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Research Article/Araştırma Makalesi

The Impact and Control of Brown Marmorated Stink Bugs on Turkish Hazelnut Production

Kahverengi Kokarca Böceklerinin Türk Fındık Üretimine Etkisi ve Kontrolü

Mahir DEMİR[*1]

[1]Department of Mathematics, Giresun University, Giresun, Turkey 28200

[1]https://orcid.org/0000-0002-9670-5210

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***Address for Correspondence:**
Mahir DEMİR
e-mail:
mahir.demir@giresun.edu.tr

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ABSTRACT

The Turkish hazelnut is a crucial commodity both in Turkey and globally, with Turkey accounting for approximately 70% of the world's hazelnut production. However, hazelnut harvesting faces significant challenges, one of which is the presence of stink bug pests such as the brown marmorated stink bug (BMSB). This study utilized a mathematical model to examine the adverse impact of pests such as the brown marmorated stink bug [Halyomorpha halys (Stål, 1855) (Hemiptera: Pentatomidae)] and similar stink bug pests on hazelnut production. The findings revealed that between 2017 and 2022, hazelnut yields in Turkey suffered damage from stink bug pests like the brown marmorated stink bug, amounting to 106,820 tonnes annually and 640,920 tonnes cumulatively. Furthermore, this study demonstrated that the application of control measures, whether through biocontrols, traps, or chemicals, to increase the death rate of BMSB-type pests by 25% or 50%, or to decrease the egg ratio by 25% or 50%, has the potential to save up to 82,506 tonnes of hazelnut production from these pests annually. Overall, this study highlights the importance of managing pest infestations in agricultural production and the potential benefits of using control methods to mitigate their impact.

Key Words: Turkish hazelnut, harvesting, brown marmorated stink bug-type pests, mathematical modeling

ÖZ

Türk fındığı hem Türkiye'de hem de küresel olarak önemli bir tarım ürünü olup, dünya fındık üretiminin yaklaşık %70'ini Türkiye sağlamaktadır. Ancak, fındık hasadı önemli zorluklarla karşı karşıyadır, bunlardan biri de brown marmorated stink bug ve benzeri zararlılarının varlığıdır. Bu çalışma, matematiksel bir model kullanarak brown marmorated stink bug (*Halyomorpha halys*) ve benzeri zararlılarının fındık üretimi üzerindeki olumsuz etkisini incelemektedir. Bulgular, 2017 ile 2022 yılları arasında Türkiye'deki fındık veriminin brown marmorated stink bug türü zararlılarından kaynaklanan zararı yıllık olarak 106.820 ton ve kümülatif olarak 640.920 ton olduğunu ortaya koymuştur. Ayrıca, bu çalışma, brown marmorated stink bug türü zararlıların popülasyonlarındaki ölüm oranını %25 veya %50 artırarak veya yumurtlama oranını %25 veya %50 azaltarak uygulanan kontrol önlemlerinin, bu zararlıların neden olduğu kaybı yıllık olarak 82.506 ton kadar azaltma potansiyeline sahip olduğunu göstermektedir. Genel olarak, bu çalışma, tarımsal üretimde zararlıların yönetilmesinin önemini ve etkilerini azaltmak için kontrol yöntemlerinin kullanımının potansiyel faydalarını vurgulamaktadır.

Anahtar Kelimeler: Türk fındığı, hasat, kahverengi kokarca böceği benzeri zararlılar, matematiksel modelleme

Introduction

Hazelnuts are one of the most important fruits in the world, and Turkey is the main producer of hazelnuts since about %70 of hazelnut production worldwide comes from Turkey. However, hazelnut productivity and efficiency of yields are questionable in Turkey due to low productivity. We have two main problems that have been affecting hazelnut production negatively. The first one is the percentage of aged hazelnut trees, unfortunately, the percentage is very high and these aged trees are less productive as compared with young hazelnut trees. Additionally, the presence of harmful insect populations in Turkey is another significant challenge that needs to be addressed. It's important to develop effective pest management strategies that can help control these harmful insect populations and reduce their impact on hazelnut yields. Thus, it is clear that solving one or both of these problems will help farmers to increase the productivity of hazelnut farms in Turkey. Overall, addressing the challenges facing hazelnut production in Turkey is critical to maintaining the country's position as the leading producer of hazelnuts and ensuring a stable global supply of this important crop.

Since stink bug pests are one of the main problems for low production per area in hazelnut orchards in Turkey (Viggiani, 1984; Tuncer and Ecevit, 1997; AliNiazee, 1998), this study will focus on the negative effect of BMSB (Brown Marmorated Stink Bug (*Halyomorpha halys*) -type pests on hazelnut orchards. In Turkey, some pests harm hazelnut production by consuming various plant parts such as leaves and fruits. On the other hand, some insect pests affect the kernel quality by consuming hazelnuts. Besides these, some stink bugs (Hemiptera: Pentatomidae, Coreidae, and Acanthosomatidae) cause economic damage in hazelnut orchards (Tavella et al., 1997; Tuncer et al., 2005). There are over 15 species of stink bugs have been identified in Turkish hazelnut orchards, as this indicates a significant risk to hazelnut production. Each species of stink bug may cause different types of damage to hazelnuts, such as discoloration, deformation, and reduced kernel weight. (Kurt, 1975; Tuncer et al., 2005).

Besides these sting bugs, another dangerous sting bug was introduced in Turkey in 2017 which is the brown marmorated stink bug (Çerçi and Koçak, 2017). The BMSB is an invasive, highly polyphagous, severe agricultural pest, that reduces the availability, quality, and value of hazelnut production (Acebes, 2016). Since 2014 a polyphagous invasive insect BMSB has been invaded by Russia (Neimirovets, 2018), distributed in west Georgia, and caused the loss of 70- 90% of the major industrial hazelnut harvest (Meskhi, 2017; Murvanidze et al., 2018; EPPO Global Database, 2019; International Nut and Dried Fruit Council, 2019).

In Turkey, the BMSB was first recorded in Istanbul in 2017 (Çerçi and Koçak, 2017). In the same year, the pest was also documented in Artvin (Güncan and Gümüş, 2019). Following the initial detection of the pest in Turkey, it was found in the Black Sea Region in Rize, Trabzon, Giresun, Ordu, and Samsun (Göktürk et al., 2018; Ak et al., 2019; Göktürk and Tozlu, 2019). Additionally, in the Marmara Region, it was identified in Sakarya and Yalova (Göktürk, 2020; Özdemir and Tunçer, 2021), and in the Aegean Region, it was detected in İzmir (Çerçi, 2021).

Since it is not easy to identify the effect of BMSB from the other sting bug effects on hazelnut orchards in Turkey, the cumulative effect of these sting bugs was considered in this study. Since BMSB was introduced in Turkey in 2017, we will investigate the effect of these sting bugs between the years 2017 and 2022. We will use a mathematical model to capture the effect of sting bugs on hazelnut production by using ordinary differential equations. Using ordinary differential equations in modeling is a very common method for modeling biological or ecological systems (Demir, 2019; Aslan et al., 2022). Note that even if we will explore the cumulative effect of all the sting bugs on hazelnut production in Turkey, we assumed that the BMSB will be the main driver in the reduction of hazelnut production between 2017 and 2022 in Turkey. We are confident with this assumption since we know that the BMSB caused annually the loss of 70- 90% of the major industrial hazelnut harvest in Georgia (Meskhi, 2017; Murvanidze et al., 2018; EPPO Global Database, 2019; International Nut and Dried Fruit Council, 2019) and this is very huge as we compare the negative effect of the other sting bugs on hazelnut production in Turkey.

In the following sections, we will introduce a mathematical model that was created for this study, and we will estimate the parameters of the model. After that we conduct a sensitivity analysis (parametric analysis). Then, we will present the results of the model and discuss and quantify the impact of BMSB-type pests on hazelnut production. In addition, we took into account several methods of control to exert influence on the egg ratio and death rate of BMSB-type pests. We aimed to assess the potential increase in hazelnut production resulting from a decrease in the egg ratio and an increase in the death rate of these pests through the application of biocontrol, chemical controls, or traps.

Material and Methods

A mathematical model, shown in Equation (1) below, was constructed to assess the impact of stink bugs, including the brown marmorated stink bug, on the production of Turkish hazelnuts. This model will allow us to estimate the annual production of hazelnuts and evaluate the detrimental effects of stink bugs on hazelnut production in Turkey. As the brown marmorated stink bugs were first observed in Turkey in 2017, this study will focus on the years between 2017 and 2022.

Model Formulation

The model given in Eq. (1) represents a predator-prey system, consisting of hazelnut fruits (*H*) and BMSB-type pests (*B*). The negative impact of the pests on hazelnut fruits is denoted as $aB(t)H(t)$, while the harvesting of hazelnuts is represented by the term $bH(t)$

$$\frac{dH}{dt} = p(t) - aBH - bH,$$
$$\frac{dB}{dt} = cBH - dB \qquad (1)$$

with the initial conditions: $H(0) = H_0$ and $B(0) = B_0$. In the given model, the term $cB(t)H(t)$ represents the growth rate of the BMSB-type pests, while $dB(t)$ represents their death rate. The term $p(t)$ is a pulse that represents the emergence of new hazelnut fruits each spring, which occurs at the beginning of June every year. The size of this pulse may vary due to various factors such as fertilization efficiency, pruning practices, weather conditions, and others. Hence, it is assumed that the size of the pulse follows a normal distribution that is random:

p(t) ~ Normal (μ, σ)

where μ *and* σ represent the mean and standard deviation of the pulse, respectively.

Parameter Estimation

The parameters of model (1) were estimated using annual hazelnut production data from Turkey (FAO, 2021; TUIK, 2022), with the Ordinary Least Squares (OLS) method used to minimize the sum of the squares of the differences between the observed hazelnut production and the model's predictions. The goodness of fit was assessed by calculating the relative error of the fit using the following formula:

$$\min\left(\frac{\sum_{k=1}^{n}\left(H_k - \widehat{H}_k\right)^2}{\sum_{k=1}^{n}(H_k)^2}\right)$$

where H_k and $\widehat{H}_k$ are the exact and estimated annual hazelnut production, respectively. An ode45 solver with fmincon from the Optimization Toolbox of MATLAB is used in this parameter estimation.

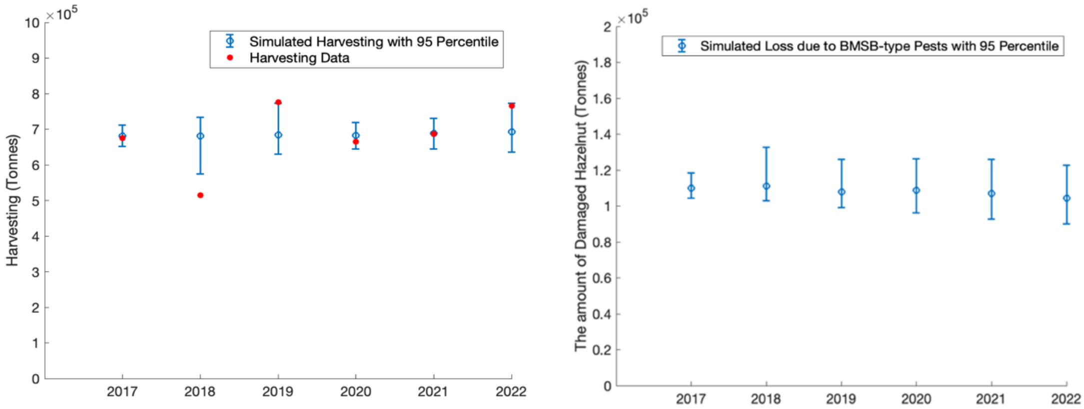

Figure 1. Left plot: the fit of hazelnut fruits with 95% simulation intervals. Right plot: the amount of hazelnut loss due to BMSB-type pests with 95% simulation intervals.

Table1. Parameter descriptions and values.

Parameters	Description	Unit	Value	Source
H_0	Initial biomass of hazelnut fruits	Tonnes	0	Assumed
B_0	Initial biomass of the BMSB-type populations	Tonnes	$2e^3$	Assumed
μ	Mean of hazelnut fruit's pulse	Tonnes	650204	Estimated
σ	Standard deviation of hazelnut fruit's pulse	Tonnes	378208	Estimated
a	Damage rate caused by BMSB-type populations on hazelnut fruits	$(week\ x\ Tonnes)^{-1}$	$1.84e^{-5}$	Estimated
b	Harvest rate of hazelnut fruits	$week^{-1}$	0.37	Estimated
c	Egg ratio of BMSB-type populations due to predation of hazelnut fruits	$(week\ x\ Tonnes)^{-1}$	$8.9e^{-7}$	Estimated
d	Death rate of BMSB-type populations	$week^{-1}$	0.05	Estimated

Note: Here *e* is the scientific notation in MATLAB and it is a shorthand for 10.

All the parameters were estimated in the model given in Eq. (1) (see Table 1) and the visualization of model fit is presented in Figure 1 with a 95% simulation interval. To obtain the mean and 95 percentiles of hazelnut harvesting and hazelnut loss due to BMSB-type pests, we run the model with estimated parameters 100 times and saved all the outputs, and then obtained the mean and 95 percentiles of these 100 outputs given in Figure 1. In addition, in the result section, all the outputs were obtained similarly by running the model 100 times. Note that we used $bH(t)$ and $aB(t)H(t)$ terms in Eq. (1) to obtain the yield of hazelnut and the hazelnut loss due to BMSB-type pests, respectively.

Sensitivity Analysis of Parameters

Several parameters play important roles in model (1). These parameters were estimated using existing data. To determine the set of parameters that are statistically significant regarding annual hazelnut production, we conducted a sensitivity analysis (parametric analysis) of the model. Utilizing Latin Hypercube Sampling (LHS) and the partial rank correlation coefficients (PRCC) method (Marino et al., 2008), we sampled parameters from the range provided in Table 2, following a uniform distribution. Subsequently, these samples were employed as input variables when running system (1) for one year, with initial conditions $H_0(0) = 0$ and $B_0(0) = 2e^3$. The annual hazelnut production at the final time serves as the output variable for our sensitivity analysis (see Figure 2). In Figure 2, we employed 300 random parameter values from each parameter interval in Table 2 to identify which parameters are more sensitive to system (1). We present PRCC values, p-values, and the range for each corresponding parameter in Table 2. It's important to note that all analyses were conducted in MATLAB, and the corresponding sensitivity analysis codes modified from the codes provided by Marino et al., 2008.

The sensitivity analysis reveals that the parameters a, b, c, and d are statistically significant due to their high PRCC values. Consequently, there is interest in investigating how the annual hazelnut production fluctuates when varying a, b, c, and d, while keeping all other parameters constant as outlined in Table 1, and maintaining the initial conditions as previously stated. Figure 2 illustrates the outcomes of these experiments, showcasing the variations in annual hazelnut production at the final time for different values of a, b, c, and d.
The PRCC values for c and d are -0.9 and 0.55, respectively. This indicates that the parameter c (the egg ratio of BMSB-type populations) is more sensitive compared to parameter d (the death rate of BMSB-type populations) when maximizing the annual hazelnut production at the final time. Consequently, reducing the egg ratio of BMSB-type populations will lead to higher annual hazelnut production than increasing the death rate of BMSB-type populations when applying the same effort to decrease the egg ratio or increase the death rate of BMSB-type populations. This result matches with the finding obtained in the following section.

Table 2. Results of sensitivity analysis with partial rank correlation coefficient (PRCC), *p*-value, and parameter ranges.

Parameters	Description	PRCC	p-value	Range
μ	Mean of hazelnut fruit's pulse	0.24	$2.6e^{-5}$	200000-1000000
σ	Standard deviation of hazelnut fruit's pulse	0.16	0.79	200000-800000
a	Damage rate caused by BMSB-type populations on hazelnut fruits	-0.61	$1.7e^{-34}$	0.000001-0.001
b	Harvest rate of hazelnut fruits	0.82	$1.8e^{-74}$	0.1-0.8
c	Egg ratio of BMSB-type populations due to predation of hazelnut fruits	-0.90	$1.6e^{-107}$	$5e^{-8} - 5e^{-5}$
d	Death rate of BMSB-type populations	0.55	$3.8e^{-25}$	0.0001 - 5

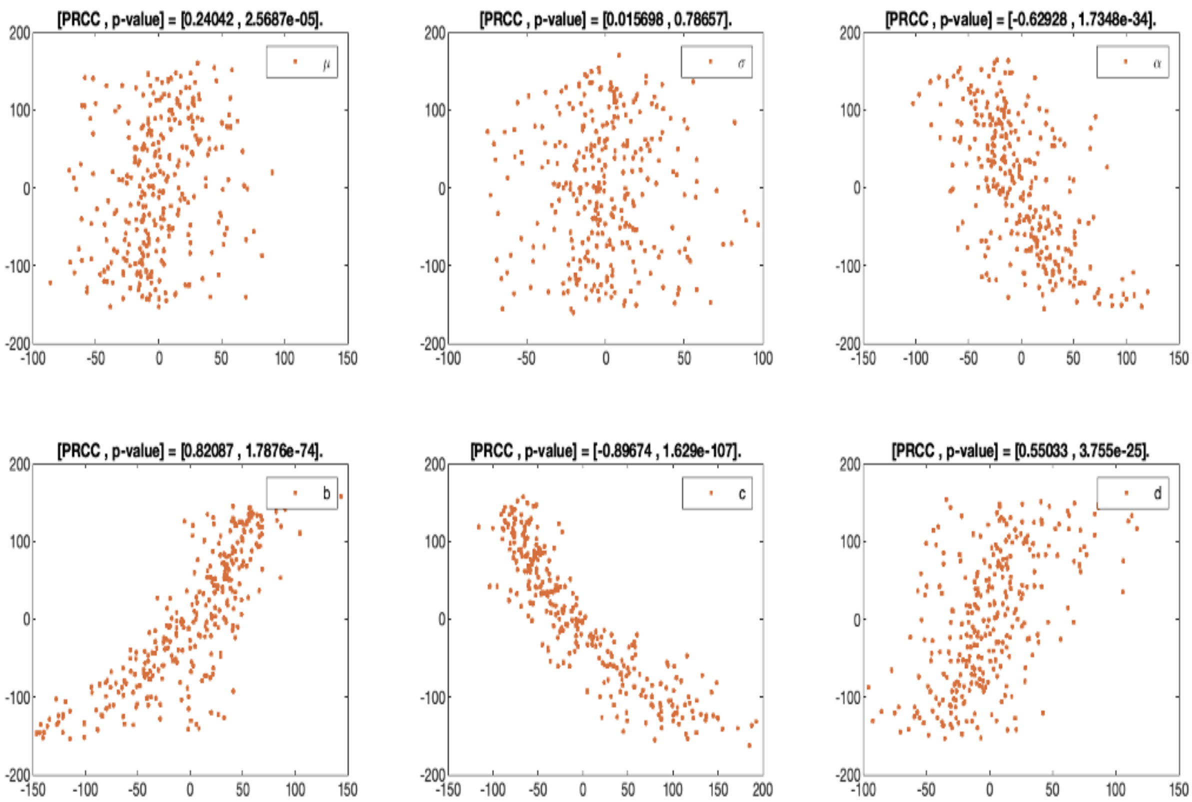

Figure 2. Visualization of sensitivity analysis: X axis denotes the variation of parameters with the ranked range of parameters given in Table 2 and Y axis denotes the change in the annual hazelnut production as we vary parameters in X axis.

Results and Discussion

This section of the study involved fitting the mathematical model with the annual hazelnut production data and presenting the outcomes. Figure 1 not only demonstrated the accuracy of the model in capturing the data but also indicated the quantity of hazelnut yield that was affected. The study found that between 2017 and 2022, approximately 106,820 tonnes of hazelnut yields were damaged per year by the BMSB-type pests in Turkey, with a 95% simulation interval of 94,709 to 120,040 tonnes.

In this result section, we also analyzed the effectiveness of various control methods such as introducing predators as a biocontrol, using chemicals or traps to increase the death rate, and introducing egg and larvae parasites or using specific chemicals to reduce the egg ratio of BMSB-type pests. The goal was to reduce the amount of hazelnut loss caused by these pests. We divided the controls into two types: (1) controls to increase the death rate of BMSB-type pests, and (2) controls to reduce the egg ratio of BMSB-type pests. We then examined the impact of these controls on hazelnut production.

Effect of increasing death rates of BMSB-type pests via biocontrol, chemicals, or traps

In this subsection, we will explore three commonly used methods to control invasive pests: bio-control, chemical control, and biotechnical control. These methods aim to reduce the abundance of BMSB-type pests and increase their death rate, *d*. Specifically, bio-control involves introducing a new predator to the system to put more pressure on the pests. Chemical control uses pesticides to eliminate pests, and biotechnical control uses attractive materials to trap them. By reducing the death rate, *d*, by 25% or 50%, we will investigate the effects of these controls on hazelnut production and quantify the increase obtained when applying such controls. (see Figure 3).

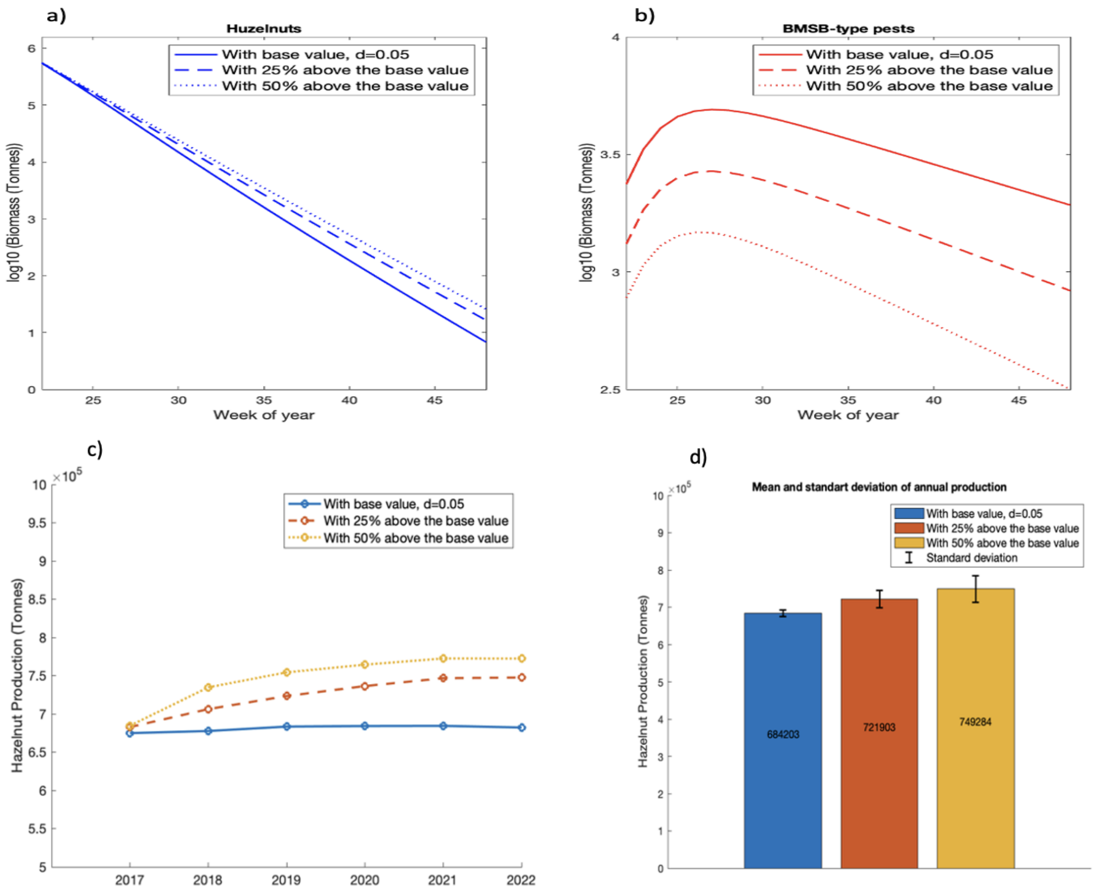

Figure 3. Seasonally averaged biomass of hazelnut fruits and biomass of BMSB-type pests over the period of six years are given in (a) and (b). The effect of varying the parameter, d (death rate of BMSB-type pests) on hazelnut production is given in (c) and (d).

The results of the investigation suggest that the extent to which we increase the death rate is a crucial factor, as we do not observe equal increases in hazelnut production when we increase the death rate by 25% or 50% (as demonstrated in Figures 3c and 3d). By increasing the death rate of the BMSB-type pests by 25% or 50%, we can produce about 721,903 (with a 25% increase) or 749,284 (with a 50% increase) tonnes of hazelnuts, whereas, without any control, the hazelnut yield would be 684,203 tonnes. This means that a 25% increase in the death rate results in an additional 37,700 tonnes of hazelnut production while increasing the death rate from 25% to 50% results in only 27,381 tonnes of additional production. Thus, we do not see the same proportional increases in hazelnut production when we apply a 50% reduction rather than a 25% reduction in the death rate. Overall, this strategy can result in up to 65,081 tonnes of extra hazelnut yield per year.

Effect of reducing the egg ratio of BMSB-type pests via biocontrol or chemicals

The egg ratio of BMSB-type pests can be lowered using biological control (eggs and larvae parasites) or chemical control. This study explores the effects of these methods on hazelnut yields. A 25% or 50% reduction in the egg ratio of the pests was applied, and the resulting increase in hazelnut yield was analyzed. The study found that a 25% increase in the egg ratio resulted in a hazelnut yield of 728,471 tonnes (compared to 681,879 tonnes without control methods), and a 50% increase in the egg ratio resulted in a yield of 756,864 tonnes. Increasing the death rate of the pests by 25% led to an additional 46,592 tonnes of hazelnuts, while a death rate increase from 25% to 50% produced an extra 28,393 tonnes. Overall, the control strategy suggests that we could potentially increase hazelnut yields by up to 74,985 tonnes per year (See Figure 4).

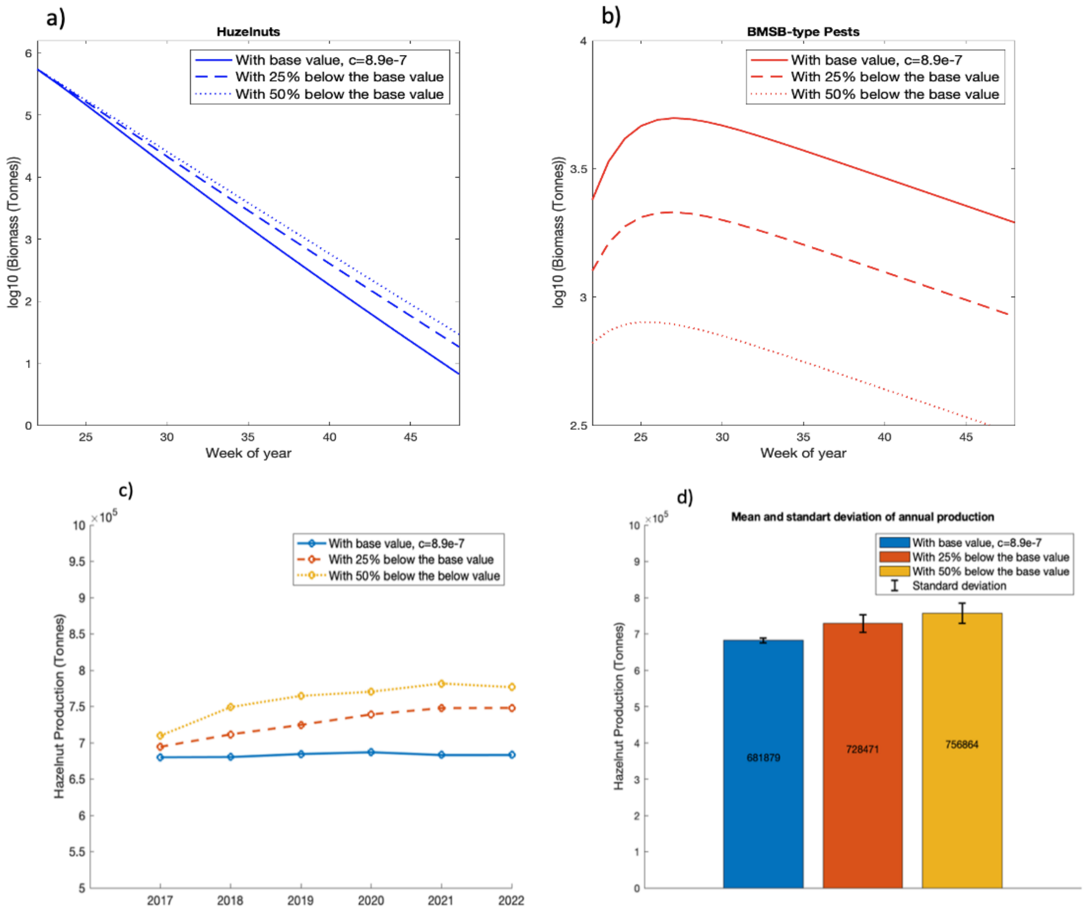

Figure 4. Seasonally averaged biomass of hazelnut fruits and biomass of BMSB-type pests over 6 years are given in (a) and (b). The effect of varying the parameter, *c* (the egg ratio of BMSB-type pests) on hazelnut production is given in (c) and (d).

Effect of simultaneously reducing egg ratio and increasing death rate of BMSB-type pests

In this subsection, we explore the effect of both strategies mentioned in subsections 3.1 and 3.2. Increasing the egg ratio, *c* by 25% (or 50 %) and reducing the death rate, *d* by 25% (or 50 %) lets us produce about 747,631 (764, 751) tonnes of hazelnuts instead of producing 682,245 tonnes (see Figure 5). Thus, decreasing the egg ratio by 25% and increasing the death rate by 25% brings extra 65,386 tonnes of hazelnut fruits but changing the effort in the death and egg ratio from 25 % to 50% brings about 17,120 tones of extra hazelnut fruits (see c and d in Figure 5). Therefore, applying this strategy can increase annual hazelnut production by up to 82,506 tonnes per year.

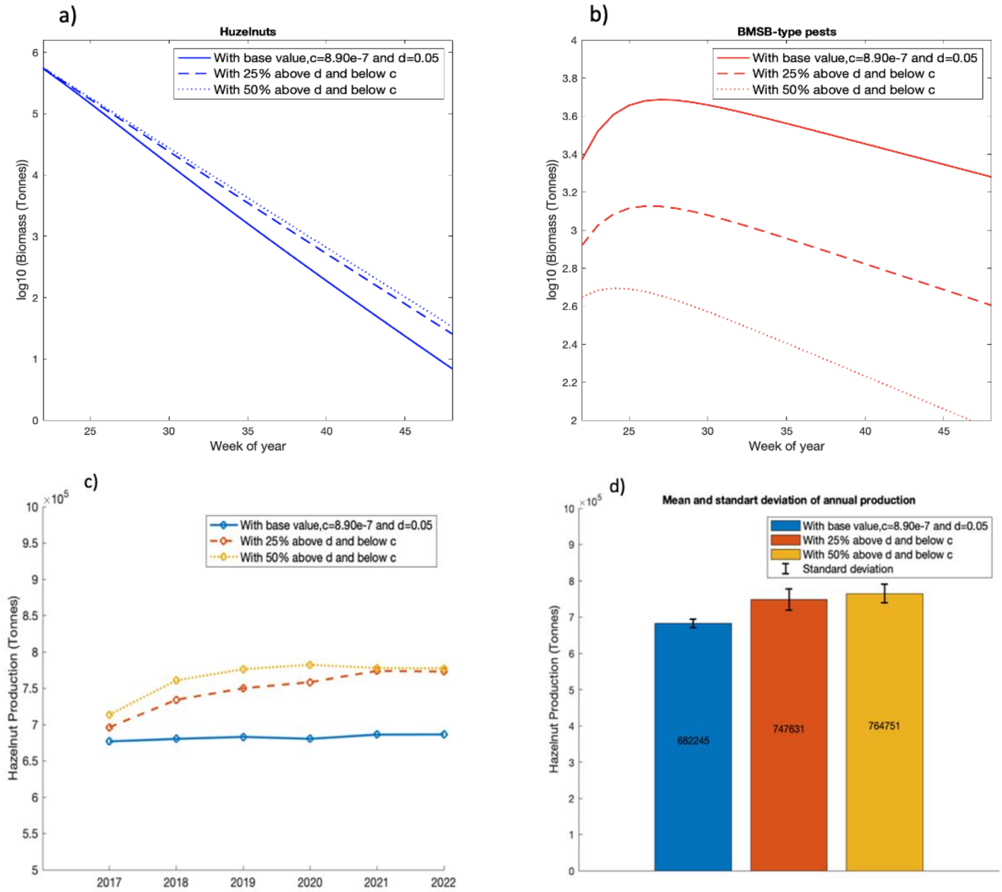

Figure 5. Seasonally averaged biomass of hazelnut fruits and biomass of BMSB-type pests over 6 years are given in (a) and (b). The effect of varying the parameter, *c* (the egg ratio of BMSB-type pests) and *d* (death rate of BMSB-type pests) on hazelnut production is given in (c) and (d).

One of the key findings of this study is that the BMSB-type pests in Turkey cause an annual loss of around 106,820 tonnes of hazelnut production, with a 95% simulation interval of 94,709 to 120,040 tonnes. This suggests that between 2017 and 2022, approximately 640,920 tonnes of hazelnuts were lost in Turkey due to these pests.

Another crucial finding of this study is that applying control methods to reduce the egg ratio of BMSB-type pests is more effective in increasing hazelnut yields than applying control methods to increase the death rate. The investigation showed that overall, these control methods can lead to an increase of up to 82,506 tonnes of hazelnut yield per year, as outlined in section 3.

Considering the cost of implementing these control mechanisms and assuming that the same amount of effort is required to achieve the percentage decreases and increases in egg ratio and death rate of BMSB-type pests, it can be concluded that focusing on controlling the egg ratio of BMSB-type pests is more cost-effective. This conclusion is based on the findings of the study, which indicate that controlling the egg ratio of BMSB-type pests leads to a higher increase in hazelnut production compared to controlling both the egg ratio and death rate simultaneously, even when the same amount of effort is applied. For instance, if we implement a control mechanism that causes a 50% reduction in the egg ratio or implement a strategy that involves a 25% reduction in the egg ratio and a 25% increase in the death rate of BMSB-type pests simultaneously (with the same cumulative effort), controlling only the egg ratio would lead to higher hazelnut yields.

Furthermore, this analysis indicated that in the long term, applying 25% and 50% effort provided the same increases in hazelnut production in the case we applied both increases in death rate and decrease in the egg ratio of BMSB-type pests (see Figure 5c).

In this study, the percentage of reductions or increases in the egg ratio and death rate of BMSB-type pests was chosen randomly because the optimal values were not known. However, the use of an optimal control technique can help estimate the optimal values for these rates and optimize the efforts required to achieve the maximum increase in hazelnut production (Demir and Lenhart 2020; Demir and Lenhart 2021).

Conclusion

The study highlights the negative impact of BMSB-type pests on hazelnut production in Turkey. It estimates that these pests cause an annual loss of around 106,820 tonnes, resulting in a cumulative loss of about 640,920 tonnes between 2017 and 2022. The study suggests that implementing measures such as biocontrols, chemicals, or traps can help mitigate the damage caused by these pests. By reducing the egg ratio of BMSB-type pests by 25% or 50% and/or increasing the death rate by 25% or 50%, hazelnut production in Turkey can be increased by up to 82,506 tonnes per year between 2017 and 2022.

This study also highlights that implementing any control measures aimed at reducing the egg ratio of BMSB-type pests will result in a greater increase in hazelnut production compared to applying controls to increase the death rate of BMSB-type pests, given the same level of effort.

Appendix A. Data used in this study

Table A1 provides the data used in this study, which is the yield of annual hazelnut production in Turkey (FAO, 2021; TUIK, 2022).

Table A1 The annual yields of hazelnut production between 2017 and 2022 in Turkey.

Years	Hazelnut Production (Tonnes)
2017	675,000
2018	515,000
2019	776,000
2020	665,000
2021	687,412
2022	765,287

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Conflict of interest

There is no conflict of interest.

Author contributions

Single author.

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