Using @RISK to Determine Potential Economic Losses to Jujube Production in China Resulting from Damage by *Carposina sasakii* (Lepidoptera: Carposinidae)[1]

Yawen Duan, Delin Kang, Zhihong Li, Minglu Yang[3], Yujia Qin, Haibing Xiao[3], and Lijun Liu[2]

China Agricultural University, Department of Plant Biosafety, Beijing, 100193, China

J. Entomol. Sci. 58(2): 201–214 (April 2023)
DOI: 10.18474/JES22-34

Abstract *Carposina sasakii* Matsumura (Lepidoptera: Carposinidae) is a serious fruit-boring pest in eastern Asia. In China, it is one of the most harmful and common pests in deciduous fruit trees, causing an annual loss of more than a billion yuan. However, economic losses to the jujube industry as a result of *C. sasakii* damage remain undefined. In this study, we collected related data on *C. sasakii*, the market price of jujube, and costs of its prevention and management. The potential economic losses of China's jujube industry caused by *C. sasakii* were predicted using @RISK (Palisade, Raleigh, NC) software and a stochastic simulation method, which is the universal model of potential economic loss assessment for economically important fruit flies. Our results showed that the total economic losses potentially caused by *C. sasakii* to China's jujube industry are approximately 8,643.41–350,524.15 million RMB (RMB is the legal tender in China; approximately 1,338.00–54,261.14 million USD) if the pest was not managed and approximately 2,487.15–123,242.12 million RMB (about 385.01–19, 077.88 million USD) when management was applied. Therefore, a loss of approximately 841.83–244,144.06 million RMB (approximately 130.32–37,793.50 million USD) can be logically retrieved after controlling this pest. As a result, we suggest that related organizations and pest management practitioners strengthen prevention and control measures of *C. sasakii* to reduce the risk of economic loss by decreasing the infestation level of *C. sasakii* in jujube production and, thus, economic losses after infestation.

Key Words @RISK, *Carposina sasakii*, jujube, potential economic loss, stochastic simulation method

Carposina sasakii Matsumura (Lepidoptera: Carposinidae) is one of the most destructive fruit-boring pests for Asian fruit trees (Cao et al. 2020, Gong 2012, Li et al. 2018). The European and Mediterranean Plant Protection (EPPO) Global Database (https://gd.eppo.int; last accessed 2018) and related reports show that this pest is widely distributed in China (Xue et al. 2010, https://gd.eppo.int/taxon/CARSSA/distribution), Japan (Ishiguri and Toyoshima 2006, https://gd.eppo.int/taxon/CARSSA/distribution), Korea (Han et al. 2000, https://gd.eppo.int/taxon/CARSSA/distribution), and Russia (Lei et al. 2012, https://gd.eppo.int/taxon/

[1]Received 14 August 2022; accepted for publication 25 October 2022.
[3]Tarim University, Department of Plant Science, Aral, 843300, China.
[2]Corresponding author (email: ljliu@cau.edu.cn).

CARSSA/distribution). In addition, the Global Biodiversity Information Facility (GBIF) website (https://www.gbif.org; last accessed 2020) reports that this pest has been found in North America, but it is not widely distributed (https://www.gbif.org/species/1735121). Moreover, *C. sasakii* is considered a quarantine pest in Europe (https://www.eppo.int/; last accessed 2003) and the United States (https://www.usda.gov/; last accessed 2011), and *C. sasakii* is on the list of pests regulated in Canada (https://www.agr.gc.ca/). Notably, *C. sasakii* is one of the main pests of jujube, *Ziziphus jujuba* Miller (Rosales: Rhamnaceae), commonly known as red date, Chinese date, or Chinese jujube. *Carposina sasakii* produces 1 to 3 generations a year in China (Liu 2020). The adult is usually nocturnal (Liu 2020), and the seasonal variations of the adult *C. sasakii* are complex. In addition, the larval survival rate of *C. sasakii* is different according to the fruit cultivar and season (Kim et al. 2000). Female *C. sasakii* lay eggs on the calyx end of the plant or the abaxial surface of a blade. The egg stage usually lasts approximately 1 week (Lin 2019). After hatching, the neonates then move into the fruit core to feed, resulting in the deformity of the fruit and the loss of edible value and marketability (Kim et al. 2000, Kim et al. 2001, Kim and Lee 2010). When the larvae mature, approximately 20 days later (Lin 2019), they leave the fruit and form pupal cocoons or larval cocoons in the shallow soil around the tree trunk for dormancy (Kim et al. 2000). Adults emerge from the pupae in approximately 10–15 days (Lin 2019). Therefore, we should combine tree control with ground control to control this pest. At present, although there is no effective control method, farmers mainly spray chemical pesticides for control, namely, diamide insecticides and pyrethroid insecticides (Qiu et al. 2009, Sun et al. 2018). In addition, they use fruit bagging and the application of attractants for control. Previous studies have shown that the main sex pheromones for *C. sasakii* are Z-7-eicosene-11-one and Z-7-nonadecene-11-one (Li et al. 2019). In addition, the prediction and risk assessment of the pest should be strengthened. However, little information related to the potential economic loss assessment of *C. sasakii* has yet to be found. It is important to define the potential economic losses caused by *C. sasakii* to jujube to assess the risks of this notorious pest and to develop management strategies for the pest.

@RISK (http://www.palisade.com/risk/; last accessed 2018) is a common software used for risk analysis. This software has applications in many fields. In 2000, Rüfenacht et al. (2001) used @RISK to conduct a Monte Carlo simulation to predict the effects of bovine viral diarrhea virus (BVDV) on fertility and gestation in dairy cattle. In recent years, there have been many reports regarding the potential economic losses caused by pests, which have been assessed using @RISK. In 2011, Cook et al. (2011) used @RISK to evaluate the economic loss caused by the bacterial disease fire blight to Australian imports of New Zealand apples. The results showed that the returns to Australian society from importing New Zealand apples were likely to be negative. Cook et al. (2012) also demonstrated a break-even-style benefit–cost analysis using the example of the banana bunchy top virus. They predicted that the disease would cause AUD 15.9–27.0 million in annual losses for the banana industry. The economic loss caused by grape downy mildew to the viticulture industry in Western Australia was assessed using @RISK, with the result indicating that the mean annual cost over 30 years of simulations after invasion of the disease was $7.3 million with a standard deviation of $2.6 million. Peak economic impact was found to occur approximately 20 years postincursion

(Taylor et al. 2018). In addition, @RISK could be used to assess the economic losses caused by pests, such as *Aedes albopictus* Skuse (Darbro et al. 2017), the invasive plant *Ageratina adenophora* Spreng (Fang et al. 2015), and plant pathogens such as the cottony leaf curl virus (Rao et al. 2011) and *Tilletia indica* Mitra (Wang et al. 2020), to related industries.

The assessment of potential economic losses can quantitatively analyze the impact of pests on crops. In addition, it can assist managers in developing prevention strategies to achieve improved management efficiency. At present, there are few reports on using @RISK to quantitatively evaluate the risk of pests in China. This quantitative assessment reported here was conducted to determine the potential economic losses of China's jujube industry caused by *C. sasakii*. Zeng (1994) defined that the economic losses caused by pests included direct quality losses, control costs, and indirect losses in environmental protection, trade, and processing. We, therefore, undertook this study to assess the potential direct economic loss of China's jujube industry caused by *C. sasakii*. The @RISK software and stochastic simulation method were used to make predictions. We also combined the relevant data on *C. sasakii*, the marker price of jujube, and *C. sasakii* cost prevention in our analyses. We designed the economic loss models in the no-control scenario and the control scenario. We compared them and obtained the economic loss that could be recovered after prevention. This study provides a scientific basis for developing prevention and management measures for *C. sasakii*.

Materials and Methods

Software and analysis method. @RISK is a software product that conducts Monte Carlo simulations in Excel as well as RISK analysis (http://www. palisade. com/risk/; last accessed 2018). Furthermore, it calculates the results of various possibilities and the probability of occurrence under any scenario, making quantitative predictions regarding the uncertainty of risk. In addition, @RISK has the capability of sensitivity analysis. With this feature, we can determine the input variables that have the greatest impact on the result. In this study, @RISK 7.5 was adopted, and the number of iterations was set to 100,000. The simulation number was 1.

Data resources. For this study, many kinds of data were used, including annual yield, planting area, infestation rate of jujube, loss rate of jujube after infestation, cost of prevention and control, and the market price of jujube. Most of these data were from the literature and government websites, including the Ministry of Agriculture and Rural Affairs of the People's Republic of China (MARA) and the National Agricultural Business Information Public Service Platform (NABIPSP). Among these data, the infestation rate for jujube, loss rate of jujube after infestation, the cost of prevention and control per unit area of jujube, and control efficiency and efficiency correction coefficient were obtained from the literature. The planting areas and annual yield of jujube in the suitable distribution area of *C. sasakii* came from the MARA of China. The data source for the market price of jujube was the NABIPSP. The data are listed in Table 1.

The analysis model for potential economic loss. In this experiment, the direct economic loss caused by *C. sasakii* to China's jujube industry was divided into the

Table 1. The potential economic loss assessment model of China's jujube industry caused by *Carposina sasakii* (6.5 RMB is approximately 1 USD).

Model[a]	The Input Variable[b]	Parameter	The Source of the Data
The no-control scenario			
F11	Q1	Pert (4,237.71, 4,640.31, 4,993.06) kiloton	MARA[c]
	I	Pert (39.84%, 60.63%, 78.29%)	Statistics and Investigation
	R	Pert (56.20%, 76.28%, 88.13%)	Statistics and Investigation
	Pc	Pert (1.26, 16.94, 40) RMB	NABIPSP[d]
	F11	$F11 = Q1 \times I \times R \times Pc/(1 - IR)$	—[e]
F12	Q2	$Q2 = Q1 \times I \times (1 - R)/(1 - IR)$	—
	P2	Pert (1.26, 7.26, 14) RMB	Half of the Pc
	F12	$F12 = Q1 \times I \times (1 - R)(Pc - P2)/(1 - IR)$	—
	F1	$F1 = F11 + F12$	—
The control scenario			
F21	S	Pert (921.60, 1,020.96, 1,116.00) thousands of hectares	MARA
	C	Pert (62.5, 109.375, 156.25)	Zhang et al. (2018)
	F21	$F21 = S \times I \times C$	—
F22	A	$A = Q1/S$	—
	M	Pert (28%, 49%, 84%)	Li (2002)
	D	2.00	Pan et al. (2014)
	E	$E = C/(A \times Pc \times M) \times D \times 100\%$	—
	F22	$F22 = Q1 \times I \times E \times Pc/(1 - IE) + Q1 \times I \times (1 - E)(Pc - P2)/(1 - IE)$	—
	F2	$F2 = F21 + F22$	—

Table 1. Continued.

Model[a]	The Input Variable[b]	Parameter	The Source of the Data
The recoverable potential economic loss	F3	F3 = F1 – F2	—

[a] F11, Economic loss caused by field decline; F12, economic loss caused by quality decline; F21, expenditures for controlling; F22, economic loss after controlling.
[b] Q1, The annual yield of jujube in the suitable distribution area of *C. sasakii*; I, infestation rate for jujube; R, loss rate of jujube after infestation; Pc, market price of jujube; F11, economic loss caused by field decline; Q2, production of infested jujube per unit area in the epidemic area; P2, market price level of infested jujube; F12, economic loss caused by quality decline; F1, potential economic loss under no control; S, planting areas of jujube in the suitable distribution area of *C. sasakii*; C, the cost for prevention and control per unit area of jujube; F21, expenditures for controlling; A, the yield per unit area of jujube; M, control efficiency; D, efficiency correction coefficient; E, the economic injury level; F22, economic loss after control; F2, potential economic loss under control; F3, potential economic loss that can be recovered after the control.
[c] MARA, The Ministry of Agriculture and Rural Affairs of the People's Republic of China.
[d] NABIPSP, The National Agricultural Business Information Public Service Platform (a total of 1,319 price data).
[e] Data that can be obtained by calculating formulas based on existing data.

following two situations: potential economic losses with and without control. The potential economic losses under the no-control condition specifically refer to the economic loss to the jujube industry caused by *C. sasakii* without manual intervention. The potential economic losses under the control condition refer to the economic loss to the jujube industry caused by *C. sasakii* after production losses reach the economic injury level (EIL) after prevention and control.

The potential economic losses under the no-control condition included the economic loss caused by the decline of jujube yield and quality. This applied model was calculated as

$$\mathrm{F1} = \mathrm{F11} + \mathrm{F12} \tag{1}$$

where F1 is the total potential economic losses under the no-control condition, F11 is the potential economic losses caused by field decline, and F12 is the potential economic losses caused by quality decline.

The analysis model for the economic loss caused by field decline was

$$\mathrm{F11} = \mathrm{Q1} \times \mathrm{I} \times \mathrm{R} \times \mathrm{Pc}/(1 - \mathrm{IR}) \tag{2}$$

and the model for economic loss caused by quality decline was

$$\mathrm{F12} = \mathrm{Q1} \times \mathrm{I} \times (1 - \mathrm{R})(\mathrm{Pc} - \mathrm{P2})/(1 - \mathrm{IR}) \tag{3}$$

where Q1 is the annual yield of jujube in the suitable distribution area of *C. sasakii*, I represents the infestation rate of *C. sasakii* to jujube, R is the loss rate of jujube caused by *C. sasakii*, Pc is the market price level of jujube, and Q1 refers to the annual yield of jujube in the jujube planting area suitable for the distribution of *C. sasakii* in China. We defined I as the probability that a single jujube can be infested by *C. sasakii*. R refers to the probability that a single jujube lost its economic value after being damaged by *C. sasakii*. The market price level of jujube was the market price of jujube not harmed by *C. sasakii*. P2 was the market price level of infested jujube.

The model of potential economic losses under control conditions included the expenditures for controlling the economic loss after prevention and control. This applied model was calculated as

$$F2 = F21 + F22 \tag{4}$$

where F2 is the total potential economic losses under control, F21 is the expenditures for control, and F22 is the potential economic losses after control.

The model for calculating the cost of controlling *C. sasakii* was

$$F21 = S \times I \times C \tag{5}$$

and the model of potential economic losses after prevention and control was

$$F22 = Q1 \times I \times E \times Pc/(1 - IE) + Q1 \times I \times (1 - E)(Pc - P2)/(1 - IE) \tag{6}$$

where S is the planting area of jujube in the suitable distribution area of *C. sasakii*, C is the cost for prevention and control per unit planting area of jujube, and E is the EIL of *C. sasakii*. We found the critical degree of the damage after the jujube was damaged by *C. sasakii*. The manual control was meaningful under this condition.

The potential economic loss that could be recovered after control was determined with the model we used to determine the potential economic losses that could be recovered after the control, namely,

$$F3 = F1 - F2 \tag{7}$$

where F3 is the potential economic losses that be recovered after the control.

The annual yield of jujube in the suitable distribution area of *C. sasakii* (Q1) was determined according to the statistical review of the industrial scale and growth of jujube from 2017 to 2018 in China, as well as according to data from the Ministry of Agriculture and Rural Affairs of the People's Republic of China. We also used MaxEnt software to predict the suitable distribution area of *C. sasakii* in China (Fig. 1). In 2012–2016, the minimum yield of jujube in the suitable distribution area of *C. sasakii* was concluded to be 4,237.71 kilotons. The maximum possible value was 4,640.31 kilotons. The maximum value was 4,993.06 kilotons.

The infestation rate for jujube (I) and the loss rate of jujube after infestation (R) defined the infestation rate of *C. sasakii* on jujube as the probability of a single fruit being infested by larvae of *C. sasakii*. According to the statistics and investigation, the infestation rate for jujube by *C. sasakii* was approximately 39.84–78.29%. Once neonate larvae move into the fruit, the jujube fruit loses all of its economic value and is no longer edible. Therefore, the hatching rate of the eggs can be used to represent the loss rate of jujube. The loss rate was approximately 56.20–88.13%.

The market price level of jujube (Pc) in 2019–2020 was obtained from the National Agricultural Business Information Public Service Platform (a total of 1,319 price data). The minimum value was 1.26 yuan (approximately $0.19) per kg. The average value was 16.94 yuan (approximately $2.61) per kg. The maximum value was 40.00 yuan (approximately $6.17) per kg.

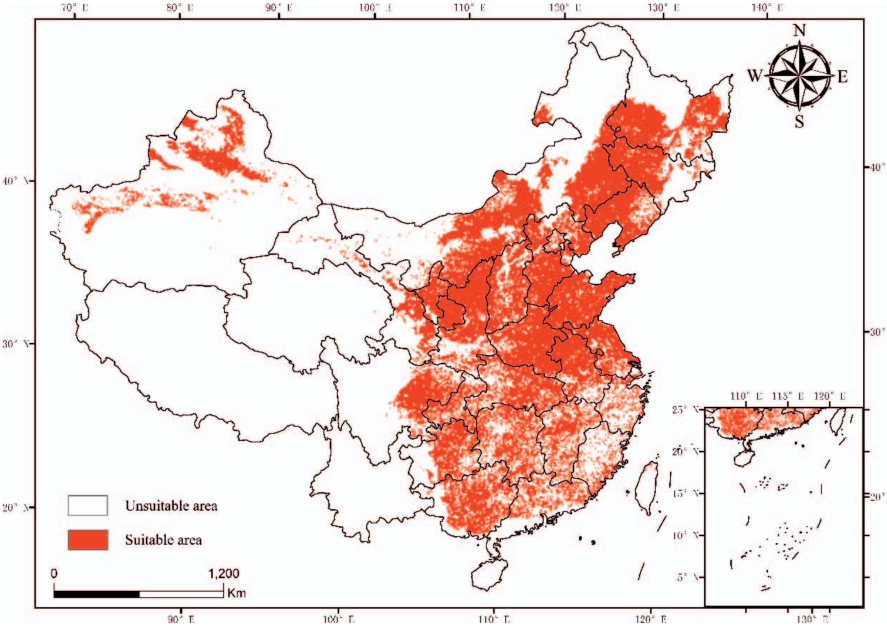

Fig 1. The potential geographical distribution of the *Carposina sasakii* in China. White represents the unsuitable area, and red represents the suitable area on the map.

Half of the market price of jujube was set as the market price level of infested jujube. It was concluded that the minimum market price of jujube with reduced quality was 1.26 yuan (approximately \$0.19) per kg. The average value was 7.26 yuan (approximately \$1.12) per kg. The maximum value was 14 yuan (approximately \$2.16) per kg.

The parameters in the model for potential economic losses under control. The planting area of jujube in the suitable distribution area of *C. sasakii* (S) was used in the model for potential economic losses under control. Similar to the jujube yield in the suitable distribution area of *C. sasakii*, the planting area was obtained from the Ministry of Agriculture and Rural Affairs of the People's Republic of China and by statistically reviewing the industrial scale and growth of jujube from 2012 to 2016 in China, combined with the suitable distribution area of *C. sasakii*. In 2012–2016, the minimum planting area of jujube in the suitable distribution area of *C. sasakii* was 921,600 ha. The average planting area was 1,020,960 ha, and the maximum area was 1,116.000 ha.

The cost for prevention and control in the per unit area of jujube (C) also was used in estimating potential economic losses under control. According to the literature and the market price of pesticides, the minimum cost of the unit area for the prevention and control of *C. sasakii* was 62.5 yuan per mu (mu is a unit of the Chinese measures of land, where 14 mu = 10,000 m^2). The average was 109.375 yuan per mu with a maximum of 156.25 yuan per mu (Zhang and Liu 2018).

Table 2. The potential economic losses of China's jujube industry caused by *Carposina sasakii* under a no-control scenario (unit: 10,000 yuan. 6.5 yuan is approximately 1 dollar).

Sign[a]	Formula	Minimum Value	Average Value	Maximum Value
F11	F11 = Q1 × I × R × Pc/(1 − IR)	438,701.33	7,116,249.83	30,585,458.95
F12	F12 = Q1 × I × (1 − R)(Pc-P2)/(1 − IR)	40.20	1,528,021.40	7,908,993.68
F1	F1 = F11 + F12	864,340.84	9,021,482.35	35,052,415.23

[a] F11, economic loss caused by field decline; F12, economic loss caused by quality decline; F1, potential economic loss under the no-control condition.

The EIL usually refers to the minimum pest population density that causes economic damage. The critical population density was first proposed by Bosch and Stern (1962). They indicated that the cost of control in such a density was comparable to recovering economic losses after using control (Bosch and Stern 1962).

The model used to calculate EIL was

$$\mathrm{EIL} = \mathrm{C}/(\mathrm{A} \times \mathrm{Pc} \times \mathrm{M}) \times \mathrm{D} \times 100\% \tag{8}$$

where C is the cost of pesticides used in prevention and control, A is the yield per unit area of jujube, Pc is the market price of jujube, M is the control efficiency, and D is the efficiency correction coefficient. It is generally concluded that profits should be twice as much as the cost (Pan et al. 2014). The efficiency correction coefficient was 2. According to the relevant literature, the control efficiency was between 28% and 84% when different pesticides were used (Li 2002). C, D, and M all were fitted to uniform distributions.

Results

The potential economic loss assessment model of China's jujube industry caused by *C. sasakii* and the data source are shown in Table 1.

Assessment and sensitivity analysis of potential economic losses for China's jujube industry caused by C. sasakii under the condition without control. The economic loss caused by the field decline was approximately 4,387.01–305,854.59 million RMB (about 679.11–47,346.29 million USD), and the average value was 71,162.50 million RMB (approximately 11,015.96 million USD) (Table 2). The economic loss caused by the quality decline was approximately 0.40–79,089.94 million RMB (approximately 0.06–12,243.12 million USD), with an average value of 15,280.21 million RMB (approximately 2,365.38 million USD). The potential economic losses under the condition without control were approximately 8,643.41–350,524.15 million RMB (approximately 1,338.00–54, 261.14 million

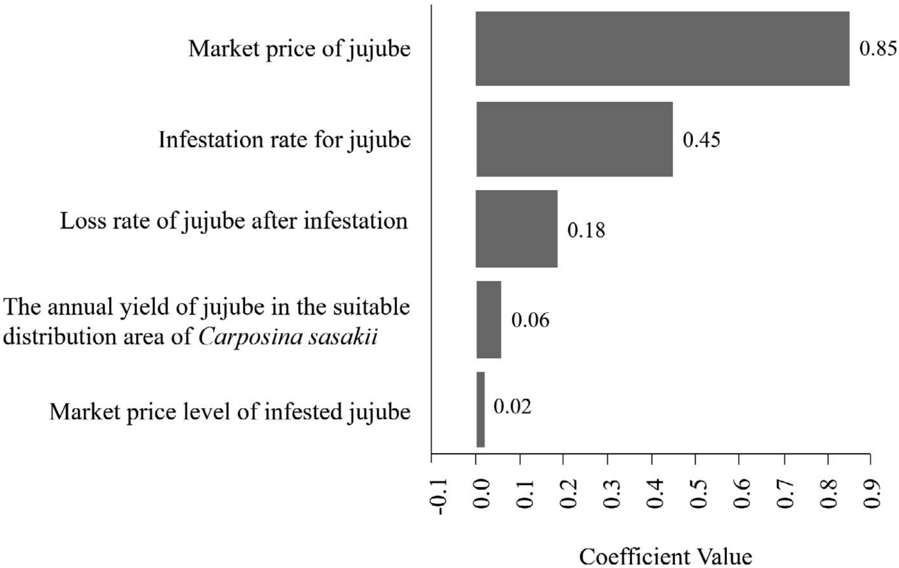

Fig 2. The variable sensitivity of the potential economic losses for China's jujube industry caused by *Carposina sasakii* with no control.

USD), with an average value of 90,214.82 million RMB (approximately 13,965.25 million USD).

The results of the sensitivity analysis are shown in Fig. 2. Under the condition without control, the market price level of jujube was the largest variable that affected the potential economic losses of China's jujube industry caused by *C. sasakii*. The second variable was the infestation rate of jujube and the loss rate of jujube being infested. The effect of market price level of infested jujube was negligible.

Table 3. The potential economic losses of China's jujube industry caused by *Carposina sasakii* under a control scenario (unit: 10,000 yuan. 6.5 yuan is approximately 1 dollar).

Sign[a]	Formula	Minimum Value	Average Value	Maximum Value
F21	F21 = S × I × C	42,849.92	100,605.76	187,182.76
F22	F22 = Q1 × I × E × Pc/(1 − IE) + Q1 × I × (1 − E)(Pc − P2)/(1 − IE)	184,758.95	3,652,938.83	12,216,044.27
F2	F2 = F21 + F22	248,714.86	3,753,569.25	12,324,211.63

[a] F21, expenditures of control expenses; F22, economic loss after controlling; F2, potential economic loss under the control condition.

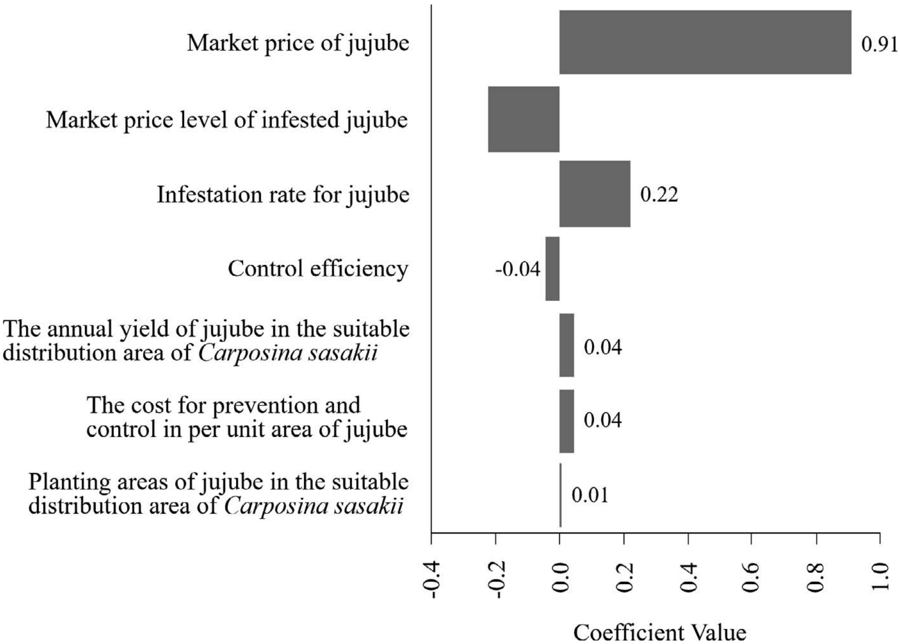

Fig 3. The variable sensitivity of the potential economic losses for China's jujube industry caused by *Carposina sasakii* with a control.

Assessment and sensitivity analysis of potential economic losses for China's jujube industry caused by C. sasakii under the control condition. The cost of controlling *C. sasakii* was approximately 428.50–1,871.83 million RMB (about 66.33–289.76 million USD), with an average value of 1,006.06 million RMB (about 155.74 million USD) (Table 3). The economic loss after using the control was approximately 1,847.59–122,160.44 million RMB (approximately 286.01–18,910.44 million USD), whereas the average value was 36,529.39 million RMB (approximately 5,654.75 million USD). The potential economic losses under the control condition were approximately 2,487.15–123,242.12 million RMB (approximately 385.01–19,077.88 million USD), and the average value was 37,535.69 million RMB (approximately 5,810.52 million USD).

The market price level of jujube was the most important variable impacting the potential economic losses of China's jujube industry caused by *C. sasakii* under the control condition (Fig. 3). The second variable was the market price level of jujube being damaged by *C. sasakii* and the jujube infestation rate of jujube. Other variables were negligible.

Assessment and sensitivity analysis of recoverable potential economic losses of China's jujube industry caused by C. sasakii after using the control. The analysis shows the recoverable potential economic losses of the jujube industry after *C. sasakii* infestation when a control was used. Recoverable potential economic losses with the control were approximately 841.83–244,144.06 million RMB (approximately 130.32–37,793.50 million), with the average value being

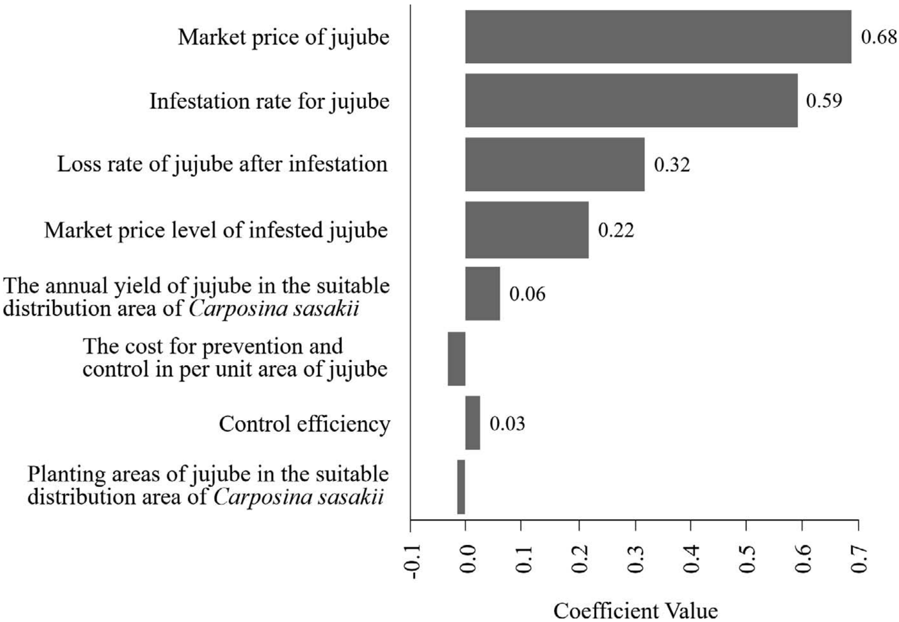

Fig 4. The variable sensitivity of reversible economic losses for China's jujube industry caused by *Carposina sasakii* after taking prevention and control measures.

52,679.13 million RMB (approximately 8,154.73 million USD). The most important variable affecting the recoverable potential economic losses was the market price of jujube, followed by the jujube infestation rate and the loss rate after being infested (Fig. 4).

Discussion

The @RISK software effectively estimated potential economic losses incurred in China's jujube industry attributed to *C. sasakii*. Without the control of the pest, the contribution to economic losses caused by field decline was 78.88% and quality decline was 16.94%. Therefore, the economic losses caused by yield change were the main source of economic losses without control. When the pest was managed, the contribution of the expenses was approximately 2.68%. When the control cost was 1,006.06 million RMB (approximately 155.74 million USD), the recoverable economic losses were 52,679.13 million RMB (approximately 8,154.73 million USD). The recoverable economic losses were 52.36 times as much as the input cost. Therefore, the benefits were much higher than the input costs. Field control has great significance for recovering economic losses.

The sensitivity analysis showed that the market price level of jujube had the most important influence on potential economic losses. However, it was difficult to control the jujube market price level. The controllable node was the jujube infestation rate and the loss rate after infestation. Therefore, we can reduce the jujube infestation rate and loss rate after infestation by artificial control to reduce the potential economic losses.

In summary, this research inherited the previous research methods, adjusted some content according to the existing data, and predicted the potential economic losses of China's jujube industry caused by *C. sasakii*. It also provided a scientific basis for prevention and control measures for related organizations. However, there also were some limitations in the study. First, there were some limitations in the underlying data. Due to the lack of specific planting area and yield data for each region, we made a general judgment based on the distribution of jujube planting areas in the relevant literature. It was inevitable that there would be some errors compared with the actual situation. When the EIL and control cost were calculated, only the pesticide cost was considered, whereas, for example, the manual cost and mechanical depreciation cost were lost. Second, in this study, because the main control method for this pest is chemical control at present, we considered only the influence of chemical control as the part of the control effect. In later studies, we can assess the differences in potential economic losses under different prevention methods. In addition, we counted only a range of infestation rates in this study, without considering the influence of temperature and other factors on this value. Third, the predicted results needed to be further verified. In general, during model running, some data should be used to verify the model's results. The Latin hypercube method was adopted in this study without the process of model verification. In the future, researchers should verify the prediction data of the model via field investigation or a field experiment.

This work is the first attempt to use @RISK to quantify the potential economic losses caused by *C. sasakii* to China's jujube industry and to carry out a relevant sensitivity analysis. Our modeling framework provides clear guidance for the management of *C. sasakii*. At the same time, it also provides valuable information for the management of relevant departments. In addition, it provides a method to analyze the potential economic losses of other pests.

In conclusion, this study used @RISK software to assess the potential economic losses of *C. sasakii* to China's jujube industry. It provides a research basis for further research on risk assessment. In addition, the results of the study can provide some theoretical reference for the precise prevention and control of this insect in future related studies and can be considered for the wide application of @RISK in the potential economic losses of other pests.

Acknowledgments

We thank all of the members of the Plant Quarantine Laboratory of the China Agricultural University (CAUPQL). Many thanks for all of the reviewer comments on this manuscript.

References Cited

Agriculture and Agri-Food Canada. 2014. The List of Pests Regulated in Canada. 4 April 2021. (https://www.agr.gc.ca/).

Bosch, R.V.D. and V.M. Stern. 1962. The integration of chemical and biological control of arthropod pests. Annu. Rev. Entomol. 7: 367–386.

Cao, L., W. Song, L. Yue, S. Guo, J. Chen, Y. Gong, A.A. Hoffmann and S. Wei. 2020. Chromosome-level genome of the peach fruit moth *Carposina sasakii* (Lepidoptera: Carposinidae) provides a resource for evolutionary studies on moths. Mol. Ecol. Resour. 21: 834–848.

Cook, D.C., L.R. Carrasco, D.R. Paini and R.B. Fraser. 2011. Estimating the social welfare effects of New Zealand apple imports. Aust. J. Agric. Resour. Ec. 55: 599–620.

Cook, D.C., S. Liu, J. Edwards, O.N. Villalta, J. Aurambout, D.J. Kriticos, A. Drenth and P.J.D. Barro. 2012. Predicting the benefits of banana bunchy top virus exclusion from commercial plantations in Australia. Plos One 7(8): e42391.

Darbro, J., Y. Halasa, B. Montgomery, M. Muller, D. Shepard, G. Devine and P. Mwebaze. 2017. An economic analysis of the threats posed by the establishment of *Aedes albopictus*, in Brisbane, Queensland. Ecol. Econ. 142: 203–213.

EPPO Global Database. 2018. *Carposina sasakii* (CARSSA). 21 April 2021. (https://gd.eppo.int/taxon/CARSSA/distribution).

European and Mediterranean Plant Protection Organization. **2003.** *Carposina sasakii*. 4 April 2021. (https://www.eppo.int/).

Fang, Y., M. Qin, Z. Li, C. Wang, T. Zhao and Z. Wu. 2015. Potential economic impact of *Ageratina adenophora* (Spreng) on peanut industry in China. J. China Agric. Univ. 20: 146–151.

GBIF. 2021. *Carposina sasakii*. 21 April 2021. (https://www.gbif.org/species/173512121).

Gong, T. 2012. Research of host selection of *Carposina sasakii* Matsumura. MS Thesis. Northwest A & F University, Xi'an.

Han, K., K. Jung, H. Choi, S, Lee and K. Boo. 2000. Sex pheromone composition and male trapping of the peach fruit moth, *Carposina sasakii* (Matsumura) (Lepidoptera: Carposinidae) in Korea. J. Asia-Pac. Entomol. 3: 83–88.

Ishiguri, Y. and S. Toyoshima. 2006. Larval survival and development of the peach fruit moth, *Carposina sasakii* (Lepidoptera: Carposinidae), in picked and unpicked apple fruits. Appl. Entomol. Zool. 41: 685–690.

Kim, D. and J. Lee. 2010. A population model for the peach fruit moth, *Carposina sasakii* Matsumura (Lepidoptera: Carposinidae), in a Korean orchard system. Ecol. Model. 221: 268–280.

Kim, D., J. Lee and M. Yiem. 2000. Spring emergence pattern of *Carposina sasakii* (Lepidoptera: Carposinidae) in apple orchards in Korea and its forecasting models based on degree-days. Environ. Entomol. 29: 1188–1198.

Kim, D., J. Lee and M. Yiem. 2001. Temperature-dependent development of *Carposina sasakii* (Lepidoptera: Carposinidae) and its stage emergence models. Environ. Entomol. 30: 298–305.

Lei, X., D. Li, Z. Li., G. Frank, L. Gao and Z. Shen. 2012. Effect of host plants on developmental time and life table parameters of *Carposina sasakii* (Lepidoptera: Carposinidae) under laboratory conditions. Environ. Entomol. 41: 349–354.

Li, D. 2002. Studies on chemical control techniques of *Carposina sasakii* Matsumura on the soil under the trees. Plant Prot. 28: 18–20.

Li J., X. Wang and L. Zhang. 2019. Identification of putative odorant binding proteins in the peach fruit borer *Carposina sasakii* Matsumura (Lepidoptera: Carposinidae) by transcriptome analysis and their expression profile. Biochem. Biophys. Res. Commun. 508: 1024–1030.

Li, X., D. Feng, Q. Xue and T. Meng. 2018. Density-dependent demography and mass-rearing of *Carposina sasakii* (Lepidoptera: Carposinidae) incorporating life table variability. J. Econ. Entomol. 112: 255–265.

Lin, Q., 2019. Optimization of artificial rearing methods for *Carposina sasakii* and expression pattern analyses of diapause hormone gene. MS Thesis. Henan Univ. of Science and Technology, Luoyang.

Liu, X. 2020. Molecular cloning and functional analysis of chemosensory protein genes in *Carposina sasakii*. MS Thesis. Chinese Academy of Agricultural Sciences, Beijing.

National Agricultural Business Information Public Service Platform Agricultural product price analysis system. 2020. TITLE. (http://nc.mofcom.gov.cn/).

Palisade Corporation. **2018.** Guide to using @RISK. (http://www.palisade.com/risk/).

Pan, F., T. Xiao, S. Qin, H. Chen, Z. Lin and S. Xie. 2014. Study on yield of bitter gourd damaged by *Bactrocera cucurbitae* and its economic thresholds. China Plant Prot. 34: 12–15.

Qiu, G., H. Zhang, W. Yan, P. Zhang, C. Liu and Y. Zheng. 2009. Comparison among different forms of lambda-cyhalothrin on controlling *Carposina sasakii*. Agrochem. 48: 62–64.

Rao, Y., L. Shen, S. Zhu, J. Yan and G. Huang. 2011. The economic losses of Cottone leaf curl virus invading China on cotton. Plant Quar. 25: 12–16.

Rüfenacht, J., P. Schaller, L. Audigé, B. Knutti, U. Küpferd, E. Peterhansa. 2001. The effect of infection with bovine viral diarrhea virus on the fertility of Swiss dairy cattle. Theriogenology 56: 199–210.

Sun, L., H. Zhang, W. Yan, Q. Yue, Y. Li and G. Qiu. 2018. Research progress of the *Carposina sasakii*. China Fruits 60: 76–81.

Taylor, A.S. and D. C. Cook. 2018. An economic assessment of the impact on the Western Australian viticulture industry from the incursion of grapevine downy mildew. J. Plant Dis Protect. 125: 397–403.

U.S. Department of Agriculture. 2011. TITLE. 4 April 2021. (https://www.usda.gov/).

Wang, Y., X. Lu, Y. Wang, R. Gao, C. Xiang, L. Xu, G. Zhang and H. Qing. 2020. Assessment of potential economic loss of China wheat industry caused by *Tilletia indica* Mitra. Plant Quar. 34: 45–49.

Xue Y., R. Ma, X. Li, L. Li and J. Li. 2010. Research and application on the sex pheromone of *Carposina sasakii* Matsumura (Lepidoptera: Carposinidae). Chin. J. Biol. Control 26:211–216.

Zeng, S. 1994. Introduction of Plant Protection System Engineering. Beijing Agric. Univ. Publishing House Press. Beijing, China.

Zhang, Y. and Z. Liu. 2018. Occurrence regularity and prevention and control measures of *Carposina sasakii* Matsumura in jujube orchard in aksu area. Rural Sci. Technol. 394: 40–41.