Postprint: Risk Assessment-Based Analysis of Insect-Resistant Cotton Cultivation in Xinjiang

Authors: WANG Zhenlin, Lü Zhaozhi

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Abstract

Based on the biological characteristics of the Xinjiang cotton bollworm and long-term population dynamics trends, and upon collecting relevant data regarding cotton planting area, yield, cotton market prices, and cotton bollworm control costs, this study employs a population simulation model (CLIMEX model) combined with stochastic simulation methods (@RISK software) to assess the potential economic losses to Xinjiang's cotton industry caused by the cotton bollworm under various scenarios. Cotton bollworm population simulations demonstrate that with future climate change, the weekly growth index (GIw) of the Xinjiang cotton bollworm will increase, the emergence date of overwintering pupae will be significantly advanced, and the risk of damage may consequently increase. Results from two simulation scenarios indicate that insect-resistant cotton can effectively mitigate damage caused by the cotton bollworm and reduce control costs per unit area. It is recommended that relevant departments in Xinjiang may reduce losses from both the cotton bollworm and secondary pests in the future through the organic integration of insect-resistant cotton cultivation and Integrated Pest Management (IPM) strategies.

Full Text

Analysis of Bt Cotton Planting in Xinjiang Based on Risk Assessment

WANG Zhenlin[1,2], LYU Zhaozhi[1], ZHANG Xin[1], LIU Yongjian[3]

[1]State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, Xinjiang, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]Agricultural Development Service Center, No. 121 Regiment, Eighth Division, Xinjiang Production and Construction Corps, Shihezi 832000, Xinjiang, China

Abstract

Based on the biological characteristics and long-term population dynamics of the cotton bollworm (*Helicoverpa armigera*) in Xinjiang, and using data on cotton planting area, yield, cotton market prices, and bollworm control costs, this study employs a population simulation model (CLIMEX) combined with stochastic simulation methods (@RISK software) to assess potential economic losses to Xinjiang' s cotton industry from cotton bollworm under different scenarios. Population simulations indicate that with future climate change, the weekly growth index (GIw) of cotton bollworm in Xinjiang will increase, the emergence date of overwintering pupae will be significantly advanced, and the risk of damage may increase. The @RISK simulation results for four scenarios demonstrate that Bt cotton can effectively reduce damage from cotton bollworm and decrease control costs per unit area. We recommend that relevant Xinjiang authorities combine Bt cotton planting with integrated pest management (IPM) to reduce losses caused by cotton bollworm and secondary pests.

Keywords: cotton bollworm; CLIMEX; Bt cotton; IPM; @RISK

1.1 CLIMEX Model and Parameters

The CLIMEX model, developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia, is primarily used to explore climate impacts on species distribution and to predict potential distribution, future trends, and population growth potential of organisms [19]. This study uses CLIMEX 3.0 software with cotton bollworm as the simulation object, with model parameters derived from Zalucki' s research [20]. To investigate population growth trends of cotton bollworm under future climate change, we adopted climate data centered on 2030 (future climate data) and 2010 (current climate data), with spatial geographic distribution data sourced from CLIMOND (https://www.climond.org). According to water requirements throughout the cotton growth period, irrigation must be added to natural precipitation to meet normal cotton growth and development. Since water requirements vary across different growth stages, we estimated irrigation needs per mu of cotton based on changes in cotton water demand in China over the past 30 years [21] and converted irrigation volume in the model to daily precipitation [22], setting annual rainfall at 2.5 mm $\cdot$ d^{-1}.

For simulating cotton bollworm population changes, we selected six representative locations in Xinjiang: Awati County (40.48°N, 80.45°E), Markit County (38.88°N, 77.62°E), Regiment 127 of Xinjiang Production and Construction Corps (Tacheng area, 45.07°N, 79.89°E), Hotan County (36.57°N, 84.38°E), Manas County (44.55°N, 82.75°E), and Jinghe County (44.61°N, 86.29°E). These points represent different climatic characteristics and planting features across Xinjiang' s cotton-growing regions.

1.2 @RISK Software and Assessment Methods

@RISK 7.6, developed by Palisade Corporation, is a software that employs Monte Carlo simulation (also known as random sampling) to perform risk analysis. It can objectively and automatically calculate and simulate different design schemes, helping users make optimal decisions under uncertain conditions, and provides sensitivity analysis and scenario analysis functions to identify key factors in the model [26]. To ensure more accurate simulation results, the iteration number in this model was set to 10,000.

1.3.1 Simulation Scenarios

Based on the proportion of Bt cotton in China compiled and analyzed by Qiao [27], Bt cotton in Xinjiang accounted for approximately 85% of total cotton planting area in 2015. Considering the annual changes in Bt cotton planting area, this study designed four scenarios: future planting of conventional cotton and planting of transgenic Bt cotton, with each type further divided into integrated pest management (IPM) and conventional control (chemical pesticide only). Wu et al. [28] noted that the Xinjiang Production and Construction Corps (XPCC) has two advantages over local Xinjiang Uygur Autonomous Region farmers: higher cotton yield per unit area and relatively lower costs, which is closely related to the adoption of IPM in pest management. According to the Xinjiang Production and Construction Corps Agricultural Statistical Yearbook [29], XPCC cotton planting area accounts for 42% of Xinjiang' s total, while its cotton production accounts for 62% of Xinjiang' s total. Based on the current situation in Xinjiang (XPCC primarily uses integrated control, while local areas mainly use chemical control), we assume that in the future, local areas will adopt conventional management methods, while XPCC units will adopt IPM (considering rational pesticide use, such as changes in pest chemical control frequency). The simulation scenario settings are shown in [Figure 2: see original paper].

1.3.2 Potential Economic Loss Model Under Simulation Scenarios

Taking conventional cotton planting as an example, the direct economic loss (F) caused by cotton bollworm in this scenario mainly includes three components: economic loss from cotton yield reduction (F_1), economic loss from quality decline (F_2), and control costs invested after management (F_3). The formula is:

$$F = F_1 + F_2 + F_3$$

(1) Economic loss from cotton yield reduction (F_1)
The economic loss model for cotton yield reduction caused by cotton bollworm damage is:

$$F_1 = Q_1 \times I \times R \times Pc/(1 - I)$$

Where Q_1 is the annual cotton yield in the cotton bollworm suitable area (10^4 t); I is the damage rate of cotton bollworm to cotton (%); R is the yield loss rate after cotton is damaged by cotton bollworm (%); and Pc is the cotton market price (yuan • kg^{-1}).

(2) Economic loss from cotton quality decline (F_2)
The economic loss model for cotton quality decline caused by cotton bollworm damage is:

$$F_2 = Q_1 \times I \times (1 - R) \times P_2/(1 - I)$$

Where P_2 is the cotton market price when quality declines (yuan • kg^{-1}).

(3) Control costs (F_3)
Control cost expenditure refers to the total investment for cotton bollworm control, including pesticides, labor, and mechanical spraying costs:

$$F_3 = S \times C$$

Where S is the cotton planting area in the cotton bollworm suitable area (10^4 hm^2), and C is the control cost per unit area in cotton-producing regions (yuan • hm^{-2}).

1.4 Model Sensitivity Analysis

Sensitivity analysis is a method to evaluate how changes in a system' s or model' s parameters or surrounding conditions affect its output [36]. The sensitivity analysis in @RISK software indicates the degree of influence by comparing the regression coefficients of input factors. In this study, we compare the regression coefficients of different factors to assess their impact on economic losses.

1.5 Parameter Determination for the Potential Economic Loss Assessment Model

The average economic loss mentioned in this paper refers to the median value taken from the minimum to maximum values in the simulation results (Table 1). To make the simulation results closer to actual conditions, this study adopts a probabilistic approach. We assume that when cotton is damaged by cotton bollworm and quality declines, its price can be set at half the normal market price [30]. Based on data released by the National Cotton Market Monitoring System [33] and considering Xinjiang' s actual situation, we estimate control costs per unit area in cotton epidemic areas under different management modes (primarily considering pesticide application frequency and costs, and labor costs). The damage rate of cotton bollworm to cotton and the yield loss rate after damage are derived from research literature [31-32] and historical statistical data provided by the Plant Protection Station of Regiment 121 of XPCC.

Xinjiang' s cotton planting area and annual yield data were obtained from the National Statistical Yearbook and local statistical bureaus [29,34-35]. The data in the table are projections of future cotton planting areas in Xinjiang extrapolated using polynomial trend lines ($R^2 > 0.95$) based on recent years' data. The annual yield data for cotton in Xinjiang were obtained in the same manner as described in "Xinjiang Statistical Yearbook" [35].

2 Results and Analysis

2.1 Comparison of Weekly Growth Index (GIw) of Cotton Bollworm in Typical Xinjiang Regions

As shown in [Figure 3: see original paper], except for Hotan County, the dates of the first GIw change for cotton bollworm in the other five regions advanced to varying degrees in 2030 compared to 2010. Specifically, in 2030, the first GIw change for cotton bollworm in southern Xinjiang (southern region) counties of Markit and Awati appeared on day 120 (early May), while in northern Xinjiang (northern region), it appeared on day 150 (mid-May). The GIw for Hotan County showed no significant change, possibly related to temperature and rainfall settings in the model. The advancement of the GIw change date will likely lead to earlier emergence of overwintering cotton bollworm pupae.

2.2 Potential Economic Loss from Cotton Bollworm to Xinjiang Cotton Under Four Scenarios

We simulated two management modes for the conventional cotton planting scenario, with results shown in Table 2. The total potential economic loss in this scenario ranges from 15.25×10^{8} to 32.99×10^{8} yuan, with an average of 23.37×10^{8} yuan. For the Bt cotton planting scenario, simulations under two management modes yielded the results in Table 2. The potential economic loss in this scenario ranges from 3.08×10^{8} to 6.36×10^{8} yuan, with an average of 4.33×10^{8} yuan. Planting Bt cotton can save approximately 81.47% of economic losses compared to conventional cotton.

2.3 Comparison of Different Management Modes Under Two Scenarios

We calculated the economic loss per unit area under different management modes in the two scenarios. As shown in [Figure 4: see original paper], in the conventional cotton planting scenario, IPM management reduces economic loss per unit area by 84.45–402.6 $\text{yuan}\cdot\text{hm}^{-2}$ on average compared to conventional management. In the Bt cotton scenario, IPM management reduces economic loss per unit area by 45.9–101.7 $\text{yuan}\cdot\text{hm}^{-2}$ compared to conventional management.

2.4 Sensitivity Analysis of Potential Economic Loss from Cotton Bollworm to Xinjiang Cotton Under Two Scenarios

In the conventional cotton planting scenario, the regression coefficients of different influencing factors under the two management modes are relatively similar, making it difficult to accurately assess the impact degree of different factors on economic loss. A similar situation occurs in the Bt cotton scenario. Therefore, this study only discusses the differences in regression coefficients of different factors under the two scenarios ([Figure 5: see original paper]). The sensitivity analysis results for potential economic loss under the two scenarios show that the regression coefficient of cotton bollworm damage rate is the largest, indicating that the damage rate is the most sensitive factor affecting potential economic loss. In the conventional cotton scenario, yield loss rate has a greater impact on economic loss than control costs. In the Bt cotton scenario, cotton bollworm is effectively controlled, and the impact of yield loss rate on economic loss decreases, while the impact of control costs increases.

3 Discussion

3.1 Analysis of Future Cotton Bollworm Population Dynamics

Research conclusions [27,37] indicate that cotton bollworm population dynamics are related to the volatility of economic losses. The impact of cotton bollworm damage rate on potential economic loss in this study confirms this conclusion. Changes in the weekly growth index in [Figure 3: see original paper] show that cotton bollworm population dynamics are closely related to climate change. Gu et al. [38] found that as global spring temperatures warm, the frequency and duration of late spring cold events decrease, leading to cotton bollworm population outbreaks in Xinjiang. Lyu et al. [39] analyzed cotton phenology in northern Xinjiang, showing that accumulated degree-days during cotton development periods vary in 4–5 year cycles, which correlates with the periodicity of cotton bollworm populations. Previous studies indicate that major cotton bollworm outbreaks in Xinjiang occur in 5–7 year cycles [40]. Climate change leads to increased cotton bollworm populations, and suitable environmental conditions increase the damage rate to cotton, making potential economic losses more severe. Xinjiang should strengthen Bt cotton promotion in the future to effectively reduce cotton bollworm damage and economic losses.

3.2 Economic Benefit Analysis of Bt Cotton Planting

According to the Ministry of Agriculture and Rural Affairs'reports on cotton pest occurrence, control, and loss recovery in various regions, cotton pests and diseases in Xinjiang cause economic losses of approximately $45\$\times10^{\{8\}-63\times10}\{8\}\$$ yuan [41]. The estimated economic loss from cotton bollworm in this study is $15.25\$\times10^{\{8\}-32.99\times10}\{8\}\$$ yuan, which falls within the reported range, primarily because this study does not consider economic losses from cotton diseases and other pests. Qiao' s research [27] shows that the benefits of transgenic Bt cotton in China are sustainable, consistent with this paper' s conclusion on future economic trends—that planting Bt cotton in Xinjiang can effectively reduce economic losses caused by cotton bollworm. Graham et al. [42] analyzed the benefits of four major genetically modified crops (soybean, maize, cotton, and rapeseed) globally, finding that genetically modified crops increased average yields by 5%-11%. After planting genetically modified maize in the United

States, the population of *Helicoverpa zea* decreased significantly, and pesticide application decreased by 19%-28% [43]. After planting genetically modified rapeseed in Canada, economic benefits increased by 5%-11% [44]. Wilhelm et al. [45] conducted an economic impact analysis of genetically modified crops, showing that the comprehensive benefits of adopting genetically modified technology significantly increased: chemical pesticide use decreased by 37%, and farmer profits increased by 68%. This study' s conclusions also indicate that after adopting Bt cotton, pesticide use in Xinjiang cotton planting decreased by 81.47%, and farmer income increased accordingly.

3.3 Analysis of Management Scenario Impacts on Bt Cotton

The CLIMEX model predicts potential economic losses from cotton bollworm under four scenarios. The results provide a reference for future decision-making on Bt cotton planting by assessing differences in cotton bollworm populations across regions. However, this study has some limitations: the integrated control cost calculation lacks details such as machinery depreciation, resulting in some error compared to actual conditions. Future work can improve the model and enhance comprehensive benefit assessments of Bt cotton based on survey questionnaires.

In the conventional cotton planting scenario, IPM management reduces economic loss per unit area by 84.45-402.6 yuan $\cdot$ hm^{-2} compared to conventional management. In the Bt cotton planting scenario, IPM management reduces economic loss per unit area by 45.9-101.7 yuan $\cdot$ hm^{-2} compared to conventional management. This indicates that in both conventional cotton and Bt cotton scenarios, IPM can reduce economic losses caused by cotton bollworm. This is consistent with Zhang's survey results [48] from cotton IPM technology training. Sheng et al. [49] also proposed in their ecological control of cotton bollworm in Xinjiang that future adoption of IPM measures, such as autumn plowing and winter irrigation and adjustment of crop planting structure, can reduce cotton bollworm damage. Although IPM can effectively reduce economic losses from cotton bollworm, economic losses from pests worldwide remain high, and pesticide use in major agricultural countries has not significantly decreased. In fact, pesticide use has increased in some regions (such as China and Southeast Asian countries), mainly due to high IPM implementation costs, long effect cycles, and limited promotion [50]. Therefore, how to truly adopt IPM on a large scale requires joint discussion by experts in relevant fields at home and abroad in the future [51].

3.4 Integrated Management and Utilization of Bt Cotton

Compared with conventional cotton planting, future planting of transgenic Bt cotton significantly reduces potential economic losses. Bt cotton not only effectively controls cotton bollworm damage to cotton but also reduces cotton bollworm damage to other crops [52]. Research by Su et al. [37,55] also shows that Bt cotton planting reduces pesticide use and control costs. There are many similar international studies, such as field trials of Bt cotton in India, farm Bt cotton assessments in Arizona, USA, and Bt cotton promotion in Australia [56]. However, with large-scale Bt cotton planting, some secondary pests (such as cotton aphids, cotton mirids, and whiteflies) have outbreak due to reduced pesticide use [57], while the risk of cotton bollworm resistance to Bt cotton continues to increase [58]. To address potential genetically modified resistance risks, Australia has adopted a refuge strategy when planting Bt cotton, effectively preventing increased cotton bollworm resistance. Combined with IPM, this can effectively reduce damage from cotton bollworm and secondary pests to cotton [59]. Future genetically modified crop planting requires scientific management methods to maximize the advantages of genetically modified crops while addressing secondary pest outbreaks and pest resistance issues [60].

3.5 Research Limitations

This study combines the actual situation in Xinjiang' s cotton regions and uses a revised model to assess the benefits of Bt cotton. However, the model still has some limitations: the calculation of integrated control costs lacks details such as machinery depreciation, resulting in some discrepancies with actual conditions. Future research can improve the model based on survey questionnaires to enhance the comprehensive assessment of Bt cotton benefits.

References

[11] Cook D C, Carrasco L R, Paini D R, et al. Estimating the social welfare effects of New Zealand apple imports[J]. Australian Journal of Agricultural & Resource Economics, 2011, 55(4): 599-620.

[12] Ros G D, Conci S, Pantezzi T, et al. The economic impact of invasive pest *Drosophila suzukii* on berry production in the Province of Trento, Italy[J]. Journal of Berry Research, 2015, 5(2): 89-96.

[13] Taylor A S, Cook D C. An economic assessment of the impact on the Western Australian viticulture industry from the incursion of grapevine downy mildew[J]. Journal of Plant Diseases & Protection, 2018, 125(4): 1-7.

[16] Xi Chao, Jiang Yuying, Gui Furong, et al. The potential distribution analysis and economic loss prediction of *Spodoptera frugiperda* (J. E. Smith) in Yunnan Province[J]. Journal of Southern Agriculture, 2019, 50(6): 1226-1233.

[19] Sutherst R W, Maywald G F. A climate model of the red imported fire ant, *Solenopsis invicta* Buren (Hymenoptera: Formicidae): Implications for invasion of new regions, particularly Oceania[J]. Environmental Entomology, 2005, 34(2): 317-335.

[20] Kriticos D J, Ota N, Zalucki M P, et al. The potential distribution of invading *Helicoverpa armigera* in North America: Is it just a matter of time?[J]. PLoS ONE, 2015, 10(3): e0119618.

[21] Chen Chao, Pang Yanmei, Pan Xuebiao, et al. Variation characteristics of water requirement of cotton in China during 1961-2012[J]. Journal of Natural Resources, 2015, 30(12): 2107-2119.

[22] Xue Yarong, Bake Batur, Luo Nana, et al. Climate response to water demand of cotton plant in growing season in Tacheng Prefecture[J]. Arid Zone Research, 2018, 35(5): 1192-1198.

[26] @RISK. Palisade Corporation Guide to Using @RISK. [EB/OL]. https://www.palisade.com/risk, 2018-10-20.

[27] Qiao Fangbin. Fifteen years of Bt cotton in China: The economic impact and its dynamics[J]. World Development, 2015, 70: 177-188.

[28] Wu Kongming, Lu Yanhui, Li Jing, et al. Evolution of cotton diseases and insect pests in Xinjiang and analysis of its influencing factors[J]. China Plant Protection, 2015, 35(11): 43-48.

[29] Xinjiang Production and Construction Corps. Xinjiang Statistical Yearbook[EB/OL]. http://tjj.xjbt.gov.cn/zwfw/sjcx/, 2018-10-20.

[30] We assume that when cotton quality declines due to cotton bollworm damage, its price can be set at half the normal market price.

[31-32] The damage rate of cotton bollworm to cotton and the yield loss rate after damage are derived from research literature and historical statistical data provided by the Plant Protection Station of Regiment 121 of XPCC.

[33] National Cotton Market Monitoring System. Cotton market price data. [EB/OL]. http://www.cncotton.com/sy_{59}/scbg/gjmhscjcxt/, 2018-10-20.

[34-35] Xinjiang's cotton planting area and annual yield data were obtained from the National Statistical Yearbook and local statistical bureaus. The data in the table are projections of future cotton planting areas in Xinjiang extrapolated using polynomial trend lines ($R^2 > 0.95$) based on recent years' data.

[36] Zhao Axing, Ma Zongjin. Appraising study for the loss evaluation system of natural disasters[J]. Journal of Natural Disasters, 1993, 2(3): 1-7.

[37] Su Jun, Huang Jikun, Qiao Fangbin. Analysis of economic benefits of Bt gene resistant cotton production[J]. Journal of Agrotechnical Economics, 2000(5): 26-31.

[38] Gu Shimin, Han Peng, Lyu Zhaozhi, et al. Climate change favours a destructive agricultural pest in temperate regions: Late spring cold matters[J]. Journal of Pest Science, 2018, 91(4): 1191-1198.

[39] Lyu Zhaozhi, Li Li, Tian Changyan, et al. Calculation and analysis of cotton phenology in the Northern of Xinjiang[J]. Arid Land Geography, 2003, 26(4): 340-344.

[40] Lu Chengzhi. The damage law and prevention of the first generation cotton bollworm in different types of cotton fields in southern Xinjiang[J]. China

Cotton, 2005, 32(1): 24-25.

[41] Fang Xue, GE Saiying, Zhang Yongsheng, et al. Analysis of economic loss from pest insects and plant disease in cotton of China during 1991-2000[J]. Chinese Journal of Applied Entomology, 2014, 51(4): 1104-1113.

[42] Graham B, Peter B. Farm income and production impacts of using GM crop technology 1996-2016[J]. GM Crops & Food, 2018, 9(3): 59-89.

[43] Dively G P, Venugopal P D, Bean D, et al. Regional pest suppression associated with widespread Bt maize adoption benefits vegetable growers[J]. Proceedings of the National Academy of Sciences, 2018, 115(13): 201720692.

[44] Gusta M, Smyth S J, Belcher K, et al. Economic benefits of genetically modified herbicide tolerant canola for producers[J]. Agbioforum, 2003, 14(1): 1-13.

[45] Wilhelm K, Qaim M. A meta-analysis of the impacts of genetically modified crops[J]. Plos One, 2014, 9(11): e111629.

[46] Zhang Qiudong. Implementation Effect and Extension Approach Assessment of Farmer Field Schools[D]. Wuhan: Huazhong Agricultural University, 2006.

[47] Ministry of Agriculture and Rural Affairs of the People' s Republic of China. The general office of the ministry of agriculture and rural affairs on the issuance of the Key points of planting industry in 2019[EB/OL]. http://www.moa.gov.cn/ztzl/2019gzzd/sjgzyd/201903/t20190315_{6176675}.htm, 2018-10-20.

[48] Sheng Chengfa, Su Jianwei, Xuan Weijian, et al. Ecological management of the cotton bollworm in Xinjiang[J]. Chinese Journal of Eco-Agriculture, 2002, 10(2): 116-118.

[49] Lyu Zhaozhi, Baker G H. Spatial and temporal dynamics of *Helicoverpa armigera* (Lepidoptera, Noctuidae) in contrasting agricultural landscapes in northwestern China[J]. International Journal of Pest Management, 2013, 59(1): 25-34.

[50] Heong K L, Cheng J, Escalada M M. Rice Planthoppers: Ecology, Management, Socio Economics and Policy[M]. Hangzhou, Zhejiang University Press, 2015.

[51] Zhai Baoping. Rice planthoppers: A China problem under the international perspectives[J]. Journal of Applied Entomology, 2011, 48(5): 1184-1193.

[52] Wu Kongming, Lu Yanhui, Hong Qiang, et al. Suppression of cotton bollworm in multiple crops in China in areas with Bt toxin-containing cotton[J]. Science, 2008, 321(5896): 1676-1684.

[53] Ning Qiwen, Hu Leming. Occurrence, Control Area and Loss of Crop Diseases and Insect Pests in Various Regions[Z]. Beijing: China Agriculture

Yearbook, 2017: 621.

[54] Zhao J H, Ho P, Azadi H. Benefits of Bt cotton counterbalanced by secondary pests? Perceptions of ecological change in China[J]. Environmental Monitoring & Assessment, 2011, 173(1-4): 985-994.

[55] Pray C, Huang J K, Hu R, et al. Five years of Bt cotton in China—the benefits continue[J]. Plant Journal, 2002, 31(4): 423-430.

[56] Cattaneo M G, Yafuso C, Schmidt C A, et al. Farm-scale evaluation of the impacts of transgenic cotton on biodiversity, pesticide use, and yield[J]. Proceedings of the National Academy of Sciences of the United States of America, 2006, 103(20): 7571-7576.

[57] Qaim M, Zilberman D. Yield effects of genetically modified crops in developing countries[J]. Science, 2003, 299(5608): 900-902.

[58] Wu Kongming, Feng H, Guo Y. Seasonal abundance of the mirids, *Lygus lucorum* and *Adelphocoris* spp. (Hemiptera: Miridae) on Bt cotton in northern China[J]. Crop Protection, 2002, 21(10): 997-1002.

[59] Downes S, Mahon R J, Olsen K, et al. Monitoring and adaptive resistance management in Australia for Bt cotton: Current status and future challenges[J]. Journal of Invertebrate Pathology, 2007, 95(3): 208-213.

[60] Tabashnik B E, Gassmann A J, Crowder D W, et al. Insect resistance to Bt crops: Evidence versus theory[J]. Nature Biotechnology, 2008, 26(2): 199-202.

[61] Lu Z Z, Zalucki M P, Perkins L E, et al. Towards a resistance management strategy for *Helicoverpa armigera* in Bt cotton in northwestern China: An assessment of potential refuge crops[J]. Journal of Pest Science, 2013, 86(4): 695-703.

Note: Figure translations are in progress. See original paper for figures.