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Cocoa Pod Borer (*Conopomorpha cramerella* Snellen) in Papua New Guinea: Biosecurity Models for New Ireland and the Autonomous Region of Bougainville

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Cocoa Pod Borer (*Conopomorpha cramerella* Snellen) (CPB) is an important pest of cocoa. Following its emergence as a pest in East New Britain, Papua New Guinea, in 2006, it was considered relevant to assess its potential spread to other cocoa growing regions. Its likelihood of introduction to the islands of Bougainville and New Ireland from East New Britain Province, Papua New Guinea, was modeled using Monte Carlo simulation. This dispersal model was based around different scenarios, identifying trends rather than explicitly attempting to encapsulate true values. The model suggested that CPB is far more likely to establish on New Ireland than on Bougainville. More important, incertitude resulting from incomplete knowledge of the amount and frequency of cocoa transported between islands had a significant effect on model outputs. Quarantine and agriculture officials will be able to refine these parameter values, and then use the relevant scenarios from those presented here as a guide to develop quarantine procedures. In addition, a contingency model was employed to estimate the optimal sampling effort to use following an incursion of CPB into Bougainville or New Ireland and the seemingly successful implementation of an initial eradication program. The model suggests that at a 1% infestation level, sampling should continue for 2.5–2.7 years (90% CI) after claiming eradication, and this estimate changed little for higher infestation levels. Through modeling variations in sampling intensity, the model also suggested that determining the full spread of CPB is more important than increased sampling within one region.

KEY WORDS: Cocoa; contingency; incursion management; Papua New Guinea; quarantine pest; risk analysis

1. INTRODUCTION

Cocoa was introduced into Papua New Guinea by 1905, becoming a significant component of Papua New Guinea's agricultural sector.(1) It represents 17% of Papua New Guinea's agricultural revenue, equivalent to about K250–K300 million (95–114 million USD) annually.(2,3) The contribution of Papua New Guinea's cocoa crop to world markets is greater than indicated by volume alone, as up to 9% of the world's fine-flavored cocoa is produced in Papua New Guinea.(4) Within Papua New Guinea, 60% of exported cocoa is produced in East New Britain Province (ENBP), while 20% is produced in the Autonomous Region of Bougainville (Bougainville).(3,4) Other cocoa-producing provinces are Madang, East Sepik, New Ireland, Oro, and Morobe (Fig. 1).(4)

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Fig. 1. Map of Papua New Guinea with provinces marked.

CPB is an important pest of cocoa, causing production losses of up to 90%.(3) CPB is considered endemic to Southeast Asia, and the first reports of CPB attacking cocoa were in the Sulawesi region of Indonesia in the 1860s.(5) Since then, reports have been made of CPB attacking rambutan (*Nephelium lappaceum* L.) and cocoa throughout Indonesia, Malaysia, the Philippines, Samoa, and Papua New Guinea.(5) CPB has also been recorded feeding on *Pometia* sp., *Nephelium* spp., *Cynometra* sp., and *Cola* sp.(1) Despite earlier records, it was not until 2006 that CPB was considered a pest in Papua New Guinea.(3) The declaration of pest status followed the discovery of an outbreak in the Kerevat area of the ENBP. Delimiting surveys attempted to determine the extent of CPB infestation, and an extensive eradication program was thought to have been successful.(4) Further monitoring subsequently showed that CPB had spread beyond the region targeted by the eradication program.(4) As such, the eradication program failed, and CPB now infests much of the ENBP.

While it has been determined that other provinces of Papua New Guinea harbor CPB, the islands of New Ireland and Bougainville (Fig. 1) are both thought to be free of CPB, with the exception of nonproblematic races.(3) At present, CPB is thought to comprise three morphologically distinct races, with only one of these attacking cocoa, but detailed studies are yet to be undertaken to determine if they are races or indeed three separate species in a complex. This is particularly important for Bougainville, where almost 20,000 ha of land is used for smallholder cocoa farms (P. Gende, pers. comm., November 2008). Cocoa has been integral to the financial stabilization of Bougainville, following extensive civil unrest during the late 20th century. Cocoa exports from Bougainville doubled in the early 21st century, compared with cocoa output during the late 20th century. A cocoa-planting program funded by the European Union, UNDP, and AusAID assisted in attaining this productivity increase, with about 2 million seedlings planted in the late 1990s, and a further 9.6 million seedlings distributed by 2003.(6–8) While New Ireland does not currently rely as heavily on cocoa as Bougainville, future expansion of the New Ireland cocoa industry seems likely. It is therefore pertinent to consider the risk of CPB dispersing from ENBP to either Bougainville or New Ireland.

Assessing the risk of CPB dispersal will highlight possible CPB incursion routes, thus informing quarantine practices and incursion management plans. In the event of CPB establishment on either New Ireland or Bougainville, this information will then inform a contingency plan. If an eradication program is attempted, a sampling program to monitor population levels will be needed. Posteradication sampling is difficult, as the collection of null samples does not necessarily indicate a null population.(9–11) Long-term iterative sampling will provide the highest level of confidence that eradication has been successful, but is usually financially prohibitive. Therefore, an ideal sampling period can be defined as one which, given successive null sample events, provides a reasonable level of confidence that the pest has been eradicated, while balancing the costs of mistakes.(11) In this approach to evaluating the success of eradication, a type I error occurs when the plan prematurely concludes eradication when the pest is actually present, and a type II error occurs when sampling continues after eradication has already been achieved.(11) The possible cost of the pest being present at the end of the sampling period versus the cost of continued sampling will determine which type of error is more serious in a given case.

This study aims to use uncertainty modeling to generate a distribution of the risk of CPB dispersing to New Ireland or Bougainville, as well as to determine the optimal level of sampling to determine pest absence after completion of an eradication program, given the logistical and financial constraints present in PNG and the importance of the cocoa industry to the economy.

2. METHODS AND MODEL CONSTRUCTION

2.1. Data

Several data sources were used to inform our models; most comprised obtaining expert opinion in different formats. These included a survey(12) and targeted interviews conducted in PNG, technical reports,(3) (e.g., CCI),(3) and published literature.(1,5) The survey and targeted interviews were conducted in Papua New Guinea from November 9–14, 2008. Cocoa Coconut Institute (CCI) staff arranged meetings with cocoa experts in Bougainville (November 10–11, 2008) and in the ENBP (November 12–14, 2008). Experts were defined at the discretion of CCI staff in Bougainville and ENBP. A detailed description of the survey process and results is omitted here, but relevant components are discussed below, and relevant questions are included in Table I.

The survey was distributed at meetings organized by CCI staff. The Bougainville meeting involved staff from CCI (Buka), Bougainville Division of Primary Industry, and the Buka Division of Economic Services, as well as local shipping, marketing, and finance corporation representatives. The meeting in ENBP coincided with a meeting of the CPB response coordinating committee, and was attended by staff from the National Agricultural Research Institute (NARI), CCI, National Agriculture Quarantine and Inspection Authority (NAQIA), PNG Cocoa Board, Centre for Agricultural Bioscience International (CABI) South-East and East Asia, PNG Growers' Association, ENBP Administration, and several tertiary institutions.

Targeted interviews were held with staff from the NAQIA, the East New Britain Provincial Administration Division of Primary Industry (DPI), and shipping company representatives from the Rabaul Port. Interviews were conducted on November 12, 2008, and involved a description of the aims of our study, followed by questions relevant to the particular agencies. CCI staff also provided information from November 9–14, 2008, as well as technical reports from earlier experiences with CPB.(3)

2.2. Dispersal Model

A conceptual model was created to assess the likelihood of dispersal through a number of different pathways, with factors such as transport survival and establishment probability creating a series of progressively shrinking subsets of a source population (Fig. 2).(13)

Small motor boats ("banana boats") travel frequently from ENBP to other regions, although large passenger boats and planes also represent potential dispersal pathways (Table I). It was suggested that small boats are a risk to New Ireland only,

Table I. Questions and Responses for Targeted Interviews

Source	Question	Response
NAQIA	How many small boats leave the shore of ENBP and arrive at (1) New Ireland or (2) Bougainville? Please give your answer as: Minimum = Maximum = Most likely =	New Ireland Province ~170 boats travel in and out per week (seven days). *Note: No response given for Bougainville.*
Survey	What is the most likely reason for deliberate transport of cocoa plant material to Bougainville or New Ireland?	23.5% of responses listed sabotage, motivated by negative feelings regarding the economic success of the cocoa industry in Bougainville. 23.6% of responses listed the importation of cocoa to provide better genetic resources as the main reason. Other responses include: ignorance of quarantine restrictions and the risk of CPB introduction; and economic reasons, with the suggestion that currently available planting material is too expensive and too low yielding.
Survey	What life stage of cocoa pod borer is most likely to be transported from elsewhere in PNG to Bougainville OR New Ireland? Choice of: egg, larvae, pupae, and adult	New Ireland: 50% - egg 30% - larvae 10% - pupae 10% - adult Bougainville: 50% - egg 30% - larvae 15% - pupae 5% - adult
CCI	From your alternative-host plant studies, if you were to take 100 alternative host plants, how many would contain CPB larvae or eggs? Please report your response as: Minimum = Maximum = Most-likely =	Minimum = 0 Maximum = 0 Most-likely = 0
CCI	From a farm within the eradication zone, if you were to take 100 pods, how many would contain CPB larvae or eggs? Please report your response as: Minimum = Maximum = Most-likely =	Minimum = 40 Maximum = 80 Most-likely = 60
Shipping representatives (anonymous)	How many large passenger boats travel between ENBP and New Ireland or Bougainville per week?	New Ireland: Zero, one, two, or three boats travel per week, depending on demand. Bougainville: Zero, one, or two boats travel per week, depending on demand.
Survey	How likely is the deliberate or accidental movement of cocoa pods or plant parts from elsewhere in PNG to New Ireland or Bougainville? Choice of: unlikely, moderately likely, and highly likely	The most common response (45%) was moderately likely, as compared to highly likely and unlikely.
CCI	How is sampling undertaken in a region suspected of having CPB?	1. We take 200 pods per farm. 2. We only sample farms that are within 200 m radially from the point of detection. 3. Pod sampling is random.

Only those that were directly incorporated into model parameters or model structure are included.

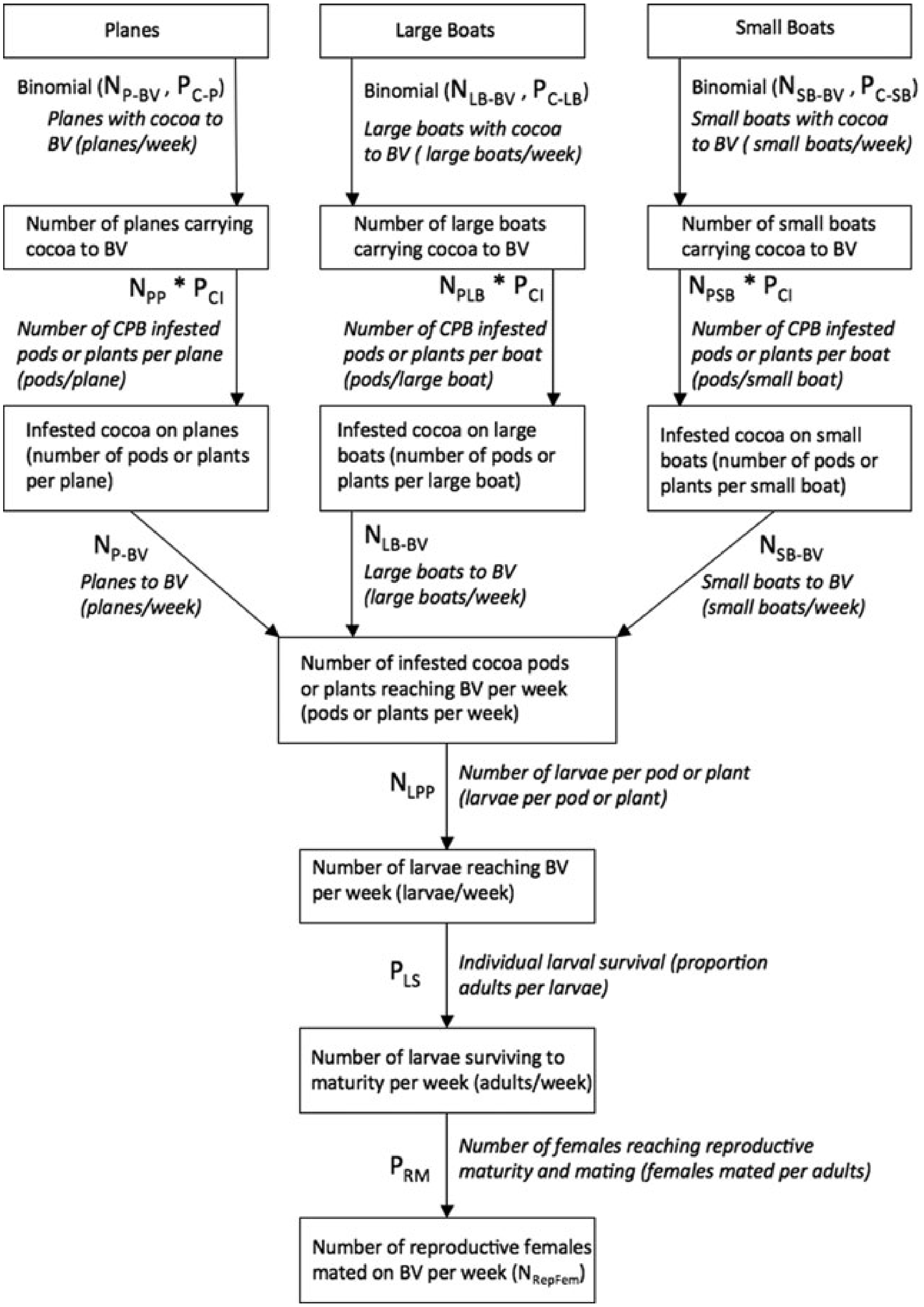

Fig. 2. Schematic outlining model structure. Arrows represent parameter applications, while nodes represent the relevant population. Parameter estimates are defined in Table II. The example shown is for cocoa transport only to Bougainville but the same structure applies to the New Ireland and alternative hosts models.

as Bougainville is too far for small boats to travel (Table I; Fig. 1).

Results from the survey suggested that CPB was most likely to be transported as larvae or eggs (Table I). Vegetative propagation of cocoa is common, and cocoa beans do not remain viable for more than one week after removal from pods;[14] therefore, larvae and eggs could be transported either on cocoa seedlings or in infested cocoa pods. Alternative host plants are most likely transported for personal consumption; therefore only the fruits of alternative host plants were considered in this model. Natural or wind-assisted dispersal has been documented in other Lepidopteran groups,[15–18] but CPB has not been shown to disperse long distances using these methods. Inclusion of a low-probability event encompassing wind-assisted dispersal (10% chance of one gravid female arriving per week, with the possibility of multiple arrivals in any given week, with four larvae surviving per female) saw no change in median values, and less than a 1% change in confidence intervals, although the influence of subsequent population dynamics remains unknown. These events were therefore not included in the final model. Human-assisted dispersal of CPB eggs and/or larvae via cocoa pods or seedlings or the fruits of alternative hosts thus became the focus of the model.

The number of CPB females successfully reproducing per week (N_{RepFem}) on New Ireland or Bougainville was modeled as:

$$\begin{aligned}N_{\mathrm{RepFem}} = {} & P_{\mathrm{RM}} \times P_{\mathrm{LS}} \times N_{\mathrm{LPP}} \\ & \times[P_{\mathrm{CI}} \times \{N_{\mathrm{PP}} \times (\mathrm{Binomial}(N_{\mathrm{P-X}}, P_{\mathrm{C-P}})) \\ & + N_{\mathrm{PLB}} \times (\mathrm{Binomial}(N_{\mathrm{LB-X}}, P_{\mathrm{C-LB}})) \\ & + N_{\mathrm{PSB}} \times (\mathrm{Binomial}(N_{\mathrm{SB-X}}, P_{\mathrm{C-SB}}))\} \\ & + P_{\mathrm{OHI}} \times \{N_{\mathrm{OHP}} \times (\mathrm{Binomial}(N_{\mathrm{P-X}}, P_{\mathrm{OH-P}})) \\ & + N_{\mathrm{OHLB}} \times (\mathrm{Binomial}(N_{\mathrm{LB-X}}, P_{\mathrm{OH-LB}})) \\ & + N_{\mathrm{OHSB}} \times (\mathrm{Binomial}(N_{\mathrm{SB-X}}, P_{\mathrm{OH-SB}}))\}]. \end{aligned} \quad (1)$$

Here, Binomial (n, p) refers to the binomial distribution with n trials and probability p of success. N represents parameters estimated as countable units, while P represents parameters estimated as proportions. X represents the destination region (New Ireland (NI) or Bougainville (BV)). Therefore, P_{RM} is the proportion of females reaching reproductive maturity (females mated/total adults), P_{LS} is the proportion of larvae surviving (adults/larvae), N_{LPP} is the number of larvae per host plant (larvae/pod or plant), P_{CI} is the proportion of cocoa infested within the source region (infested cocoa/all cocoa), P_{OHI} is the proportion of other CPB hosts infested within the source region (infested fruits/all fruits), and $N_{\mathrm{P/OH-P/LB/SB}}$ is the number of pods per plane, large boat, or small boat (pods/plane, large boat, or small boat). $P_{\mathrm{C/OH-P/LB/SB}}$ represents the average proportion of planes, large boats, or small boats with cocoa or other hosts present (planes, large boats, or small boats with cocoa or other hosts/all planes, large boats, or small boats) and $N_{\mathrm{P/LB/SB-X}}$ represents the number of planes, large boats, or small boats that travel to destination X per week (plane or boat/week).

2.2.1. Parameter Estimation

The paucity of data and heavy reliance on expert opinion meant that uncertainty in parameters was difficult to quantify. To combat this, scenarios were created based on varied values for parameters not informed by quantitative data. Each scenario represented a different possible case, and thus encapsulated incertitude in our outputs. Modeling parameters as random variables incorporated natural variation. Unfortunately, in many cases distributional choices and the data used to inform parameter estimates were subject to incertitude. The Latin hypercube sampling (LHS) technique was used to ensure that the tails of the input probability distributions were adequately sampled. Output distributions were generated using @Risk version 4.5.2, Professional Edition (Palisade Corporation, Newfield, New York). Simulations were run with 10,000 iterations, and Spearman rank correlation coefficients (r_s) were calculated to assess the relationship between each input and the output.

Day[1] and Lim[5] suggest that CPB can potentially disperse via alternative hosts such as rambutan, taun (*Pometia* spp.), and banana (*Musa* spp.). A CCI study on CPB emergence from alternative hosts has found no CPB emerging from any suggested alternative host plants (Table I). In this study, no CPB emerged from 100 fruits. A uniform distribution was used to model this, with a minimum of zero fruits infested, and a maximum of one in 100 fruits infested (Tables I and II). The level of cocoa infestation (P_{CI}) was modeled as the average proportion of cocoa pods infested with CPB, estimated from the number of pods infested in a random sample of 100 pods (Tables I and II). A PERT distribution was used to model this (Table I). Such estimates could also be modeled

Table II. Parameters Used in the Dispersal Models to Assess the Risk of CPB Arriving on New Ireland or Bougainville

Parameter	Description	Distribution
P_{C-P}	Average proportion of planes carrying cocoa	Constant = 0.01, 0.1, or 0.2
P_{C-LB}	Average proportion of commercial passenger boats carrying cocoa	Constant = 0.01, 0.1, or 0.2
P_{C-SB}	Average proportion of small boats carrying cocoa	Constant = 0.01, 0.1, or 0.2
P_{OH-P}	Average proportion of planes carrying other hosts	Constant = 0.01, 0.1, or 0.2
P_{OH-LB}	Average proportion of commercial passenger boats carrying other hosts	Constant = 0.01, 0.1, or 0.2
P_{OH-SB}	Average proportion of small boats carrying other hosts	Constant = 0.01, 0.1, or 0.2
P_{CI}[b]	Average level of CPB infestation in cocoa	PERT Min = 0.4 Most likely = 0.6 Max = 0.8
P_{OHI}[b]	Average level of CPB infestation in other hosts	Uniform {0, 0.01}
N_{P-BV}[b]	Number of planes traveling to Bougainville per week	Discrete {0,3,4,5}{0.1,1,1,0}[a]
N_{LB-BV}[b]	Number of large boats traveling to Bougainville per week	Discrete uniform {0,1,2}
N_{P-NI}[b]	Number of planes traveling to New Ireland per week	Discrete {0,6,7,8}{0.1,1,3,1}[a]
N_{LB-NI}[b]	Number of large boats traveling to New Ireland per week	Discrete uniform {0,1,2,3}
N_{SB-NI}[b]	Number of small boats traveling to New Ireland per week	Poisson $\lambda = 170$
$N_{P/OH-P/LB/SB}$	Number of cocoa pods or seedlings or other host fruits per plane or boat	Constant = 1, 5 or 10
N_{LPP}[c]	Average number of CPB larvae or eggs in any given host plant (including cocoa)	Discrete {1,2,3,4,5}{0.15,0.12,0.1,0.07,0.56}[a]
P_{LS}[d]	Proportion of individual larvae surviving to adulthood	Uniform {0.5, 0.75}
P_{RM}[c]	Proportion of females reaching reproductive maturity	Constant = 0.14

Superscripts in the parameter column represent source of information for each parameter.
[a] @RISK software automatically normalizes all distributions.
[b] See Table I.
[c] Parameter estimated from information in Lim.(5)
[d] Parameter estimated from information in Day.(1)

using triangular or uniform distributions, but these would likely overestimate the tails of our distribution, as these data were informed by extensive studies, generating a reliable "most likely"estimate.

The number of planes or small/large boats traveling to both New Ireland and Bougainville ($N_{P/LB/SB-X}$) was estimated using targeted interviews and airport data (Tables I and II). The number of planes traveling between islands (N_{P-X}) was estimated from airport data, recording the number of flights traveling from ENBP to Bougainville or New Ireland per week. These values varied, and a discrete (nonuniform) distribution was used to model natural variation in weekly flight numbers (Table II). Note that the possibility of zero flights in a given week was included as a low-probability event, as this occurs during times of high volcanic activity around Rabaul. The number of small boats traveling from ENBP to New Ireland or Bougainville (N_{SB-X}) was estimated from targeted interviews with NAQIA staff (Table I). A senior NAQIA employee interviewed a number of foreshore community representatives, and compiled estimates of the number of small boats leaving the ENBP shoreline. Unfortunately, while minimum, maximum, and most likely estimates were requested, this information was compiled and summarized, providing us with only a point estimate of the number of boats leaving the foreshore, along with the number arriving at each possible destination (Table I). This estimate was used to inform a Poisson distribution, as it provided the average (we assume) frequency of boat departures per week, subject to an unknown amount of natural variation (Table II). Unfortunately, multiple estimates were not provided, nor were estimates of minimum and maximum numbers of boats leaving the foreshore. Therefore, we had to make the assumption that each boat departure was independent, along with the assumption that the Poisson distribution accurately models the natural variation in boat departures. To test the possible impact of these assumptions, these data were also modeled using a discrete uniform distribution, as well as a point estimate for the number of boats departing per week. The number of large passenger boats departing each week (N_{LB-X}) was determined from targeted interviews with shipping company representatives (Table I). This information was modeled as a discrete uniform distribution, as the number of large passenger boats varied between zero and three per week (Table II).

Lim(5) recorded the number of larvae emerging from a large sample of pods; these data were used to estimate N_{LPP}. These data informed a discrete (nonuniform) distribution of the number of larvae emerging from any given pod (Table II). Day(1) recorded mortality rates in different CPB life stages; pupal mortality rate from this study was used to estimate P_{LS} (Table II). This approximation was considered more accurate than assuming that all larvae successfully pupate. Note that N_{LPP} already considers larval mortality, hence only pupal mortality is considered for P_{LS}. Day's(1) study suggested that pupal survival varies naturally between approximately 0.5 and 0.75. A continuous uniform distribution was used to represent this (Table I).

P_{RM} was estimated using data from Lim.(5) This parameter further reduces our invading population from those that survive to maturity to those females that go on to reproduce. A point estimate was used to represent the proportion of females that go on to mate once or more, as opposed to those who never mate (Table II).

The above parameters were obtained from numerical data, and if we assume that such data are reliable, this reduces incertitude. Unfortunately, $N_{\mathrm{P-P/SB/LB}}$, $N_{\mathrm{OH-P/SB/LB}}$, $P_{\mathrm{C-P/LB/SB}}$, and $P_{\mathrm{OH-P/LB/SB}}$ were not able to be determined from numerical data, and thus any estimates were subject to large amounts of incertitude, alongside any inherent natural variation. For these simulations, $N_{\mathrm{P-P/SB/LB}}$, $N_{\mathrm{OH-P/SB/LB}}$, $P_{\mathrm{C-P/LB/SB}}$, and $P_{\mathrm{OH-P/LB/SB}}$ were set at constant values, representing alternative states (Table II). The different scenarios considered the likelihood of cocoa or other hosts being transported, and the number of host pods or plants transported per plane or boat. For all scenarios, parameter values were determined relative to each other. While these values do not necessarily represent the true situation (which remains unknown), the relative influence of increasing or decreasing the prevalence of CPB host transport can still be assessed using this model. $N_{\mathrm{P/OH-P/LB/SB}}$ represent the number of cocoa pods or plants or other host fruits on a given plane or boat. Values of 1, 5, and 10 were used for these parameters (Table II). $P_{\mathrm{C/OH-P/LB/SB}}$ represents the proportion of planes or boats that carry host plant material. Three cases were considered here: one in every 100 planes and boats carrying host plant material; one in every 10 planes and boats carrying host plant material; and one in every five planes and boats carrying host plant material (Table II). Combinations of the above parameters were used to create the scenarios. Two further scenarios examined extreme situations: deliberate transport of large amounts of cocoa and other hosts; and frequent transport of small amounts of cocoa and other hosts. The former scenario considered one in every 100 planes or boats carrying 100 pods, seedlings, or fruits, while the latter considered one in every two planes carrying one pod, seedling, or fruit. A final scenario was run to consider the separate influence of cocoa and other host transport on CPB introduction rates. In this scenario, two simulations were run: first with only cocoa being transported, and second with no cocoa and only other host plants being transported.

It was important to assess the impact each different transport route (plane, small boat, or large boat) had on the center and spread of output probability distributions. This was incorporated as part of the sensitivity analyses, whereby separate simulations were run, considering only one transport route at a time.

2.2.2. Assumptions

Assumptions were made during the construction of this model. It was assumed that cocoa or other hosts from all parts of ENBP are equally likely to be transported, and that CPB larvae or eggs will survive the duration of any journey. After incorporation of pupal mortality rates, it was assumed that all surviving pupae became viable adults. Also, while CPB life stages are present as discrete units, infestation level was modeled as a continuous random variable.

We assumed that all parameters are independent. This assumption is significant, as any dependencies could greatly influence model outputs. However, it was considered important to assess the impact minor dependencies ($r = 0.5$) had on outputs. Simulations were run including these dependencies and were found to cause less than a 2.5% change in output confidence intervals, with independent parameters generating more conservative results in all cases. Dependencies were thus not considered in the final model. These minor dependencies included positive seasonal dependencies in transport routes and negative dependencies between number of larvae or eggs and survival rates. Other seasonal factors were not included, for example, timing of cocoa growing seasons and the pest-host dynamics. CPB has been shown to be active all year round, and there is no evidence to suggest that transport of cocoa or other host plants is localized to any particular time of year.

Finally, CPB was assumed to display a random distribution among transported cocoa (or other host) pods or plants. While CPB is known to display an aggregated distribution within a region,(5) there are no data to suggest that CPB displays an aggregated distribution within an infested crop. For example, regional aggregation may result from the aggregation of cocoa crops rather than the aggregation of CPB *per se*. Also, the selection of cocoa pods by those transporting them may well be random, as cocoa pods and seedlings do not display signs of damage until a threshold is crossed.(1,5) Thus, the pods and plants that are transported represent a random selection from all pods and plants. Finally, if the aggregated distribution of CPB within crops does alter the likelihood of particular dispersal pathways, this model will produce conservative results. Therefore, in the absence of more conclusive evidence, and given the importance of this particular pest, this assumption was considered acceptable.

2.3. Contingency Model

A model was applied to determine the optimal sampling effort for inferring absence after an eradication program, defined on a cost-benefit basis. Regan *et al.*(11) outline a rule of thumb to determine optimal sampling effort. This rule of thumb was used to approximate a more thorough stochastic dynamic programming (SDP) approach, and was found to be valid for the present scenario. Regan *et al.*(11) determined optimal sampling by minimizing an equation for the net expected cost of a pest species per year. The equation considers the cost of sampling and the cost of an outbreak, and weights these according to likelihood of pest detection. The optimal number of years to sample posteradication, n^*, is given as:

$$n^* = \ln\{-C_s/(C_e \times \ln\{r\})\}/\ln\{r\}, \qquad (2)$$

where $r = p\,(1 - q)$, p is the probability of CPB population survival for one year, q is the probability of detection of a CPB population, C_s is the cost of sampling, and C_e is the cost of a CPB outbreak.

2.3.1. Parameter Estimation

Due to uncertainty surrounding parameters in this model, parameters were modeled as random variables, based on relevant data. Here, parameter estimates incorporated both incertitude and natural variation. Separate simulations were run to encapsulate incertitude, giving scenarios of different situations, rather than assuming that a single chosen scenario adequately represents reality. As before, this attempts to separate incertitude and natural variation. Unfortunately, parameter estimates in a given simulation also contain incertitude, confounding the different types of uncertainty in our model output. To address this, the nature of the uncertainty in parameters is stated explicitly, which will improve our ability to identify the source of the uncertainty. We adopted the LHS technique to ensure that the tails of the input probability distributions were adequately sampled. Simulation was conducted using @Risk version 4.5.2, Professional Edition (Palisade Corporation). Each simulation was run with 10,000 iterations, and Spearman rank correlation coefficients were calculated to identify those parameters that contribute most to uncertainty in the output and thus require clarification or further research.

For this model, both C_s and C_e were determined from CCI(3). CCI(3) gives a point estimate for C_s, based on sampling undertaken during and after an eradication program in ENBP. This estimate can be assumed to be representative; however, natural variation is also likely to occur. Therefore, a triangular distribution was used to represent this parameter, with the minimum value set at 90% of that recorded, and the maximum value set at 110% of that recorded (Table III). This attempts to capture possible variation due to increases or decreases in costs associated with sampling.

C_e was determined based on likely yield loss given an outbreak. Here, data from CCI(3) were used to estimate minimum, maximum, and most likely CPB infestation levels once CPB is introduced. A yield loss equation(5) then determined average yield loss from a given infestation, and this loss was subsequently converted to a monetary value. The monetary value was estimated as the yield loss (%) multiplied by the average annual value of cocoa in ENBP. This information was then represented by a triangular distribution (Table III). It would be possible to model this using a uniform or PERT distribution but the former does not accurately represent the central tendency of our "most likely" estimate, and the latter may underestimate the tails.

The parameter q was determined using a theoretical model based on infestation level.(19) Current CCI sampling methods sample 200 pods from all farms within 200 m of CPB detection (Table I). Therefore,

Table III. Parameters Used in the Contingency Model (After Regan *et al.*)(11)

Parameter	Description	Distribution
C_s[a]	Annual cost of sampling	Triangular Min = K11,70,000 Most likely = K13,00,000 Max = K14,30,000
C_e[a]	Estimated annual cost of CPB outbreak	Triangular Min = K8,00,00,000 Most likely = K11,20,00,000 Max = K14,40,00,000
p[b,c]	Likelihood of CPB surviving one year	Uniform Min = 0.8 Max = 0.95
q[a,d,e]	Likelihood of detection given presence	$q = 1 - (1 - f)$^n – Uniform (0, 0.05) where f is the infestation level ($f = 0.01, 0.05, 0.1, 0.15$) and n is the number of samples taken in any given block ($n = 20, 200$).

[a] Parameter estimated from information in CCI.(3)
[b] Parameter estimated from information in Day.(1)
[c] Parameter estimated from information in Lim.(5)
[d] Parameter estimated from information in Burgman.(19)
[e] See Table I.

in subsequent years, CPB sampling is anchored to regions previously infested. Using this, we defined q as the probabilistic complement of the event of no detections in n trials ($n = 200$), but reduced this figure to account for the possibility that CPB had translocated into an unsampled region. In this case, CPB would not be detected, but would still be present. This reduction was accounted for by introducing an arbitrary value, modeled as a uniform distribution with a minimum of zero and a maximum of 0.05 (Table III). This event is unlikely, but given the small size of the area sampled, and the fact that subsequent sampling locations are anchored to the point of first discovery, it was considered important to include this event, with a low probability of occurrence. Setting such an arbitrary value can greatly impact model outcomes, and sensitivity analyses were used to gauge the relative importance this value had on model outputs. An estimate of undetectable CPB infestation levels was also required, and was inferred from experience in ENBP. CPB was not discovered in ENBP until infestation increased above 16% of blocks.(3) Note that this value was determined on a landscape scale, and local infestations may have been higher. For our model, any infestation levels between 1% and 16% were considered likely to escape detection; the model considered different scenarios of infestation level to interpret the effect this had on outputs ($f = 0.01, 0.05, 0.1, 0.15$).

All information regarding the parameter p was drawn from literature on CPB.(1,5) Here p applies not to individual survival, but to population survival. In the absence of complete life-table information, information on potential fecundity and life-stage survival rates was used to estimate a probability that a CPB population would survive one year.(5) This information suggested a relatively high probability of survival, which we represent as a continuous uniform distribution between 0.8 and 0.95 (Table III). Note that the maximum value of 0.95 is used because this rule of thumb is neither accurate nor informative when higher values are used.

2.3.2. Assumptions

The major assumption in using this rule of thumb is that the approximation to the exact SDP solution is accurate. This particular rule of thumb simplifies the SDP problem by ignoring the cost of further surveys if the species happens to reemerge before reaching the optimal number of surveys.(11) This simplification was shown to be accurate, except in the case when the probability of persistence is high ($p > 0.95$) and the probability of detection is low ($q < 0.05$).(11) All scenarios in our model meet this criteria. However, the more extreme scenarios ($f = 0.01$, $n = 20$) do approach this lower threshold, so it is worth noting that the model may underestimate the optimal result for these cases. Given the relative uncertainties in our data, using SDP to find an exact solution for these cases was not feasible. The rule of thumb was therefore considered acceptable for our purpose, which was to identify trends in the sampling regimes used to detect CPB, and to aid decisionmakers in the event of a CPB incursion and subsequent eradication program.

Another assumption important in this analysis is that of independence of parameters. However, there is no evidence to suggest any correlations between parameters. While probability of detection and cost of sampling may be negatively correlated, in this example we consider fixed sampling regimes, thus removing potential correlations. Sensitivity analyses were run to gauge the effect minor dependencies may have on model outputs.

Despite being applied to ENBP, this model was assumed to be equally applicable to Bougainville or New Ireland. This is because any scaling factor introduced to relate ENBP to Bougainville or New Ireland would apply to both C_e and C_s, yet not to p or q. Such a scaling factor would therefore cancel out in the calculation of n^* (see Equation (2)).

Some assumptions were made regarding sampling and CPB behavior. First, we assume the cost of sampling is constant across scenarios. Second, CPB is known to display an aggregated distribution within a given region.(5) This is not formally considered in our analysis; rather, we assume a random distribution of CPB in any given block. However, the determination of parameter q assumes random sampling within designated sampling zones, and it assumes that cocoa pods from all blocks in an infested area are sampled. A regionally aggregated CPB population is unlikely to display a random distribution on a local scale, but by randomly sampling all blocks in a region these assumptions should yield a valid approximation to the true CPB distribution.

Finally, pheromone traps are not explicitly included in the determination of the parameter q; further data will be required before this can be achieved. In its current form, the model will be slightly conservative due to this assumption.

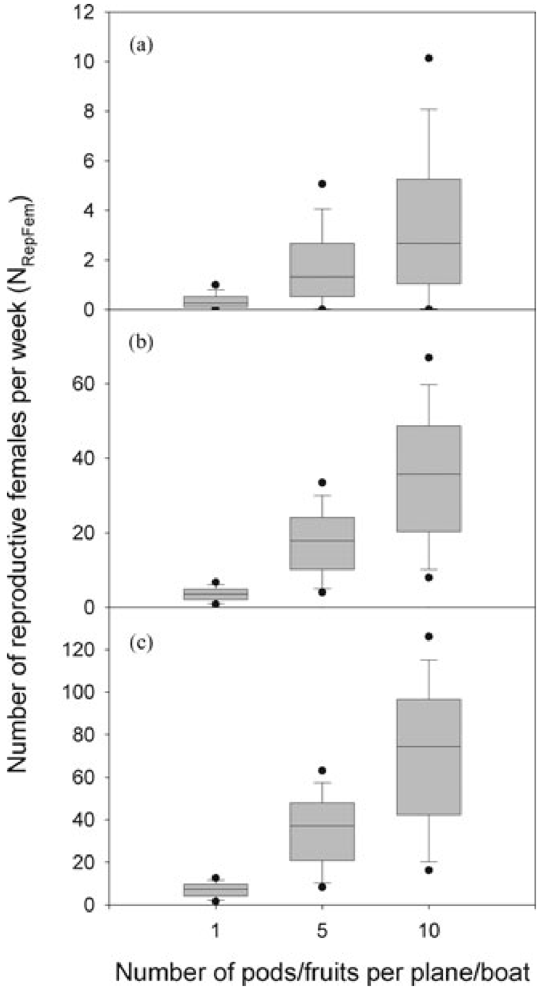

Fig. 3. Number of reproductively mature CPB reaching New Ireland per week. Panels represent different frequencies of cocoa transport from East New Britain Province: (a) one in every 100 boats and planes carrying infested cocoa and other hosts; (b) one in every 10 boats and planes carrying infested cocoa and other hosts; (c) one in every five boats and planes carrying infested cocoa and other hosts. Note the different scales on the y-axes. The box represents the interquartile range, with the median shown as a line within it; whiskers show the 25% and 75% quantiles, and dots mark the 5% and 95% quantiles.

3. RESULTS

3.1. Dispersal Model

3.1.1. Dispersal to New Ireland

The dispersal model suggested that the frequency of CPB dispersal to New Ireland was quite high in scenarios where large amounts of cocoa were transported. In these scenarios (five or more pods/seedlings/fruits transported), the median number of reproductively mature CPB females arriving on New Ireland ranged from 1 to 74 per week (Fig. 3). In contrast, for those scenarios with only one cocoa pod/seedling or other host fruit transported per boat or plane, the model yielded median values of 0–7 reproductively mature CPB arriving on New Ireland per week (Fig. 3). Holding cocoa transport to zero suggested that alternative hosts are of negligible concern in regard to transport of CPB (Fig. 4a). Scenarios restricted to one transport route (small boat, large boat, or plane) suggested that output distributions

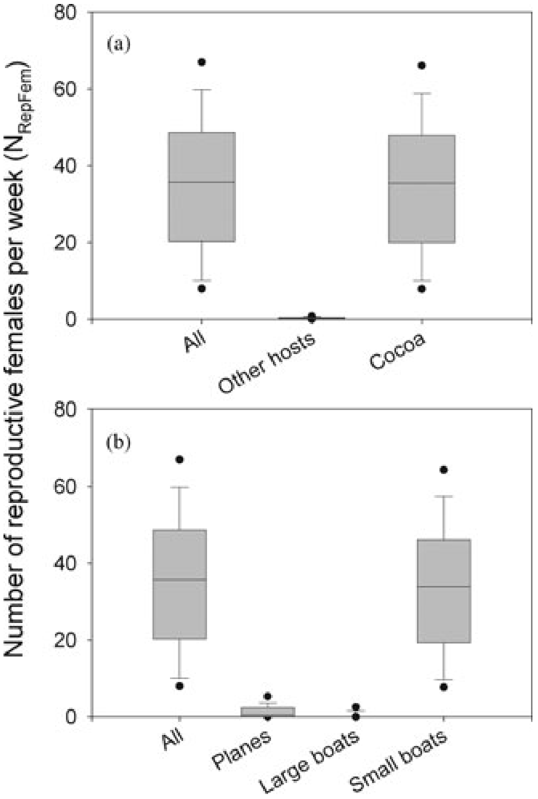

Fig. 4. Relative impacts of different hosts and different transport routes on the number of reproductively mature females reaching New Ireland per week. (a) Transport of all hosts compared with transport of only alternative hosts and only cocoa. (b) Transport of all hosts on all transport routes compared with transport restricted to planes, large boats, and small boats. Presentation as per Fig. 3.

are determined almost entirely by small boat transport of cocoa, with large boats and planes having little influence on the shape or location of output distributions (Fig. 4b). The extreme of 100 pods/fruits per plane/boat (not shown in Fig. 3 for ease of presentation), yielded a median of 27 (5% = 0, 95% = 101) reproductively mature female CPB per week. Similarly, increasing the frequency of cocoa transport to every second boat yielded a median of 19 (5% = 4, 95% = 30) reproductively mature female CPB per week.

Sensitivity analyses suggested that for scenarios with one in 100 boats or planes carrying cocoa, the number of small boats carrying cocoa [Binomial ($N_{\mathrm{SB-NI}}, P_{\mathrm{C-SB}}$)] was strongly correlated with output distributions ($r_s > 0.75$). For scenarios with 1 in every 2, 5, or 10 boats and planes carrying cocoa and other hosts, uncertainty in the number of larvae per plant (N_{LPP}) had the strongest relationship with uncertainty in output distributions ($r_s > 0.8$). Scenarios with the number of small boats traveling to New Ireland represented by a discrete uniform distribution and a point estimate did not create markedly different outputs from those scenarios presented above.

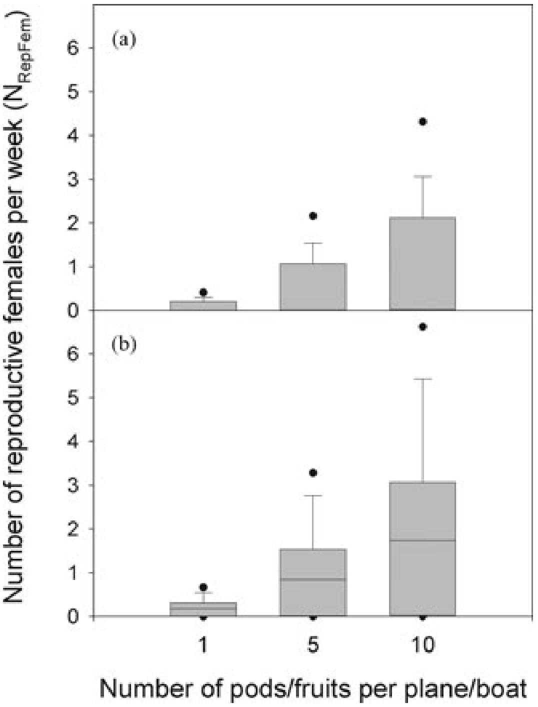

Fig. 5. Number of reproductively mature CPB reaching Bougainville per week. Panels represent different frequencies of cocoa transport from East New Britain Province. (a) One in every 10 boats and planes carrying infested cocoa and other hosts. (b) One in every five boats and planes carrying infested cocoa and other hosts. Presentation as per Fig. 3.

3.1.2. *Dispersal to Bougainville*

The dispersal model suggested that the frequency of CPB dispersal to Bougainville was low, with medians ranging from 0 to 2 reproductively mature female CPB per week (Fig. 5). Scenarios with more than one in every 10 boats or planes carrying 5 or more cocoa pods/seedlings or other host fruits transported median values of 0–2 reproductively mature CPB females (Fig. 5). These values are substantially lower than equivalent scenarios for New Ireland. For scenarios with one in 100 boats or planes carrying cocoa, even those with 100 pods or fruits carried per boat or plane did not transport CPB in large numbers, with a median of zero reproductively

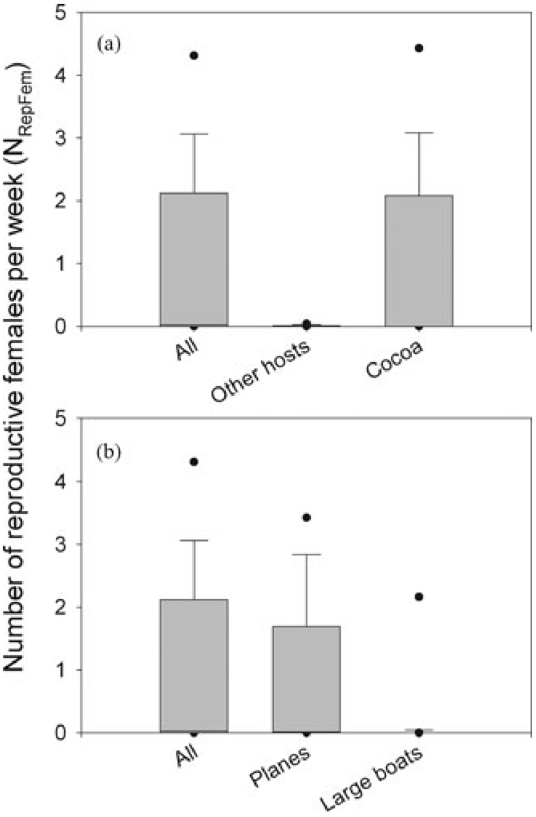

Fig. 6. Relative impacts of different hosts and different transport routes on the number of reproductively mature females reaching Bougainville per week. (a) Transport of all hosts compared with transport of only alternative hosts and only cocoa. (b) Transport of all hosts on both transport routes compared with transport restricted to planes and large boats. Presentation as per Fig. 3.

mature females arriving per week for all scenarios. Frequent transport (one in every two boats or planes) of only one pod per seedling or fruit also did not transport many CPB, with a median value of zero reproductively mature CPB transported per week. Setting cocoa transport to zero suggested that alternative host plants are of negligible concern for transport of CPB, transporting a median value of zero (95% = 0) reproductively mature CPB females per week in a scenario with one in 10 planes or boats carrying one host fruit (Fig. 6a). Restricting scenarios to either large boat or plane transport suggested that a majority of CPB are transported via plane, with large boats transporting a median value of zero (95% = 0) reproductively mature CPB females per week, in a scenario with one in 10 boats carrying one host (Fig. 6b).

Sensitivity analyses suggested that uncertainty in the number of larvae per plant (N_{LPP}) had the largest impact on output uncertainty, but this was only noticeable for scenarios with more than one in every five boats carrying cocoa. In these scenarios, Spearman rank correlation coefficients were greater than 0.3. For other scenarios, no Spearman rank correlation coefficient value was greater than 0.1.

3.2. Contingency Model

For all levels of CPB infestation, these results suggested relatively short sampling periods. For infestation levels of 1%, results suggested that sampling should continue for 2.4–2.8 years posteradication, with a mean of 2.6 years (Fig. 7). For 5%, 10%, and 15% infestation levels, 1.0–1.8 years of posteradication sampling are suggested, with a mean of 1.5 years (Fig. 7). Decreasing the sampling effort from 200 pods to 20 pods per block saw a four-fold increase in sampling period for an infestation level of 0.01, but only a 1.3-fold increase in sampling period for an infestation level of 0.15 (Fig. 7).

Sensitivity analyses suggested that in all scenarios the probability of detection (q) had the greatest impact on output uncertainty ($r_s > 0.75$), while all other parameters had little influence ($r_s < 0.2$).

4. DISCUSSION

The arrival of CPB in New Ireland or Bougainville could have significant effects on the economic and social well-being of these islands. In particular, Bougainville's heavy reliance on exported cocoa suggests that a loss in productivity could affect the majority of residents. There are therefore strong incentives to refine the parameters used in the models above. This is expected; the models above were intended to provide decision-making criteria for quarantine officials, but were also intended to expose those parameters that are particularly uncertain.

4.1. Dispersal Model

4.1.1. Dispersal to New Ireland

New Ireland has a substantially smaller cocoa industry than Bougainville. Less cocoa acreage means that in the event of CPB introduction, CPB's potential range is limited, and control measures may be more likely to succeed if restricted to those regions that are suitable for CPB establishment. This is because much of the cocoa that leaves ENBP will

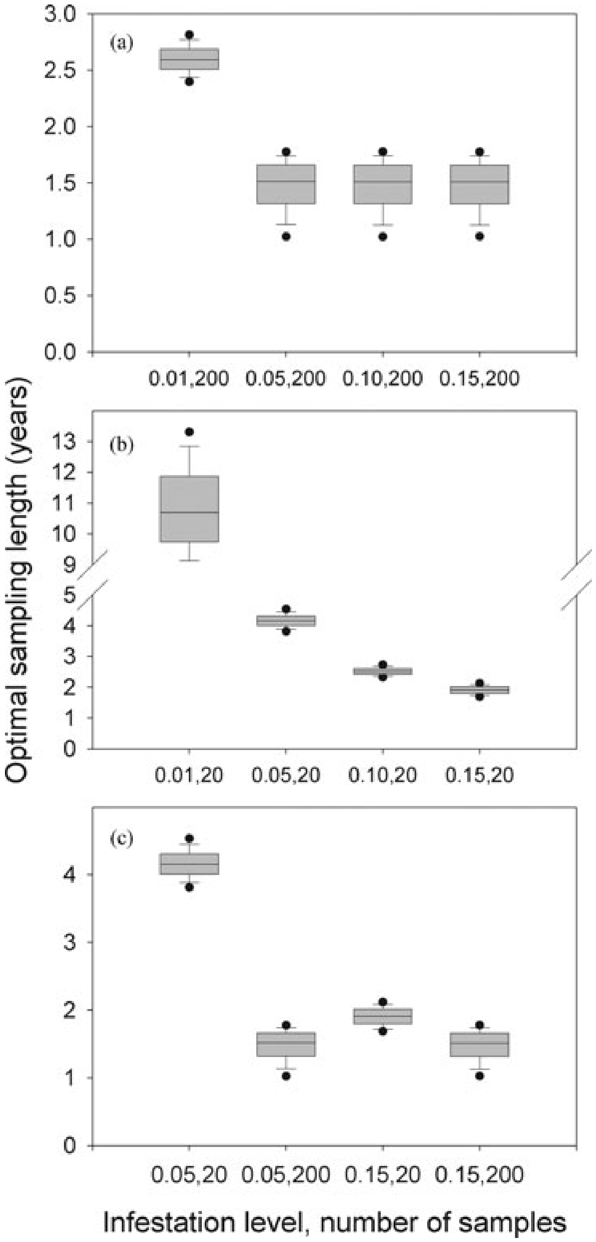

Fig. 7. Optimal sampling length following a CPB eradication program, based on a rule of thumb from Regan *et al.*[11] Optimal sampling length (years) is displayed for scenarios with: (a) 200 pods sampled per site and (b) 20 pods sampled per site. (c) Compares optimal sampling time for scenarios wherein 200 pods are sampled per site with scenarios wherein 20 pods are sampled per site, for infestation levels of 0.05 and 0.15. Presentation as per Fig. 3.

not reach an area suitable for CPB establishment, and, as such, it would be a waste of resources to monitor all boats and planes leaving ENBP. Little information was available regarding where cocoa is transported within New Ireland. As a result, proximity of cocoa crops to the regions where cocoa is taken is unknown. Our model is based on a worst-case scenario, wherein all infested cocoa is transported within range of a suitable CPB host plant. In reality, this situation is unlikely, as cocoa crops are mostly restricted to the southern end of New Ireland, and people are likely to transport cocoa to any number of places within New Ireland. Therefore, in our current scenarios, estimates of the number of CPB transported to New Ireland are likely to be higher than the true number, as they are subject to uncertainties beyond those included in the model.

The final output for the model was the number of reproductively mature female CPB reaching the island. It would be interesting to further reduce this set by including the probability of offspring survival, and subsequently the probability of population establishment. However, full life table information was not available for this study, and these events were therefore not included. Application of such information to this and other similar models would greatly improve the utility of results.

The model suggested that small boats are likely to transport significantly higher numbers of CPB than large passenger boats or planes. The sensitivity analyses also suggested that uncertainty in the number of small boats traveling to New Ireland greatly influenced output uncertainty. Therefore, a study of the number of small boats traveling to New Ireland and where they go would improve the accuracy of model outputs. These sensitivity analyses also suggested that uncertainty in the number of larvae per plant (N_{LPP}) had a large impact on output uncertainty. In this case, however, the uncertainty is considered to be natural variation, and does not warrant further study.

As well as highlighting the relative influence of small boats on the number of CPB introduced to New Ireland, the results also highlight the importance of cocoa relative to other hosts. Where only alternative hosts are considered, the number of CPB arriving on New Ireland is negligibly small.

The model suggested that increasing frequency of cocoa or other host transport was most likely to increase the risk of CPB introduction. For example, transporting 100 pods/seedlings/fruits on every 100th boat or plane did not introduce as many CPB as transporting five or 10 pods/seedlings/fruits per every five or 10 boats or planes. The former scenario here is representative of deliberate cocoa introduction; large amounts of cocoa are transported relatively infrequently. In contrast, the latter scenario represents cocoa transport for private use; relatively frequent transport of small amounts of cocoa. Considering this, the results suggest that relatively frequent transport of small amounts of cocoa may be as significant as, or more significant than, infrequent transport of large amounts of cocoa. Quarantine officials may improve their knowledge of this situation by surveying the amount and frequency of cocoa and other host plant transport. Once accurate values are known, either this model may be refined, or results from above may already be applicable. Relatively frequent transport of small amounts of cocoa may occur purely as a result of ignorance; if this is the case, education efforts may be effective in reducing the risk of CPB transport.

Three major conclusions can be drawn from this model. First, small boats are the most likely route of CPB transport to New Ireland. Second, alternative hosts are unlikely to transport CPB, as the infestation levels are extremely low relative to cocoa. Third, frequency of cocoa transport may be a more important determinant of CPB transport than the amount of cocoa transported. It is now important to study the number of small boats traveling from ENBP to New Ireland, and to gauge the relative amounts and frequency of cocoa transport. With better estimates of these parameters, the above model can be refined, or relevant results can be applied from those already presented.

4.1.2. Dispersal to Bougainville

Bougainville has a relatively large cocoa industry, and will be severely impacted if CPB becomes established. Experts in ENBP suggested large passenger boats and planes as potential CPB transport routes. Small boats were considered unlikely to travel to Bougainville, due to the large distances involved. Therefore, planes and large passenger boats are the most likely routes of CPB dispersal to Bougainville. The results suggested that much smaller numbers of CPB would reach Bougainville than New Ireland. While this may be correct, the larger cocoa industry in Bougainville means that cocoa is more widespread, and therefore CPB is more likely to reach an area suitable for establishment.

The model suggested that planes were more likely to transport CPB to Bougainville than passenger boats. The positive aspect of both planes and passenger boats is that they are much easier to monitor and control than small boats as quarantine can be localized to airports and areas where passenger boats dock. In addition, these vectors are amenable to being screened prior to leaving ENBP, further minimizing costs already reduced by localization of quarantine efforts.

While much lower numbers of CPB were transported in these scenarios than those for New Ireland, the general trends in the results are similar. In particular, the relative importance of cocoa as a host is highlighted, with alternative hosts transporting few (≈ 0) CPB to Bougainville. Also, increased frequency of cocoa transport was shown to be more significant than increased amounts of cocoa on each boat or plane. It was only in scenarios with more than one in 10 boats or planes carrying infested cocoa that CPB was transported at a noticeable level. In particular, almost no CPB were transported in the scenario with large amounts of cocoa (100 pods/seedlings) transported infrequently (one in 100 boats or planes). This mirrors the results for New Ireland.

Sensitivity analyses suggest that uncertainty in the number of larvae per plant (N_{LPP}) has the greatest impact on output uncertainty. Variation in this parameter is most likely natural variation, and is therefore unlikely to be further reduced. It will still be important for quarantine officials to determine the relative frequency and amounts of cocoa transported on large boats and planes. Until this is done, a large amount of incertitude remains regarding which of the above scenarios is most likely. With further information, this model can be improved, or the appropriate scenario can be identified from those presented here.

The general trends seen in the results for New Ireland are also apparent for Bougainville. However, given the lower numbers of CPB transported, there is greater potential to prevent CPB dispersal to Bougainville. Further study on the amount and frequency of cocoa transport is crucial if CPB introduction is to be prevented.

4.2. Contingency Model

4.2.1. Comparison of Scenarios

The contingency model was based on comparing different hypothetical scenarios; this was considered the best way to address a paucity of data. Scenarios comprised set CPB infestation levels and predetermined sampling regimes. It is important to note that due to limitations in the rule of thumb used to calculate optimal sampling times, the simulated values may underestimate the true optimal value.

While these scenarios may therefore not be representative, they are still comparable, and the trends identified are certainly relevant to sampling CPB posteradication.

When comparing scenarios, increasing the sampling effort decreased the optimal length of a sampling program. However, a 10-fold increase in sampling effort saw only a 1.3-fold to 4-fold decrease in sampling program length. This would suggest that a decreased sampling effort (20 pods) may be more efficient than an increased sampling effort (200 pods).

For scenarios wherein 200 pods were sampled at each site, further increases had very little effect on the output distribution for infestation levels > 0.05. This is due to the calculation of the parameter q. This calculation includes a correction factor [Uniform (0,0.05)], adjusting for the possibility that CPB populations have translocated beyond the region being sampled. Sampling in these scenarios was anchored to the region of initial CPB detection; if CPB were to translocate to a new area, they may still be present but go undetected. Once infestation levels reached 5% or greater, this correction factor became the dominant term in calculating q. As such, further changes in infestation level had negligible influence on the value of q. The underlying trend identified here is that at a certain point increased sampling does not increase the probability of finding CPB. Rather, determining the geographic extent of spread of a CPB population is more important than extensively surveying one particular region. Reduction in our correction factor can only be achieved by becoming more certain that CPB is not present beyond the range being sampled. Of course, a better understanding of CPB population dynamics would also be beneficial. With the advantage of hindsight, we can see that the intense sampling regime used in the attempted eradication program in ENBP was probably within too small a region to completely contain CPB. During this program, it may not have been practically feasible to survey a broader area, but this should certainly be considered in any future eradication programs.

One limitation of the scenarios presented here is that they assume static infestation levels. In reality, infestation levels are dynamic, and they fluctuate. To accurately model this situation, a dynamic model is required. Given the uncertainty in data, such a model was considered unfeasible. Also, if control measures such as rampassan (heavy pruning) and regular harvesting are implemented properly, then it is likely that infestation levels will remain low, possibly leading to extinction, even if an eradication program was not completely successful. In contrast, if control measures are relaxed, then CPB population growth will be rapid, and CPB will likely be detected. For these reasons, infestation levels were not considered in great detail, relying rather on scenarios to suggest patterns of sampling effort and infestation.

Sensitivity analyses highlighted uncertainty in the probability of detection (q) as the major driver of output uncertainty. As mentioned above, this uncertainty can only be reduced by more accurately determining the presence or absence of CPB. This is best achieved by sampling a large area, with a large number of sampling sites, and relatively low sampling effort within each site. Other parameters in these models did not have a large impact on output uncertainty, though they almost certainly had an impact on the location of output distributions. Considering this, it might be useful to improve estimates of other parameters, particularly C_e and C_s. But given the uncertainties introduced by using an approximate rule of thumb rather than an exact SDP model, efforts may be better rewarded if a more complex SDP (or similar) model is created. Regardless of which option is considered more appropriate, parameter estimates will be required to be refined before more representative results are determined.

4.3. Conclusions

Despite a paucity of data, the value in these particular models is the consideration of multiple scenarios; this provides comparisons between different management options, and can suggest parameters to further target, or parameters that are resilient to different management options. As such, even in a data-poor environment, management options can be contrasted, and likely outcomes can be modeled and considered. The models presented above are intended only to provide rough estimates of risk. More important, these models suggest areas that require further study, and optimal targets for controlling CPB spread.

The dispersal model highlights the likely routes of CPB dispersal. Small boats were considered a major risk for New Ireland, while planes were considered the predominant risk for Bougainville. In both cases, the major underlying factor was the frequency and amount of cocoa that actually gets transported. To determine this figure, further study will be required. In particular, estimates of the number of small boats traveling to New Ireland could be significantly improved, as could estimates of the amount and frequency of cocoa transport on small boats, large boats, and planes.

While implementation of our contingency model is dependent on an apparently successful eradication program providing low or null posteradication pest samples, we suggest this scenario is feasible, as indicated by initial experience in ENBP. This model is therefore a useful contribution to the future management of any future CPB outbreak in Papua New Guinea. The contingency model also highlighted parameters worthy of refinement, and suggested the incorporation of data gained from other sampling techniques to improve estimates of optimal sampling duration. In its current form, the model suggests that the optimal sampling time for a 1% infestation level is 2.5–2.7 years (90% CI) after claiming eradication, and this estimate changed little for higher infestation levels. While this result may underestimate the optimal value, other patterns to emerge from the model are: (1) a lower sampling effort may be more efficient than the current method of sampling 200 pods per site and (2) determining the full extent of geographic spread of the pest may be more important than extensively sampling one region. These results provide valuable insight, and their incorporation into the development of an eradication program may greatly improve the likelihood of success.

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