha$^{-1}$ when competition for resources was low. Economic criterion was better for promising than for current management sequences for all three types because of the increased number of fruits harvested and the greater average fruit weight (the latter would increase the selling price). With respect to fruit weight, fruits produced in promising systems weighed > 600 g, and the price never dropped below 0.8 (€ kg$^{-1}$) regardless of the targeted market. As a result, the promising systems simulated by SIMPIÑA did not promote the production of small fruits.

Fig. 5. Boxplots of weight per fruit at harvest in relation to harvest months for current pineapple systems (white) and promising systems (gray) for farm-type 1, 2, and 3. The numbers on the X-axis correspond to the months of the year, e.g., 1 = January.
The selection of promising management sequences was based on four simple indicators simulated with the SIMPIÑA model: yield, TSS/TA, N leaching and prices of product to estimate agronomic, economic, fruit quality and environmental criteria. In future studies, it would be interesting to complete the set of indicators to assess promising management sequence for each criteria. For example, a more elaborate economic module could be used for the evaluation of gross margins. The costs associated with practices that require additional labor such as sucker calibration or high density planting would be also taken into account and could change the ranges of practices selected. In our case, the environmental criterion could be evaluated with a relatively simple criterion (N leaching) because no pesticides are used and erosion is limited by plastic mulch on Reunion Island. But additional criteria should be taken into account to match with the conditions of production in other country with others issues; these include soil fertility and erosion (Dogliotti et al., 2004) and water exposure to pesticides (Tixier et al., 2008).

Our study showed that pineapple farmers can maintaining a high level of productivity and fruit quality while improving their environmental criteria. Thus the use of SIMPIÑA model could help pineapple farmers improve their pineapple management sequences according to their specific weather and farm structure constraints.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2017.10.006.

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