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A novel method for estimating P&Ds related yield loss in cacao pods in the Peruvian Amazonia.

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ABSTRACT.

Cacao pest and diseases (P&Ds) infect and affect their hosts in specific ways, which adds complexity to study their global impact on production. Commonly, incidence is used as an indicator to evaluate P&Ds, however, it does not provide any information on yield loss, whether we look at it as a loss in quantity or quality. Therefore, from an agronomic point of view, incidence is not enough to evaluate the impact and the damage of P&Ds over production. By focusing on three specific P&Ds (Black Pod disease, Frosty Pod Rot and the "Mazorquero", local name for the American Cocoa Pod Borer) within the P&D complex that affect the cocoa pod in the Peruvian Amazonia, this research aims to produce a simple and replicable model that will allow to estimate more accurately the P&Ds incidence related yield loss and help us simulate different scenarios to calculate crop loss under different market situations. To evaluate the amount of damage caused by these P&Ds, 30 pods were opened per monitored P&Ds (each set infected with either one or a combination of the P&Ds outlined above), totalling 120 pods for the four evaluated P&Ds combinations on the CCN-51 cacao variety. Then the seeds were counted and classified in Healthy (unaffected), Affected (affected by disease but still usable) and Destroyed (unusable due to disease) to establish a Seed Damage Ratio (SDR) for each disease and disease combination. Furthermore, we elaborated a model that combines the SDRs and P&D's incidence per plot to have an estimation of the yield loss at plot scale. Our results show that the Black Pod and the Mazorquero, as well as their combination, tend to cause the least amount of damaged seeds, while the Frosty Pod Rot tends to cause the most damage. Black Pod and Mazorquero tend to have similar impact, showing mixed results between healthy and usable seeds, while their combination has a bigger impact with more usable than healthy seeds. By modifying the yield loss model for the plot, two simulations of different scenarios predicting the crop loss were elaborated. These showed that the P&D composition is highly relevant for crop loss estimation and the SDRs allow to take into consideration this composition for integrated P&D management.

Keywords: Pest and Diseases; Incidence; Yield Loss; Seed Damage Ratio.

1. Introduction

Cacao production is one of the major sources of income for millions of small farmers from all over the world, however losses due to P&Ds can go up to 38% of the global annual harvest, equating to a yield loss of approximately 4.7 million metric tons according to the ICCO in 2017 *(Marelli et al., 2019)*.Given the significance of this loss, it becomes important to develop indicators and models that can accurately measure and predict it, as well as understand which P&Ds are the most devastating, in order to support small farmers in their decision-making process against P&Ds. In Latin America, there are currently three P&D that cause the most production losses. The Frosty Pod Rot (causal agent, *Moniliophthora roreri*) can cause losses that go up to 90% of the total production *(Thevenin & Trocme, 1996)*; The Black Pod (causal agent, *Phytophthora palmivora*) disease can go up to 90% as well if left unattended *(Vanegtern et al., 2015)*; and Witch's Broom (causal agent, *Moniliphthora perniciosa*) losses range in between 50-90% *(Meinhardt et al., 2008)*. In addition, a new threat has surfaced in the Amazonia in the last decade, the American Cocoa Pod Borer (APB), locally known as "Mazorquero" (causal agent, *Carmenta foraseminis* (Busck) Eichlin), which if compared to the other diseases, it causes less direct damage (in between 11–24% to the seeds), but a high amount of indirect damage (introduction of secondary infections through the lesion caused by the nymphaea emerging from the pod) *(Fachin et al., 2019; Ninnin, 2020).*

Commonly, P&Ds are evaluated through incidence, which provides an indication of the number of diseased individuals in a population. Yet, this does not provide information on the impact the P&Ds

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have over production or the damage they cause. The damage can be measured through the Severity, as this indicator quantifies the gravity and progress of P&Ds symptoms on their hosts. Fungal diseases have a higher dispersal capacity at higher severity levels due to their dispersal mechanisms, it is recommended that these diseases are eliminated as soon as they are detected*(Fachin et al., 2019; Meinhardt et al., 2008; Ninnin, 2020; Thevenin & Trocme, 1996; Vanegtern et al., 2015)*. Moreover, the Sanitary Harvest, considered as the only practical control method for small farmers, is commonly practiced to reduce the incidence and dispersal of P&Ds *(Soberanis et al., 1999)*, making it difficult to find infected pods with high severity levels. Therefore, severity is not available for damage quantification either. In addition, P&Ds have interactions that may be synergistic or antagonistic in nature and cannot be properly quantified through these indicators *(Alomía et al., 2021)*. This creates a necessity to repurpose existing indicators or develop new ones in order to properly evaluate the damages to the productivity, and furthermore the utilization of these indicators for the development of models to estimate the actual damage P&Ds cause. Yield Loss has demonstrated to be a valuable indicator for evaluating P&Ds damage, as it is a direct result of all the interactions that P&Ds have between themselves, their environment and their hosts *(Allinne et al., 2019; Avelino et al., 2018)*.

The objective of this article is primarily to propose the utilization of yield loss as an indicator to measure the impact of P&Ds over production. We estimate the yield loss related to P&Ds through a series of mathematical models that integrate existing indicators such as incidence and severity. This article aims to provide a real application of the proposed models through a series of simulations that consider the P&D complex in the San Martin region in the Peruvian Amazonia, as well as the available markets where farmers sell their yield in this region.

2. Materials and Methods

2.1 Study area and market description.

The study area is located in the Alto Huayabamba Valley, within the San Martin Region, in the Peruvian Amazonia (-7.32°, -76.78°). With a tropical humid climate, temperatures oscillate in between 19°C and 31°C, with a daily average of 28°C. Rainfall is common throughout the whole year, with its peak during the months of January to March, when most of the 1600-2000mm of annual rainfall occurs *(Ninnin, 2020)*. The most common cacao variety utilized in the zone is the CCN-51, which makes up for almost 90% of the cacao trees in the zone. The uniformity in cacao variety and organic practices allowed unbiased comparisons in between the cacao trees in the examined communities. Farmers on average cultivate three hectares of CCN-51 and have a production of 600-800kg ha^{-1}, but it can go up to 200kg ha^{-1}in other Latin American countries *(Jaimez et al., 2022; Ninnin, 2020)*.

Three different markets for commercializing the cacao exist in the zone based on the quality of the seeds they commercialize: The Conventional Market, in which most healthy seeds can be sold. The Organic Market, in which only healthy seeds obtained through organic conditions can be sold, which is to say without the use of external chemical inputs. Lastly, the Black Market, which buys all types of seeds no matter if they are healthy, or affected by P&Ds. Most farmers have access to either the Conventional Market or the Organic Market, as well as the Black Market.

2.2 Experimental design and measurements.

Characterization of Pest & Diseases:

To establish the proper methodology for the P&D related yield loss quantification, an evaluation of the P&D situation in the area for the target crop was required. This evaluation can vary in function of the number of P&Ds, their damage mechanism, and the possibility of coinfection for these P&Ds. Literature and local data were used to determine the most common P&Ds, their damage mechanism, and if co-infection was possible in the study area.

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The three most prominent P&Ds were monitored taking into consideration the type of damage (they all affected cacao pods) and their incidence: Black Pod, Frosty Pod Rot and the APB. As cocoa pod coinfection was possible, seven combinations were considered; However, only four combinations were realistically occurring: *Black Pod Only* (SDR_{BP})*, Frosty Pod Rot Only* (SDR_{M})*, APB Only* (SDR_{MAZ}) *and Black Pod + APB* (SDR_{BP+MAZ}). CCN-51 is abundant in the area and boasts resistance against the Witch's Broom, reason as to why the disease though present in the area, was not considered for the study.

Seed Damage Ratio Estimation:

Each of the evaluated P&D combinations has an impact on the attainable seeds from the cacao pods, which worsens as time progresses. If the pod is harvested as soon as symptoms of a combination are identified, it is possible to still obtain healthy seeds. We established three seed classes considering how the P&Ds affect the seeds and the existent local markets: Healthy Seeds do not present any signs of disease; Affected Seeds present signs of disease but can still be commercially exploited; and Destroyed Seeds, which present clear signs of infection and can no longer be exploited commercially. We developed a Seed Damage Ratio (SDR) to quantify the damage taking into consideration the established seed classes. We collected only pods within one month to maturation, as infected pods with less than 5 months are not harvestable and equal a loss of 100%. We calculated the SDRs by opening 30 cacao pods per P&D combination (SDR_{BP}, SDR_{M}, SDR_{MAZ}, SDR_{BP+MAZ}) and counting the amount of seeds per seed category. The Equation (1) shows how SDRs allow to quantify the yield loss in terms of affected and destroyed seeds:

$$SDR_i = ASR_i + DSR_i \qquad (1)$$

In (1) SDR_i stands for Seed Damage Ratio of a Pest or Disease i, and equals to the sum of the damage ratio for affected seeds (ASR_i - Affected Seeds Ratio for a Pest or Disease i) plus the damage ratio for destroyed seeds (DSR_i – Destroyed Seeds Ratio for a Pest or Disease i). Then to obtain the ASR_i and the DSR_i, Equations (2) and (3) were developed:

$$ASR_i = \frac{\sum_{i=1}^{n}\left(\frac{AS_i}{S_i}\right)}{n} * 100 \qquad (2)$$

&

$$DSR_i = \frac{\sum_{i=1}^{n}\left(\frac{DS_i}{S_i}\right)}{n} * 100 \qquad (3)$$

For (2) and (3), AS_i and DS_i stand for the amount of affected and destroyed seeds in each evaluated pod respectively, while the S_i and n for both equations stand for the total amount of seeds in each evaluated pod and the total number of evaluated pods respectively. This resulted in four sets of SDRs, ASRs, and DSRs, one set for each P&D Combination established (Figure 1). We calculated the average number of seeds per pod (meanS) for the CCN-51, resulting in 46 seeds. The meanS was calculated by averaging the seeds per pod of all the harvested pods, excluding the ones affected by Frosty Pod Rot, as the damage causes the seeds to fuse, making it difficult to count the exact amount of seeds. Aside from this exception, the apparition of disease does not modify the amount of seeds per pod as this number is set at the moment of pollination *(Doaré et al., 2020).*

P&Ds related yield loss at plot scale:

Equation (4) was developed to calculate the total yield loss for the plot:

$$Yield\ Loss = \sum_{i=1}^{n}(AP \times IC_i \times meanS \times SDR_i) \qquad (4)$$

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Equation (4) combines the obtained SDRs with the P&D distribution and allows the estimation of the yield loss in terms of total amount of seeds affected and lost. For this model, AP equals the total amount of affected pods and IC_i equals the given incidence for a P&D combination.

2.3 Market simulation.

Market Simulation:

The simulations were done through the utilization of (4), along with the data collected on market prices from interviewing several farmers in the area (Table 1). These simulations only take into consideration the seed losses and the amount the farmer will gain and loss according to the category of seeds obtained through (1) and (2) Therefore, other factors (such as paid labor costs, costs of external inputs, transportation, etc…) are not considered in these simulations. The loss is considered for this research as Crop Loss (CL) as opposed to Economic Loss, which does consider all the factors involved.

Table 1. *Identified markets in the zone and the price per kilogram of seeds in soles and euros.*

Market	Market Price (Soles/kg)	Market Price (Euros/kg)
Conventional Market	7.31	1.83
Organic Market	7.7	1.93
Black Market	6.52	1.63

Equation (5) describes the model utilized to calculate the crop loss:

$$CL = \overbrace{[P * \Pi L]}^{\text{Potential Gain}} - \overbrace{\{\underbrace{[(P - AP) * \Pi L]}_{\text{Gain from Conventional or Organic Market (Healthy Pods)}} + \underbrace{[\textstyle\sum_{i=1}^{n}((AP * IC_i) * (1 - SDR_i) * \Pi L)]}_{\text{Gain from Conventional or Organic Market (Affected Pods)}} + \underbrace{[\textstyle\sum_{i=1}^{n}((AP * IC_i * ASR_i) * \Pi B))]}_{\text{Gain from Black Market}}\}}^{\text{Actual Gain}} \quad (5)$$

To calculate **CL** directly, additional constants were set to the yield loss model: Local Market Index (**ΠL**), which refers to the product of Average Seeds per Pod (**meanS** = 46) by the Average Seed Weight (**SW** = 0.00562 kg, according to Doare et al. 2020) by the Local Market Value (**MV_{Local}** = 1.83€/kg for Conventional & 1.93€/kg for Organic); and **ΠB** (Black Market Index), refers to the product of **meanS** by **SW** by the Black Market Value (**MV_{Black}** = 1.63€/kg). **CL** is directly estimated by subtracting the **Actual Gain** from the **Potential Gain**. Potential Gain refers to the maximum profit the farmers could obtain assuming there are no pods infected by P&Ds, and it is obtained by multiplying the Total Pods (**P**) by the **ΠL**. The Actual Gain refers to the actual amount of profit the farmers obtain, and it is traditionally obtained by subtracting the CL from the Potential Gain. Through (5), the Actual Gain can be predicted by summing the Gain from the Healthy Pods in the Conventional Market plus the Gain from the Affected Pods in the Conventional Market plus the Gain from the Affected Pods in the Black Market. (Table 2).

To estimate the CL, two simulations were made under similar production situations, excepting the composition of the P&D complex. The total amount of pods was set to a theoretical 3095, this equals 800kg. The global incidence was set to 60%. For the Simulation 1 (Sim1) the distribution of the global incidence was 15% Black Pod, 15% Black Pod + Mazorquero, 10% Frosty Pod Rot and 60% Mazorquero. For Simulation 2 (Sim2) the distribution was 15% Black Pod, 15% Black Pod + Mazorquero, 60% Frosty Pod Rot and 10% Mazorquero.

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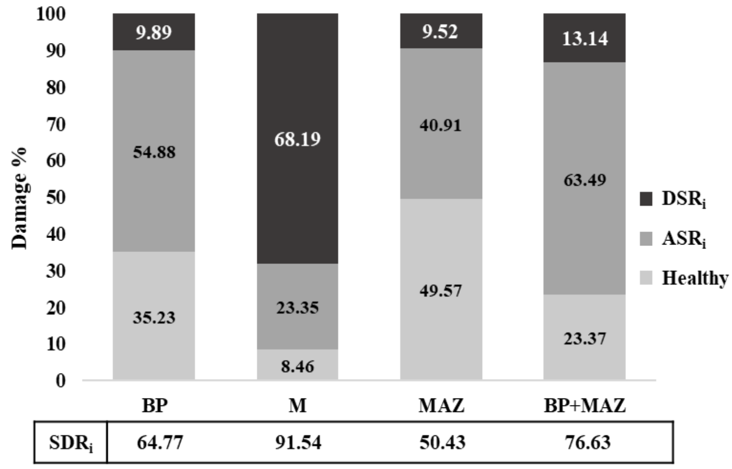
Table 2. Identified markets in the area & equations to obtain the gain per type of seed for each market. Blocks with Sim1 & Sim2 show the equations utilized to calculate each simulation.

Seed Type / Market	Destroyed Seeds	Gain From Healthy Pods	Gain from Affected Pods		Crop Loss $CL = [P * \Pi L]$ - [Gain from Healthy Pods + Gain from Affected Pods]
			Healthy Seeds	Affected Seeds	
		$[(P - AP) * \Pi L]$	$\sum_{i=1}^{n}((AP * IC_i) * (1 - SDR_i) * \Pi L)$	$\sum_{i=1}^{n}((AP * IC_i * ASR_i) * \Pi B)$	
Local Conventional (ΠL) - 1.83€/kg		Sim1	Sim1		CL Sim 1
Local Organic (ΠL) - 1.93€/kg		Sim 2	Sim 2		CL Sim2
Local Black (ΠB) - 1.63€/kg				Sim1 & Sim2	

3. Results & Discussion

3.1 Seed Damage Ratios & Yield Loss Quantification:

Results for the SDRs are shown in Figure 1. The most damaging disease in the area is the Frosty Pod Rot which has an SDR of 91.54% where 68.19% of the seeds are lost. In comparison, the APB causes the least amount of damage with an SDR of 50.43% and a loss of 9.52% seeds. SDRs from the Black Pod (SDR_{BP} = 64.77%) and the APB (SDR_{MAZ} = 50.43%) show that Black Pod affects more seeds, however the amount of seeds lost remain similar (DSR_{BP} = 9.89% vs DSR_{MAZ} = 9.52%). Finally, the combination of Black Pod & APB causes more damage than each of them alone (SDR_{BP+MAZ} = 76.63%



vs SDR_{BP} = 64.77% & SDR_{MAZ} = 50.43%), which may indicate synergy between the pest and the disease, though the damage does not appear to be additive.

Figure 1. Seed Damage Ratios obtained per P&Ds Combination. Black Pod Only (BP), Frosty Pod Rot Only (M), APB Only (MAZ) and Black Pod + APB (BP+MAZ). Bar plots represent the distribution of the ratios for each P&D combination evaluated. SDRi represent the sum of the DSRi & ASRi for each P&D combination.

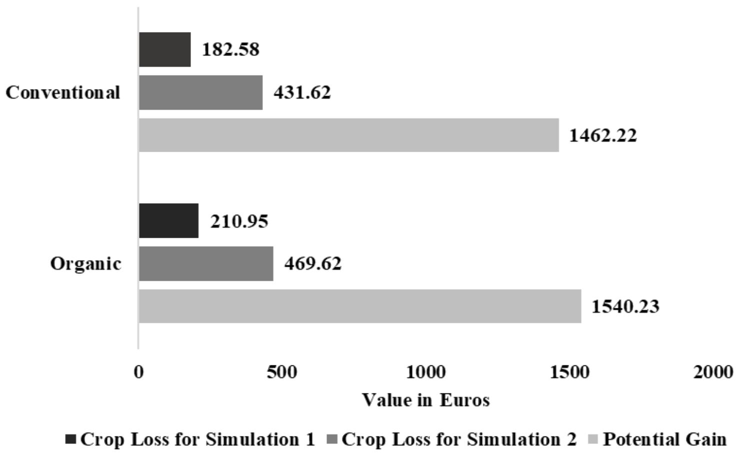
SDRs provide meaningful information about the P&Ds in terms of affected and destroyed seeds, even taking into consideration if coinfection exists. The SDRs allow to assign a severity to each pest, disease or combination that is otherwise not measurable in the field due to the risk of P&Ds causing a strong epidemic. It also permits to assign a numeric value to the perceptions farmers have on the severity of each P&Ds, as shown by the results obtained for the APB, which farmers perceived to be highly harmful, and found to be the least harmful P&D evaluated.

SDRs are rather simple calculations and only require to be calculated once for a specific cacao variety in a specific zone. The materials and methods required to calculate them are inexpensive, and remain non-intrusive to the farmers day to day tasks. They are versatile enough to be adapted to different cacao varieties under different situations and agronomic systems. Further research is necessary though, as SDRs do not consider the loss that occurs when P&Ds affect cacao pods at early phenological stages. The SDRs were designed only taking into consideration P&Ds that affect the seeds, however, other diseases such as the Witch's Broom that affects the plant at a physiological level, or the Cocoa Stem Borer, that can damage other plant tissues, can also impact yield. Developing more complex models that take these factors into consideration would permit more precise evaluations of damage and crop loss.

Lastly, as SDRs allow quantification of yield loss related only to P&Ds, it may open new research paths in functional ecology. If yield loss can be considered as a direct result of the interactions of the P&Ds and their environment, and a black box approach is taken, it may be possible to utilize the yield loss as an indicator of the P&D regulating service, which considers all of these interactions to regulate the appearance and severity of diseases in an ecosystem *(Allinne et al., 2019; Avelino et al., 2018; Mortimer et al., 2018; Poeydebat et al., 2017; Ratnadass et al., 2012)*.

3.2 Market Simulations:

The results for the market simulations are shown in Figure 2. Results show small differences in CL for each simulation considering the evaluated markets. Both simulations show a slightly higher CL and Potential Gain in the Organic Market in comparison to the Conventional Market. The CL is markedly



higher for Sim2, effectively doubling the CL of Sim 1. We can attribute the difference to the composition of P&Ds and their incidence distribution, being that Simulation 1 had a higher incidence (60%) of APB, and Sim2 had a higher incidence (60%) of Frosty Pod Rot.

Figure 2. Crop Loss & Potential Gain in Euros for Simulation 1 & Simulation 2

If fed with real incidence data collected in the field, the equations could provide useful predictive information for decision making in integrated P&D management. The equations allow to quantify the crop loss taking into consideration all the available markets as well as the P&D composition. It also allows to predict the crop loss utilizing incidence, which is the most common indicator utilized by technicians. Having this tool may help prioritize the most damaging P&Ds at a certain period, and help choose specific control practices that target these particular P&Ds, in order to optimize time and resources.

4. Conclusion

We developed a methodology to establish Seed Damage Ratios for the CCN-51 cacao variety in the Alto Huayabamba Valley in San Martin. We developed a series of models that utilized the obtained Seed Damage Ratios along with the P&D incidence to calculate the yield loss and consequently, the crop loss for each specific evaluated P&D and P&D combination. The Seed Damage Ratios showed that the most damaging disease in the zone is the Frosty Pod Rot (91.54%) followed by the combination of Black Pod and APB (76.63%). The APB (50.43%) proved to be the least damaging pest on it own. Finally, the P&D composition is highly important and needs to be considered when designing strategies for P&Ds control, as shown by the crop loss calculation model.

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