Research Article

Received: 23 December 2013 Revised: 25 August 2014 Accepted article published: 9 October 2014 Published online in Wiley Online Library: 21 November 2014

(wileyonlinelibrary.com) DOI 10.1002/ps.3923

The cumulative damage index method: a new method for evaluating the effectiveness of control measures for *Plutella xylostella* (Lepidoptera: Plutellidae)

Fang Mu,[a] Lijuan Sun,[a*] Sifang Wang,[a] Fangmeng Duan,[a] Songdong Gu,[a] Shujian Sun,[b] Yanzhou Zhang[c] and Changpeng Shen[a*]

Abstract:

BACKGROUND: All previously and currently used methods for effectiveness evaluation of control measures for the diamondback moth (DBM) do not simultaneously take the actual damage and population size into consideration. Here, we propose a new method, the cumulative damage index method, in which the number of larvae and their amount of food consumption are simultaneously included in the calculation of the theoretical cumulative damage index (*T*) and actual cumulative damage index (*A*). Evaluation was based on the reduced degree of damage calculated according to indexes *T* and *A*.

RESULTS: Based on the new method, the corrected effectiveness of the combined use of biological measures, chemical insecticides, *Bacillus thuringiensis* (*Bt*) and *P. xylostella* granulosis virus (*Px*GV) on DBM was 35.85, 2.37, 12.50 and 11.77% respectively. Under the action of natural factors, the Population Developmental Index (*I*) of DBM was 5.1 ± 1.4; under the integrated actions of natural factors and these four types of measure, index *I* of DBM was 0.34 ± 0.1, 6.1 ± 1.5, 2.1 ± 0.5 and 1.1 ± 0.3 respectively. The sole effectiveness of *Trichogramma* spp. when integrated with other natural factors, integrated biological measures and chemical insecticides was 21.43 ± 1.69%, 45.27 ± 4.09% and 20.68 ± 2.60% respectively.

CONCLUSIONS: There was some difference between the effectiveness evaluated by the new method and index *I*, and the actual damage caused by DBM could be reflected well by index *A*. The new method is more scientifically appropriate and practical for effectiveness evaluation than existing methods.

Keywords: *Plutella xylostella* (L.); effectiveness; evaluation; cumulative damage index

1 INTRODUCTION

The diamondback moth (DBM), *Plutella xylostella* (L.) (Lepidoptera: Plutellidae), is a type of pest that seriously damages cruciferous crops.[1] Measures used to control DBM include chemicals,[2–4] natural predators or parasites, physical measures, agricultural measures and integrated management, in which different measures are combined.[5–7] Effectiveness evaluations of these control measures are very important, especially for biological measures, because the evaluation of biological control will provide some information for the determination of the amount of a natural enemy to be prepared for release.

Various methods can be used to evaluate the effectiveness of pest control measures in the field.[8] Mortality or corrected mortality is the most commonly used index,[9] which can only partially indicate the transient effectiveness of control measures, and the conclusions drawn based on the two indexes are not always reliable.[10] Ruppel and Robert[11,12] suggested 'cumulative insect-days' as an index for the evaluation of the protective effect of control measures on crops. This index takes both population and damage time caused by the insect pest into consideration, and therefore it can be used as an index for overall effectiveness evaluations of pest control.[13] Zhao *et al.*[14] proposed that the 'corrected cumulative insect-days' should be used as the index for effectiveness evaluations, while Hu *et al.*[15] suggested using 'the protecting rate to foliage' for effectiveness evaluations of slow-release insecticides. None of the indexes mentioned above took into consideration the actual damage caused by pests.

Pang *et al.*[16,17] proposed the use of a life table based on effective factors and a Morris–Watt mathematical model to evaluate the

* Correspondence to: Lijuan Sun (first) and Changpeng Shen (second), Key Lab of Integrated Crop Pest Management of Shandong Province, College of Agronomy and Plant Protection, Qingdao Agricultural University, Qingdao 266109, China. E-mail: sunlijuan1975@gmail.com; cps168@hotmail.com

a Key Lab of Integrated Crop Pest Management of Shandong Province, College of Agronomy and Plant Protection, Qingdao Agricultural University, Qingdao, China

b Plant Protection Station of Laiyang Agricultural Bureau, Laiyang, Shandong Province, China

c Institute of Zoology, Chinese Academy of Science, Beijing, China

effectiveness of natural enemies and chemicals and the combined use of crop resistance and natural enemies. The authors later proposed the use of the population development trend control index and the population development trend disturbance index, which were both calculated according to the life table, to evaluate the effectiveness of the combined use of control measures.[17] On the basis of the method proposed by Pang *et al.*,[17] Wang *et al.*[18] evaluated the effectiveness of chemicals on DBM, Zhang and Pang[19] evaluated the effectiveness of *Trichogramma* spp. on DBM and Shen[20] evaluated the effectiveness of cultivar, chemicals, single biological measures and the combined use of biological measures on DBM. Subsequently, a method for constructing and analysing the continuous generation life table for DBM was presented by He and Pang.[21] Zhou *et al.*[22] improved the life table on the basis of effective factors by proposing to determine the developmental duration of DBM according to the average temperature recorded during each survey (rather than over the whole duration) and making the data analysis more accurate. Currently, the improved life table is widely accepted for effectiveness evaluations of different control measures for DBM or other defoliators,[8] and the Population Developmental Index (*I*) has been used as the main index. Index *I* is essentially the ratio of the population size of the next generation to the current generation, and is commonly calculated on the basis of the number of eggs. Based on the assumption that the base number of DBM eggs in different fields investigated is equivalent, the highest DBM egg count in a field after treatment indicates the worst possible effect of the control measures implemented in that field. In practice, there are few cases in which the base number of the DBM population in different fields is equivalent. Therefore, when the life table was used to evaluate the effectiveness of different measures, in some cases[23] index *I* appeared to be high, while the actual damage caused by DBM was less serious or index *I* was not so high, and the actual population level of DBM was very high and serious damage was caused. Thus, it is necessary to develop a new evaluation method to reflect the real situation that occurs, including the damage caused by insect pests in the field.

The objective of pest control is to reduce economic losses caused by pests. Therefore, reduced damage should be taken into consideration. Generation overlapping is a typical characteristic of the life history of DBM,[24,25] and visible damage can be caused by several different instars of larvae acting together. Damage to a crop results from the cumulative food consumption of each instar, and can be affected by the age distribution of DBM. It would not be accurate to evaluate the effectiveness solely based on population variation after treatment. The population size and food consumption of different instars of DBM larvae should be considered simultaneously. Population size data for each instar can be obtained from the life table based on effective factors, and the food consumption data can be obtained experimentally. Here, we propose a new method for evaluating the effectiveness of different control measures for DBM, which we have termed the cumulative damage index method. To verify the scientific accuracy and rationality of this new method, we have compared the results yielded by it with index *I* to determine which method could best reflect the actual damage caused by DBM in the field.

2 METHODS

2.1 The construction of a life table based on effective factors

Fields in which Chinese flowering cabbages were sown at the same time and in which the population base number of DBM differed were selected for investigation. The DBM population was

Table 1. The symbols representing data in the DBM life table, and the formulas used in calculations

Survey order n	Converted amount of eggs E_n (number m^{-2})	Converted amount of first and second instars $L_{1\&2(n)}$ (number m^{-2})	Converted amount of third instars $L_{3(n)}$ (number m^{-2})	Converted amount of fourth instars $L_{4(n)}$ (number m^{-2})	Theoretical damage index T_n	Actual damage index A_n	Control effect C_n(%)
1	E_1	$L_{1\&2(1)}$	$L_{3(1)}$	$L_{4(1)}$	–	–	–
2	E_2	$L_{1\&2(2)}$	$L_{3(2)}$	$L_{4(2)}$	$FC_{1+2}*E_{(2-1)}*S_e + FC_3*L_{1\&2(2-1)}*S_{1\&2} + FC_4*L_{3(2\text{-}1)}*S_3$	$FC_{1+2}*L_{1\&2(2)}$	$[(T_2 - A_2)/T_2]*100$
3	E_3	$L_{1\&2(3)}$	$L_{3(3)}$	$L_{4(3)}$	$FC_{1+2}*E_{(3-1)}*S_e + FC_3*L_{1\&2(3-2)}*S_{1\&2}$	$FC_{1+2}*L_{1\&2(3)} + \mathrm{FC}_3*L_{3(3)}$	$[(T_3 - A_3)/T_3]*100$
4	E_4	$L_{1\&2(4)}$	$L_{3(4)}$	$L_{4(4)}$	$FC_{1+2}*E_{1(4-1)}*S_e + FC_3*E_{(4-2)}*S_e*S_{1\&2} + FC_4*E_{(4-3)}*S_e*S_{1\&2}*S_3$	$FC_{1+2}*L_{1\&2(4)} + FC_3*L_{3(4)} + FC_4*L_{4(4)}$	$[(T_4 - A_4)/T_4]*100$
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
n	E_n	$L_{1\&2(n)}$	$L_{3(n)}$	$L_{4(n)}$	$FC_{1+2}*E_{(n-1)}*S_e + FC_3*E_{(n-2)}*S_e*S_{1\&2} + FC_4*E_{(n-3)}*S_e*S_{1\&2}*S_3$	$FC_{1+2}*L_{1\&2(n)} + FC_3*L_{3(n)} + FC_4*L_{4(n)}$	$[(T_n - A_n)/T_n]*100$

Table 2. The converted amount of each developmental stage of DBM in the life table that was investigated in one area of the Chinese flowering cabbage field without control (effectiveness of natural factors $C_c = 53.77\%$)

Survey order n	Converted amount of eggs E_n (number m^{-2})	Converted amount of first and second instars $L_{1\&2(n)}$ (number m^{-2})	Converted amount of third instars $L_{3(n)}$ (number m^{-2})	Converted amount of fourth instars $L_{4(n)}$ (number m^{-2})	Actual damage index A_n	Theoretical damage index T_n
1	9.2	1.8	0.0	0.0	–	–
2	17.2	2.6	0.0	0.0	0.37	3.14
3	34.4	6.2	1.0	0.0	1.07	3.41
4	12.8	3.6	1.6	1.2	1.62	7.83
5	3.3	1.0	1.8	1.6	1.55	7.77
6	7.8	2.2	2.6	1.5	1.81	8.25
7	11.5	2.4	2.3	1.8	1.98	3.86
8	5.2	1.0	2.6	1.0	1.31	2.82
9	14.6	2.6	1.8	1.8	1.91	3.13
10	18.6	4.8	6.4	4.6	4.98	4.67
11	43.6	8.8	7.2	10.4	9.55	4.68
12	25.2	7.2	2.6	5.4	5.10	10.27
13	68.2	14.2	3.6	2.8	4.56	10.43
14	26.2	4.8	2.2	1.8	2.30	19.89
15	132.2	29.8	4.8	7.2	9.90	13.74
Σ					48.02	103.88

Table 3. The converted amount of each developmental stage of DBM in the life table that was investigated in one area of the Chinese flowering cabbage field with integrated biological control (effectiveness of combined-use control measures integrated with natural factors $C_t = 92.87\%$)

Survey order n	Converted amount of eggs E_n (number m^{-2})	Converted amount of first and second instars $L_{1\&2(n)}$ (number m^{-2})	Converted amount of third instars $L_{3(n)}$ (number m^{-2})	Converted amount of fourth instars $L_{4(n)}$ (number m^{-2})	Actual damage index A_n	Theoretical damage index T_n
1	19.2	5.9	0.0	0.0	–	–
2	33.8	28.6	0.0	0.0	4.0	6.2
3	39.2	38.9	4.5	0.0	6.3	41.4
4	40.2	33.7	1.1	0.0	5.0	124.8
5	23.8	18.4	0.9	2.7	4.6	115.9
6	21.2	9.0	7.5	2.1	4.1	110.9
7	7.8	5.4	2.0	1.9	2.4	101.4
8	9.4	5.6	1.4	1.4	2.0	65.3
9	12.4	10.4	1.0	0.7	2.1	49.9
10	48.8	19.5	18.5	2.3	7.9	31.2
11	69.6	3.8	5.8	0.6	2.1	64.1
12	29.4	16.4	13.4	26.3	22.4	97.0
13	85.0	13.0	0.8	1.9	3.2	142.3
14	105.4	30.0	5.6	2.1	6.7	190.0
15	83.2	37.2	9.6	6.0	11.1	176.7
Σ					83.9	1317.8

investigated by random sampling (1/9 m^2) in the east, west, south, north and middle areas in a field every 3 days from the two-euphylla stage until harvest (from September to December 1996). For each survey, 45–55 individuals were randomly collected and observed daily to determine the mortality caused by parasitism in the laboratory, and the rate of natural control was calculated according to the method reported by Pang and Liang.[26] Pupae were collected and incubated in the laboratory to determine the fecundity of the DBM. Newly emerged adults were paired (one female with one male) and fed 10% honey solution. The sex ratio and fecundity of more than 20 pairs were determined.

The developmental duration of the ith stage (t_i) of DBM in the field was determined according to the temperature data provided by a local weather bureau, and the developmental duration of the experimental population was studied by Dan *et al.*[27] Data for individuals that did not survive to pupa or that did not develop from the individuals in the first survey were removed. The amount of each stage of DBM in each survey was summed to determine the cumulative amount of the ith stage N_{is}. Then, the converted amount (N_{im}) (number m^{-2}) of each stage was calculated according to formula (1),[28] the initial number of each stage (N_{ib}) was calculated according to formula (2)[26] and the survival rate (S_i) of each

Table 4. The converted amount of each developmental stage of DBM in the life table that was investigated in one area of the Chinese flowering cabbage field with chemical control (effectiveness of chemical insecticides integrated with natural factors C_t = 58.16%)

Survey order n	Converted amount of eggs E_n (number m^{-2})	Converted amount of first and second instars $L_{1\&2(n)}$ (number m^{-2})	Converted amount of third instars $L_{3(n)}$ (number m^{-2})	Converted amount of fourth instars $L_{4(n)}$ (number m^{-2})	Actual damage index A_n	Theoretical damage index T_n
1	2.0	1.0	0.2	0.2	–	–
2	1.6	1.5	0.0	0.0	0.21	0.44
3	6.1	2.0	0.0	0.0	0.28	0.54
4	8.2	0.8	0.0	0.0	0.11	1.23
5	4.7	0.6	0.0	0.0	0.08	1.68
6	2.6	0.5	0.0	0.0	0.07	2.25
7	3.3	0.4	0.0	0.0	0.06	2.20
8	3.0	0.8	0.2	0.2	0.28	1.48
9	2.0	0.5	0.3	0.2	0.26	1.07
10	3.2	1.6	0.8	0.8	0.91	1.07
11	6.8	1.8	2.5	1.6	1.80	1.10
12	9.6	0.5	0.8	2.2	1.69	1.41
13	12.2	1.2	0.2	1.5	1.20	2.20
Σ					6.97	16.65

Table 5. The converted amount of each developmental stage of DBM in the life table that was investigated in one area of the Chinese flowering cabbage field with *Bt* applied (effectiveness of *Bt* integrated with natural factors C_t = 68.64%)

Survey order n	Converted amount of eggs E_n (number m^{-2})	Converted amount of first and second instars $L_{1\&2(n)}$ (number m^{-2})	Converted amount of third instars $L_{3(n)}$ (number m^{-2})	Converted amount of fourth instars $L_{4(n)}$ (number m^{-2})	Actual damage index A_n	Theoretical damage index T_n
1	6.2	0.0	0.0	0.0	–	–
2	15.2	5.4	0.0	0.0	0.76	0.78
3	13.8	13.4	0.6	0.0	2.00	2.23
4	17.2	2.8	1.3	1.0	1.31	4.45
5	6.0	3.0	1.5	1.6	1.78	6.64
6	1.6	2.0	1.0	1.5	1.47	5.24
7	1.8	1.2	0.6	1.1	1.02	4.36
8	2.0	0.9	0.8	1.2	1.08	1.63
9	4.2	1.8	0.6	0.8	0.90	0.75
10	7.4	1.2	1.4	1.4	1.37	1.09
11	23.3	2.6	2.8	1.8	2.11	1.74
12	27.2	1.0	1.2	2.8	2.23	4.51
13	22.3	0.8	2.0	1.1	1.23	7.15
14	10.8	0.6	0.8	1.0	0.90	10.22
15	6.0	0.7	0.0	0.8	0.63	9.13
Σ					18.80	59.94

stage was calculated according to formula (3):[26]

$$N_{im} = \left(N_{is} * D\right)/t_i \quad (1)$$

$$N_{ib} = \left(t_{i-1} * N_{im} + t_i * N_{(i-1)m}\right) / \left(t_i + t_{i-1}\right) \quad (2)$$

$$S_i = N_{(i+1)b}/N_{ib} \quad (3)$$

where N_{is} represents the cumulative amount of the ith stage, D represents the intervals between two surveys, t_i represents the developmental duration of the ith stage of DBM in the field and N_{ib} represents the initial number of the ith stage.

We designated ‘400’ as the standard fecundity (F_s) of a DBM female according to the literature,[29] and the standard fecundity probability (P_F) was calculated according to formula (4). The Population Developmental Index (I) was calculated according to formula (5):[29]

$$P_F = F_a/F_s \quad (4)$$

where F_a represents the actual average fecundity of DBM females, and F_s the standard fecundity. The index of the intrinsic rate of

Table 6. The converted amount of each developmental stage of DBM in the life table that was investigated in one area of the Chinese flowering cabbage field with *Plutella xylostella* granulosis virus (*Px*GV) applied (effectiveness of *Px*GV integrated with natural factors $C_t = 69.64\%$)

Survey order n	Converted amount of eggs E_n (number m^{-2})	Converted amount of first and second instars $L_{1\&2(n)}$ (number m^{-2})	Converted amount of third instars $L_{3(n)}$ (number m^{-2})	Converted amount of fourth instars $L_{4(n)}$ (number m^{-2})	Actual damage index A_n	Theoretical damage index T_n
1	8.6	0.0	0.0	0.0	–	–
2	15.8	6.8	0.0	0.0	0.96	1.04
3	16.8	10.4	2.2	0.8	2.426	2.48
4	6.4	3.2	2.2	1.0	1.546	4.59
5	8.4	1.8	0.8	0.6	0.81	4.66
6	6.2	2.8	1.2	0.8	1.16	4.39
7	8.7	2.8	4.6	1.2	2.09	2.43
8	6.2	1.8	2.6	1.0	1.43	2.94
9	2.2	2.3	4.5	1.2	2.00	2.42
10	1.2	0.6	4.2	3.4	3.16	2.20
11	50.5	2.2	3.2	3.2	3.06	1.38
12	72.2	1.2	2.4	2.6	2.36	6.56
13	86.2	3.2	5.5	4.0	4.18	12.29
14	40.4	1.4	3.2	1.2	1.62	24.08
15	52.6	0.8	2.0	2.2	1.96	23.29
Σ	382.4	41.3	38.6	23.2	28.76	94.74

Table 7. The symbols representing data used for the effectiveness evaluation of *Trichogramma* spp. (among several functional factors) for DBM, and the design formula used for calculations

Survey order n	Converted amount of eggs E_n (number m^{-2})	Survival rate of eggs E_{T_n}	Reduced damage index R_n	Theoretical damage index T'_n	Damage control rate P_n (%)
1	E_1	E_{T_1}	$\left(1 - E_{T_1}\right) * E_1 * 1$	$E_1 * 1$	$R_1/T'_1 * 100$
2	E_2	E_{T_2}	$\left(1 - E_{T_2}\right) * E_2 * 1$	$E_2 * 1$	$R_2/T'_2 * 100$
3	E_3	E_{T_3}	$\left(1 - E_{T_3}\right) * E_3 * 1$	$E_3 * 1$	$R_3/T'_3 * 100$
⋮	⋮	⋮	⋮	⋮	⋮
$n-2$	E_{n-2}	$E_{T_{n-2}}$	$\left(1 - E_{T_{n-2}}\right) * E_{n-2} * 1$	$E_{n-2} * 1$	$R_{n-2}/T'_{n-2} * 100$

increase

$$I = S_1 * S_2 \ldots S_i \ldots S_k * F * P_F * P_♀ \quad (5)$$

where $S_1, S_2 \ldots S_i \ldots S_k$ represent the survival rate under the influence of a variety of lethal factors from egg to pupa, F represents standard fecundity (400 female^{-1}), P_F represents the probability of the standard fecundity being reached and $P_♀$ indicates the proportion of females.

The field life table of DBM was based on effective factors and constructed using the data described above.

2.2 A new method, the cumulative damage index method

According to data from the field life table of DBM based on effective factors,[20,22] the immature stage of DBM can be divided into three stages: first–second instar, third instar and fourth instar; the converted amounts (N_{im}) of eggs and first–second-instar, third-instar and fourth-instar larvae in each survey were expressed as E_n, $L_{1\&2(n)}$, $L_{3(n)}$ and $L_{4(n)}$ respectively. The food consumption and food consumption proportion of each developmental stage of DBM were quoted from the literature, as reported by Zhao *et al.*[30] The study by Zhao *et al.* indicated that the food consumption proportions of first–second instar (FC_{1+2}), third instar (FC_3) and fourth instar (FC_4) of the DBM larvae were 0.1405, 0.1962 and 0.6633, respectively, when they were fed leaves of the Chinese flowering cabbage *Brassica parachinensis* LH Bariley. The damage index was calculated as the product of N_{im} of certain developmental stages and the food consumption proportion of that stage.

2.2.1 *An evaluation of the overall effectiveness of the combined use of control measures*

The damage indexes of first-instar larvae that successfully developed from eggs in the present survey and the damage indexes of different developmental stages of larvae that successfully developed from the larvae in the present survey were combined to generate the theoretical damage index (T_n) of the next survey. The actual damage index (A_n) was the 'cumulative value' of damage indexes of different developmental stages of larvae in the present survey. Index T_n represents the damage caused by DBM solely under the control of natural factors, while A_n indicates the actual damage caused by all larvae under the control of natural and artificial factors:

$$A_n = 0, \quad T_n = 0 \quad \text{for } n = 1$$

$$A_n = FC_1 * L_{1\&2(n)}, \quad T_n = FC_1 * E_{(n-1)} * S_e \quad \text{for } n = 2$$

$$A_n = FC_1 * L_{1\&2(n)} + FC_3 * L_{3(n)}, \quad T_n = FC_1 * E_{(n-1)} * S_e + FC_3 * E_{(n-2)} * S_e * S_{1\&2} \quad \text{for } n = 3$$

$$A_n = FC_1 * L_{1\&2(n)} + FC_3 * L_{3(n)} + FC_4 * L_{4(n)},$$
$$T_n = FC_1 * E_{(n-1)} * S_e + FC_3 * E_{(n-2)} * S_e * S_{1\&2} + FC_4 * E_{(n-3)} * S_e * S_{1\&2} * S_3 \quad \text{for } n = 4$$

where n represents the order of the survey, E, $L_{1\&2(n)}$, $L_{3(n)}$ and $L_{4(n)}$ represent the converted amount (N_{im}) of eggs and first–second-instar, third-instar and fourth-instar larvae respectively, S_e, $S_{1\&2}$ and S_3 represent the survival rate of eggs and 1st–2nd-instar and third-instar larvae under the control of natural factors respectively. The control effect (%)

$$C_n = \left(T_n - A_n\right) / T_n * 100 \qquad (6)$$

where T_n represents the theoretical damage index, and A_n the actual damage index.

The symbols representing data in the field life table for DBM and the design formula used in the index calculation are described in detail in Table 1.

The cumulative theoretical damage index

$$T = \sum_{n=2}^{N} T_n \qquad (7)$$

The cumulative actual damage index

$$A = \sum_{n=2}^{N} A_n \qquad (8)$$

The cumulative control effect (%)

$$C_t = \left[(T - A) / T\right] * 100 \qquad (9)$$

where T_n represents the cumulative theoretical damage index, A_n represents the cumulative actual damage index and N represents the total number of investigations.

The DBM life table data were collected from different Chinese flowering cabbage fields, calculated and listed in tables according to the design formula shown in Table 1. The life table data for DBM in a field without control, in a field with combined biological control, in a field with chemical control, in a field with *Bacillus thuringiensis* (*Bt*) implemented and in a field with *Plutella xylostella* granulosis virus (*Px*GV) implemented, along with the indexes, are listed in Tables 2 to 6 respectively. The cumulative control effects in the control field (C_c) and in the treated fields (C_t) were calculated according to formula (9). For the corrected effectiveness of the different control measures, see Table 12.

Table 8. The symbols representing data used for effectiveness evaluations of single factors (among several functional factors) that act upon more than one developmental stage of DBM, and the design formulas used for calculations

Survey order n	Converted amount of first and second instars $L_{1\&2(n)}$ (number m^{-2})	Converted amount of third instars $L_{3(n)}$ (number m^{-2})	Converted amount of fourth instars $L_{4(n)}$ (number m^{-2})	Reduced damage index R_n	Theoretical damage index T'_n	Damage control rate P_n (%)
1	$L_{1\&2(1)}$	$L_{3(1)}$	$L_{4(1)}$	–	–	–
2	$L_{1\&2(2)}$	$L_{3(2)}$	$L_{4(2)}$	$L_{1\&2(2)}*M_{1\&2(2)}*FC_{1+2}$	$L_{1\&2(2)}*FC_{1+2}*S_{1\&2}$ [a]	R_2/T'_2*100
3	$L_{1\&2(3)}$	$L_{3(3)}$	$L_{4(3)}$	$L_{1\&2(3)}*M_{1\&2(3)}*FC_{1+2} + L_{3(3)}*M_{3(3)}*FC_3$	$L_{1\&2(3)}*FC_{1+2}*S_{1\&2} + L_{3(3)}*FC_3*S_3$	R_3/T'_3*100
4	$L_{1\&2(4)}$	$L_{3(4)}$	$L_{4(4)}$	$L_{1\&2(4)}*M_{1\&2(4)}*FC_{1+2} + L_{3(4)}*M_{3(4)}*FC_3 + L_{4(4)}*M_{4(4)}*FC_4$	$L_{1\&2(4)}*FC_{1+2}*S_{1\&2} + L_{3(4)}*FC_3*S_3 + L_{4(4)}*FC_4*S_4$	R_4/T'_4*100
⋮	⋮	⋮	⋮	⋮	⋮	⋮
n	$L_{1\&2(n)}$	$L_{3(n)}$	$L_{4(n)}$	$L_{1\&2(n)}*M_{1\&2(n)}*FC_{1+2} + L_{3(n)}*M_{3(n)}*FC_3 + L_{4(n)}*M_{4(n)}*FC_4$	$L_{1\&2(n)}*FC_{1+2}*S_{1\&2} + L_{3(n)}*FC_3*S_3 + L_{4(n)}*FC_4*S_4$	R_n/T'_n*100

[a] $S_{1\&2}$, S_3 and S_4 represent the survival rate of eggs and first–second-instar, third-instar and fourth-instar larvae (excluding the mortality caused by predation and climate factors).

Table 9. The converted amount of DBM eggs in the life table found in one area of the Chinese flowering cabbage field without control, and the indexes for effectiveness evaluations of *Trichogramma* spp. ($P_c = 22.09\%$)

Survey order n	Converted amount of eggs E_n (number m^{-2})	Survival rate of eggs E_{T_n}	Reduced damage index R_n	Theoretical damage index T_n	Damage control rate P_n (%)
1	8.2	1.0000	0.00	8.2	0.00
2	17.8	1.0000	0.00	17.8	0.00
3	19.8	0.9755	0.49	19.8	2.45
4	17.6	0.8232	3.11	17.6	17.68
5	3.6	0.9527	0.17	3.6	4.73
6	9.6	0.8286	1.65	9.6	17.14
7	13.2	1.0000	0.00	13.2	0.00
8	5.4	1.0000	0.00	5.4	0.00
9	14.6	0.7712	3.34	14.6	22.88
10	24.6	0.8116	4.63	24.6	18.84
11	39.2	0.6810	12.50	39.2	31.90
12	30.2	0.7264	8.26	30.2	27.36
13	68.8	0.6210	26.08	68.8	37.90
Σ			60.23	272.6	

Table 10. The converted amount of DBM eggs in the life table found in one area of the Chinese flowering cabbage field with integrated biological control, and the indexes for effectiveness evaluations of *Trichogramma* spp. ($P_c = 46.18\%$)

Survey order n	Converted amount of eggs E_n (number m^{-2})	Survival rate of eggs E_{T_n}	Reduced damage index R_n	Theoretical damage index T_n	Damage control rate P_n (%)
1	25.4	0.9848	0.39	25.4	1.52
2	40.6	0.7010	12.14	40.6	29.90
3	49.6	0.5130	24.16	49.6	48.70
4	49.4	0.5832	20.59	49.4	41.68
5	30.4	0.4032	18.14	30.4	59.68
6	26.2	0.3020	18.29	26.2	69.80
7	10.4	0.5162	5.03	10.4	48.38
8	14.6	0.4425	8.14	14.6	55.75
9	17.4	0.6538	6.02	17.4	34.62
10	62.6	0.7064	18.38	62.6	29.36
11	68.6	0.3802	42.52	68.6	61.98
12	34.8	0.6346	12.72	34.8	36.54
13	104.2	0.4186	60.58	104.2	58.14
Σ			246.71	534.2	

The corrected effectiveness (%) was calculated according to the formula

$$E_c = \left[\left(C_t - C_c\right)/C_c\right] * 100 \qquad (10)$$

where C_t represents the control effect in the treated fields, and C_c the control effect in the control field.

2.2.2 An evaluation of the effectiveness of one of the factors

In each survey, individual DBM were randomly sampled from each area of the field and observed in the laboratory to determine the mortality (M_i) caused by parasitism. Therefore, the effectiveness of any one of the parasitic factors could be evaluated using the cumulative damage index method. Here, effectiveness evaluation of the parasite of the eggs of DBM, *Trichogramma* spp., in a Chinese flowering cabbage field was used as an example, and the symbols representing data used for the effectiveness evaluation and the design formula used in those calculations are listed in Table 7.

If an egg was parasitised, it could not develop to a first-instar larva and would not cause any damage, so the remaining food consumption equalled ‘1’, which made the effectiveness evaluation relatively straightforward. Most of the eggs in the final two surveys could not complete larval development, and the damage caused by them could be neglected. Furthermore, the vegetables were about to be harvested, so the damage caused by lower-instar larvae should be neglected too. Therefore, when calculating the cumulative damage index, the possible damage caused by eggs and lower-instar larvae in the last two surveys should not be included in the calculation. If the factor to be evaluated could only act on a certain developmental stage of DBM, the index used for the effectiveness evaluation could be calculated in the manner described above (Table 7). For those factors that could act on different developmental stages of DBM, such as *Bt* or fungus, the index could be calculated according to Table 8.

Table 11. The converted amount of DBM eggs in the life table found in one area of the Chinese flowering cabbage field with chemical control, and the indexes for effectiveness evaluations of *Trichogramma* spp. ($P_c = 21.79\%$)

Survey order n	Converted amount of eggs E_n (number m^{-2})	Survival rate of eggs E_{T_n}	Reduced damage index R_n	Theoretical damage index T_n	Damage control rate P_n (%)
1	1.46	0.7634	0.35	1.46	23.66
2	1.34	0.9282	0.10	1.34	7.18
3	4.60	0.9085	0.42	4.60	9.15
4	7.20	0.8250	1.26	7.20	17.50
5	3.50	0.6545	1.21	3.50	34.55
6	1.80	0.9132	0.16	1.80	8.68
7	2.20	0.8632	0.30	2.20	13.68
8	2.40	0.9240	0.18	2.40	7.60
9	1.80	0.9760	0.04	1.80	2.40
10	2.80	0.6415	1.00	2.80	35.85
11	6.20	0.8616	0.86	6.20	13.84
12	8.80	0.7654	2.06	8.80	23.46
13	11.2	0.6025	4.45	11.2	39.75
Σ			12.05	55.3	

Table 12. A comparison between the effectiveness evaluated by two methods

Control measures	Average converted amount of larvae per square metre	Average actual cumulative damage index *A*	Effectiveness (%)	Corrected effectiveness E_c (%)	Population Developmental Index *I*
Integrated biological control	53.7 ± 10.2 aA[a]	16.45 ± 1.83 cBC	93.29 ± 1.49 aA	35.85	0.3 ± 0.1 cB
*Px*GV	33.8 ± 5.1 abAB	30.40 ± 8.82 bAB	69.21 ± 4.74 bcBC	11.77	1.1 ± 0.3 bcB
Bt	17.0 ± 2.8 cdBC	18.87 ± 4.27 bcBC	69.94 ± 5.15 bB	12.50	2.1 ± 0.5 bB
Chemical control	6.1 ± 1.6 dC	12.56 ± 3.12 cC	59.81 ± 6.33 cC	2.37	6.1 ± 1.5 aA
Control	27.3 ± 8.5 bcB	46.17 ± 12.31 aA	57.44 ± 5.99 dC	–	5.1 ± 1.4 aA
df	4	4	4	–	4
F	17.886	17.798	39.581	–	35.316

[a] The SPSS 11.5 program was used to analyse data. Different lower- and upper-case letters indicate significant differences between various average converted amounts of larvae per square metre, average actual cumulative damage index, effectiveness of different measures and values of index *I* in different fields at $P < 0.05$ and $P < 0.01$ respectively.

The reduced damage index (R_n) due to the death of larvae during certain instars in survey *n* was calculated according to the following design formula:

$$R_n = N_{im(n)} * M_{i(n)} * FC_i \qquad (11)$$

where $N_{im(n)}$ represents the converted amount of *i*th stage in survey *n*, $M_{i(n)}$ represents the mortality of the *i*th stage of DBM caused by the factor to be evaluated in survey *n* and FC_i represents the food consumption proportion of the *i*th stage.

The population size of DBM was investigated in different fields. According to the design formulas listed in Table 4, data obtained from a field without control, a field with integrated biological control and a field with chemical control were calculated, and the results are listed in Tables 9 to 11. The cumulative damage control rate (%) was calculated according to the formula

$$P_c = \left(\sum_{n=1}^{N-2} R_n / \sum_{n=1}^{N-2} T'_n \right) * 100 \qquad (12)$$

where *i* represents the order of survey, R_i represents the reduced damage index and T'_i represents the theoretical damage index.

3 RESULTS

3.1 Effectiveness evaluations using the cumulative damage index method

3.1.1 Evaluation of the overall effectiveness of the combined use of control measures

According to the design formulas in Table 1, the life table data for DBM were obtained in different fields to assess integrated biological control (the combined use of *Trichogramma* spp., *Bt* and granular virus), chemical control, *Bt* and *Px*GV. Data were calculated separately and are given in Tables 2 to 6.

From Table 12 we can see that the effectiveness of natural factors in the field without control was 57.44 ± 5.99%; when integrated with natural factors, the effectiveness of the combined use of biological measures, chemical insecticides, *Bt* and *Px*GV was 93.29 ± 1.49%, 59.81 ± 6.33%, 69.94 ± 5.15% and 69.21 ± 4.74% respectively; the corrected effectiveness of the four control measures was 36.84, 2.96, 14.31 and 11.91% respectively (Table 12).

3.1.2 *Evaluation of the effectiveness of one of the control factors*

The effectiveness of *Trichogramma* spp. in different fields is shown in Table 13. We established that DBM eggs sampled for observation in the laboratory were mainly parasitised by *Trichogramma bilingensis* if *T. confusum* was not artificially released. The effectiveness of *Trichogramma* spp. in the field without control was 21.43 ± 1.69%; in the field with biological control it was 45.27 ± 4.09% after the artificial release of *T. confusum*; in the field with biological control it was 20.68 ± 2.60%. The parasitism rate of *Trichogramma* spp. in the field without control and in the field with chemical control did not differ ($F = 111.185$, df = 2, $P < 0.01$) (Table 13). The effectiveness of *Trichogramma* spp. on DBM was most apparent in the late periods of crop development (Tables 9 to 11).

3.2 A comparison of the effectiveness evaluated by the cumulative damage index method with index *I*

Index *I* was calculated on the basis of the life table of DBM, and the corrected effectiveness was calculated according to our new method, the cumulative damage index method, as shown in Table 12. It appeared that, in evaluation based on index *I*, the chemical insecticides scarcely affected DBM, because the population of DBM multiplied 6.1 ± 1.5-fold, and index *I* of the DBM population in the field with chemical control did not differ from index *I* (5.1 ± 1.4-fold) in the field without control ($F = 35.316$, df = 4, $P < 0.05$). However, when evaluated according to index *C*, which was calculated on the basis of the cumulative damage indexes *A* and *T*, the chemical insecticides were obviously effective, with a corrected effectiveness of 2.37%. After treatment, index *I* of DBM was highest in the field with chemical control, while the actual population level in that field was lowest ($F = 17.886$, df = 4, $P < 0.01$), as it was further away from the turnip field (see the Appendix).[20] Although index *I* and the cumulative damage index can both reflect the superiority of *Bt* and integrated biological measures over chemicals ($F = 39.581$, df = 4, $P < 0.01$), index *I* could not reflect the actual damage of DBM in different fields any better than index *A* included in the new method (Table 12). We also found that the effectiveness of integrated biological control did not differ from the effectiveness of *Bt* and *Px*GV when evaluated on the basis of index *I* ($F = 35.316$, df = 4, $P < 0.01$), but differed when evaluated on the basis of the cumulative damage index method ($F = 39.581$, df = 4, $P < 0.05$). Thus, our new method – the cumulative index method – could provide more information in effectiveness evaluations of control measures, and therefore yield evaluations that had a more scientifically appropriate basis.

4 DISCUSSION

The cumulative damage index not only represents the converted amount of larvae that successfully survive to the next stage per unit area but also reflects the actual damage per unit area during individual and global surveys. By using the cumulative damage index to evaluate the effectiveness of different measures on DBM, we could adequately utilise life table data and make more accurate evaluations. By this method, the amount of each instar of DBM larvae and the amount of damage caused by them were combined to evaluate the reduced damage that resulted from the implementation of control measures, and the cumulative damage index could provide additional information about actual damage to DBM. This method not only can be used to evaluate the overall effectiveness of the combined use of control measures but also can indicate the effectiveness of single measures or one of the measures during certain or all growing seasons of crops. Additionally, the cumulative damage index could reflect the effectiveness of different measures during different periods, and it is helpful for understanding the sensitive period of DBM to control measures.

Biological control is an indispensable means of integrated pest management,[7,31] but reasonable evaluations of biocontrol have always been a challenge in the domain of pest control. For example, *Trichogramma confusum* and *Diadromus collaris* are both natural enemies of DBM, but when used as control measures, their protective effects on crops are clearly different. *T. confusum* can parasitise the eggs of DBM[31] and result in the eggs failing to develop to larvae, and thus it will not cause any damage. *D. collaris* is parasitic to DBM pupae,[1,32–35] and although it can eventually kill an individual, the damage had already been caused. If the effectiveness was evaluated using index *I* calculated according to the life table, there seemed to be no difference between the killing of eggs by *Trichogramma* spp. and pupae by *D. collaris*. Therefore, the intrinsic index of increase could not reflect the protective effects of different parasitic wasps to crops.

The converted amount of each developmental stage that was used in the new method was calculated on the basis of the developmental duration, which was determined according to the study of Dan *et al.*[27] and the average temperature recorded during each survey.[22] The developmental duration of DBM in the study of Dan *et al.* was determined using a constant temperature, which is different from the conditions in the field. In the field, the developmental duration of DBM is influenced not only by temperature but also by other biological and abiotic factors. For example, virus infection[36] and chemicals[37] often change the developmental duration of certain larval stages, and therefore change the amount of damage. The food consumption data quoted from the literature were measured using Chinese flowering cabbage seedlings as material, so further studies will be needed to confirm whether these data are suitable for effectiveness evaluations at a later period of crop development.

The cumulative damage index method is a new method for evaluating the effectiveness of different measures to control leaf-consuming insect pests, but is not suitable for evaluating juice-sucking insect pests.

ACKNOWLEDGEMENTS

This project was supported financially by the Chinese National Science Foundation (31272044), the Special Project of Public Welfare Agriculture Research of China (201103021), the Science and Technology Supporting Project of the National 'Eleventh Five-Year' Plan of China (2008BADA5B02), the High-level Personnel Start-up Funds of Qingdao Agriculture University (630737), the Key Project of the Knowledge Innovative Programme of the Chinese Academy of Science (KSCX2-YW-NF-02) and the Tai-Shan Scholar Construction Foundation of Shandong Province.

APPENDIX

Table A1

The distance of different experimental Chinese flowering cabbage fields from the radish field

Breeds that were sown in the fields	Treatment	Distance from radish field (m)
Raphanus sativus L.	Control	–
Brassica parachinensis LH Bariley	Control	50
Brassica parachinensis LH Bariley	*Px*GV	50
Brassica parachinensis LH Bariley	Integrated control	10
Brassica parachinensis LH Bariley	*Bt*	70
Brassica parachinensis LH Bariley	Chemical control	500

REFERENCES

1 Talekar NS and Shelton AM, Biology, ecology and management of the diamondback moth. *Annu Rev Entomol* **38**:275–301 (1993).
2 Sial AA and Brunner AJ, Lethal and sublethal effects of an insect growth regulator pyriproxyfen on obliquebanded leafroller (Lepidoptera: Tortricidae). *J Econ Entomol* **103**:340–347 (2010).
3 Nehare S, Ghodki BS, Lande GK, Pawade V and Thakare AS, Inheritance of resistance and cross resistance pattern in indoxacarb-resistant diamondback moth *Plutella xylostella* L. *Entomol Res* **40**:18–25 (2010).
4 Santos VC, de Siqueira HAA, da Silva JE and de Farias MJDC, Insecticide resistance in populations of the diamondback moth, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae), from the state of Pernambuco, Brazil. *Neotrop Entomol* **40**:264–270 (2011).
5 Liu F, Sun LB,Yao JL and Wu QJ, Evaluation of the trapping efficacy of different sex pheromone lures to *Plutella xylostella* (L.) and the monitoring of its population dynamics. *J Plant Prot* **37**(5):210–212 (2011).
6 Hooks CRR and Johnson MW, Impact of agricultural diversification on the insect community of cruciferous crops. *Crop Prot* **22**:223–238 (2003).
7 Endersby NM and Morgan WC, Alternatives to synthetic chemical insecticides for use in crucifer crops. *Biol Agric Hort* **8**:33–52 (1991).
8 You MS and Wei H, *Study on Diamondback Moth, Plutella xylostella L.* Chinese Agriculture Publishing House, Beijing, China (2007).
9 Xue M, Mao YX and Li Q, Study on the biological character and insecticide controlling of *Plutella xylostella* L. *J Laiyang Agric Coll* **11**(Suppl.):137–140 (1994).
10 Huang FK, Reviews of evaluation methods to pest control effect. *J Guangxi Agric* (**4**):34–36 (1990).
11 Ruppel RF, Cumulative insect-days as an index of crop protection. *J Entomol* **76**(2):375–377 (1983).
12 Ruppel RF, Model for effective timing of an insecticide. *J Econ Entomol* **77**:1083–1085 (1984).
13 Chi H, Timing of control based on the stage structure of pest populations: a simulation approach. *J Econ Entomol* **83**(4):1143–1150 (1990).
14 Zhao SH, Chen WK, Zhang X, Pan WL and Zhang JY, Recent advances in studies on field toxicology of insecticides. *J South China Agric Univ* **12**(4):1–4 (1991).
15 Hu S, Xu HH, Zhang ZX, Chen XJ and Cheng DM, Application of leaf protection rate to bioassay of insecticides. *Plant Prot* **32**(4):100–103 (2006).
16 Pang XF, On the suppression of pest population and evaluation of pest control effect. *J Guangdong Agric* (**4**):35–40 (1979).
17 Pang XF, Liang GW and You MS, Control effects of the spiders on rice leaf roller life system. *J South China Agric Univ* **9**(1):16–23 (1988).
18 Wang WZ, Chen WP, Tao FL and Wu WJ, Life tables of diamondback moth (DBM), *Plutella xylostella* (L.), and evaluation of insecticides. *J South China Agric Univ* **13**(4):77–80 (1992).
19 Zhang ML and Pang XF, Question on using *Tritrogramma* to control diamondback moth, *Plutella xylostella* (L.). *Ecol Sci* **2**:84–87 (1995).
20 Shen CP, Studies on the problems and tactics of chemical insecticide control to diamondback moth *Plutella xylostella* (L.). *PhD Thesis*, South China Agriculture University, Guangdong, China (1997).
21 He YR and Pang XF, Construction and analysis of the natural population life table for continuous generation of the diamondback moth, *Plutella xylostella* L. *J South China Agric Univ* **21**(1):34–37 (2000).
22 Zhou HX, ZL Yuan, SD Gu, Sun SJ, Wang SF and Zheng CY, Life table of *Plutella xylostella* (L.) in which duration of each stage was determined by temperature during each survey. *J Environ Entomol* **33**(4):448–455 (2011).
23 Southwood TRE, *Ecological Method with Particular Reference to the Study of Insect Populations*. Methuen, London, UK (1978).
24 Hardy JE, *Plutella maculipennis* Curt, its natural and biological control in England. *Bull Entomol Res* **29**:342–372 (1938)
25 Staley JT, Girling RD, Stewart-Jones A, Poppy GM, Leather SR and Wright DJ, Fertilizer affects the behaviour and performance of *Plutella xylostella* on brassicas. *Agric For Entomol* **11**:275–282 (2009).
26 Pang XF and Liang GW, *Systematic Pest Control*. Guangdong Science and Technology Publishing House, Guangdong, China (1995).
27 Dan JG, Liang GW and Pang XF, Studies on the laborotory population of diamondback moth under different temperatures. *J South China Agric Univ* **16(3):** 11–16 (1995).
28 Southwood TRE and Jepson WF, Studies on the populations of *Ocinella frit* L. (Dipt: Chloropidae) in the oat crop. *J Anim Ecol* **31**:481–495 (1962).
29 Lü LH, He YR and Pang XF, Effects of cruciferous vegetables on experimental population of diamondback moth *Plutella xylostella*. *Chin J Appl Ecol* **14**(10):1732–1734 (2003).
30 Zhao SM, Liu H, Guo MF and Huang SH, The measurement and mathematic model on feeding amount of *Plutella xylostella* larvae to the leaf of *Brassica parachinensis*. *J Environ Entomol* **33**(3):414–417 (2011).
31 Talekar NS, Biological control of diamondback moth in Taiwan – a review. *Plant Prot Bull* **38**:167–189(1996).
32 He YR and Pang XF, Species and natural parasitism of *Trichogramma* on the diamondback moth, *Plutella xylostella*, in Shengzhen, China. *Nat Enemies Insects* **22**(1):1–5 (2000).
33 Hu JF and Zhao SX, Selective toxicities of several insecticides to the diamondback moth such as *Plutella xylostella* and its parasitoids, *Cotesia plutellae* and *Oomyzus sokolowskii*. *J Fujian Agric For Univ Nat Sci Edn* **32**(4):443–446 (2003).
34 Wang XG, Liu SS, He JH and Guo SJ, Investigations on parasitoids of diamondback moth in the suburb areas of Hangzhou. *J Plant Prot* **25**(3):20–26 (1998).
35 Ke LD and Fang JL, Studies on the biology of the braconid wasp, *Apanteles plutellae* Kurdjumov. *J Plant Prot* **9**(1):27–34 (1982).
36 Lü LH, He YR, Feng X, Chen HY, Impact of a granulosis virus on larval food consumption and development duration of the diamondback moth, *Plutella xylostella* (L.), in ed. by Endersby NM, Ridland PM. *The management of diamondback moth and other crucifer pests. Proceedings of the Fourth International Workshop*, Melbourne, Australia, pp. 26–29 (2001).
37 Han WS, Ren CC, Yan HY, Zhang SF, Shen FY, Gao XW, Sublethal effects of metaflumizone on abamectin-resistant and susceptible strains of the diamondback moth, *Plutella xylostella* (Lepidoptera: Plutellidae). *Acta Entonologica Sinica* **55**(6): 694–702 (2012).