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Efficient predation modeling of three predator species on two apple aphids

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Abstract
The purpose of this study was to estimate the predatory effect of *Coccinella septempunctata* L. and *Adalia bipunctata* L. and *Orius insidiosus* (Say), on apple aphids *Aphis pomi* DeGeer and *Dysaphis plantaginea* Passerini. In laboratory conditions, small clear plastic cages were used. Each predator species was fed separately by the two aphid species. One single female predator corresponded to a prey of 10, 15, 20, 25, 30 individuals per cage and survivor of prey was counted. The adult female predators were starved before the introduction. All predators showed no indications of hunger satiation exhibiting a linear model of effective predation until 1/30 predator/prey ratio and thus predation was considered effective. The two coccinelid species used, and especially *C. septempunctata*, were more effective predators than *O. insidiosus*. Furthermore, a machine learning model was produced, based on current dataset and the J48 classification method, to assist us in future data modeling processes.

Keywords: predators, effective predation, model, machine learning

1. Introduction

Apple aphids are considered very harmful enemies, causing direct damages on fruits in case of increased populations (Oatman & Legner, 1961) [28], but they also can cause indirect damages by virus infects (Cho *et al*., 2016) [4], decreasing also tree robust (Hamilton *et al*., 1986) and photosynthesis levels (Kaakeh *et al*., 1992) [19]. Aphids also can cause direct damages on leaves and other parts of the trees, resulting in crop lose with negative economic impact (Graf, 1984) [14].

In Greece, two main aphids' species are known to cause damages on apple trees (Deligeorgidis *et al*., 2013) [9]. The adult of *Dysaphis plantaginea* (Passerini) (Hemiptera: Aphididae) which apterous form is about 2.5 mm long, is globe-shaped and purplish to mauve covered with a whitish pubescence. The winged adult is dark green to brown. This species is harmful only to apple trees (*Malus* spp.). This aphid has 6-9 generations per year, 4 on apple trees where colonies develop usually in early spring migrating up to late July. Winged adults return to apple trees in September. It causes damages on leaves and leaf dropping, resulting even in dropping of fruits. Migration of aphids may result in wide virus spreading. The green apple aphid *Aphis pomi* DeGeer (Hemiptera: Aphididae) is a smaller species 1.5 to 2 mm long, green in colour for apterous adult forms and green to black for winged adult forms. Main host plants are the apple trees, but it can be found also other trees. It has 10-15 generations per year. The most apparent damages occur on leaves, but occasionally aphids feed on immature apples, which may become malformed. Damages are more severe on nurseries.

Insect predator species and parasitoids of arthropods are recorded for their importance to handle insect populations below economic damage levels in various ecosystems (Losey & Vaughan, 2006; Landis *et al*., 2008; Schipanski *et al*., 2016; Zhao *et al*., 2016) [23, 21, 35, 42]. In general, biological control has been proved an effective method for handling pest populations, using bacteria, fungi, nematodes, other insects etc (Machar & Drobilova, 2012) [25]. Useful insects are considered the most common predators (in a location) of harmful prey (Ogurlu, 2000) [30].

Predator-prey interactions within a certain ecosystem, is considered essential for handling harmful insects (Evans & England, 1996) [10]. This complex relationship is depended mainly on the efficiency of predators, because a biological control program depends on a successful introduction and action of predators. Thus, the efficiency of predators is a prerequisite for choosing the correct predator species (Deligeorgidis 2002; Deligeorgidis *et al*., 2005a; 2005b) [6, 7]. There are many insect families to be used as predators in order to control harmful species, like Anthocoridae, Coccinellidae, Chrysopidae, Hemerobiidae (Onillon, 1990) [32].

Coccinellidae family is one of the most common in biological control programs, being used against aphids, thrips and whiteflies (Gerling, 1990; Holmer *et al*., 1993; Mari *et al*., 2005; Solagni & Lohar, 2005) [12, 16]. Especially the species *Coccinella septempunctata* L. and *Adalia bipunctata* L. (Coleoptera: Coccinellidae) are the most useful, being used against many prey species (Gordon, 1985; Obrycki & Kring, 1998; Iperti, 1999; Deligeorgidis *et al*., 2005a; 2005b; Omkar & Pervez, 2005) [13, 29, 17, 6, 7, 31]. Another species known for its capability to control harmful insects is *Orius insidiosus* (Say) (Hemiptera: Anthocoridae) which is fed by too many prey species and nectar as well (Bugg, 1987; Pumarino *et al*., 2012; Wong & Frank 2013) [3, 34, 41]. *O. insidiosus* is a very polyphagous predator, with extreme mobility and satisfactory efficiency (Isenhour & Yeargan, 1981; Van de Veire & Degheele, 1995; Nemec *et al*., 2016; Tran *et al*., 2016; Bernardo *et al*., 2017; Bannerman *et al*., 2018) [18, 39, 27, 37, 2, 1].

Modeling of predatory efficiency is essential for applying a successful biological control program and previous work on this concept was summarized by Deligeorgidis *et al*. (2005a;

2005b; 2011; 2013) [6-9]. These references were based mainly on predator/prey interactions and predator/prey ratio. Machine learning was used to help companies to find and achieve their main financial targets (Witten & Frank 2005) [40]. Artificial Intelligence and, more specifically, machine learning have been used in workforce analytics, or by using unsupervised latent models for estimating a matching score between employees and activities (Luo *et al*., 2019) [24]. Predictions based on machine learning and modeling may be implemented in biological procedures to assist researchers in future biological models by setting the limits of their models (Kalamatianos *et al*., 2018) [20].

The purpose of this experimental study was to estimate the predatory effect of *C. septempunctata*, *A. bipunctata* and *O. insidiosus*, on apple aphids *A. pomi* and *D. plantaginea*, based on previous work of modeling of predator behaviour. Furthermore, a machine learning model was produced to support us in future data processes. This research work introduces the combination of classical approach of biological modeling and newer techniques based on machine learning procedures.

2. Materials and Methods

In order to estimate the predatory effect of the three predator species: *Coccinella septempunctata* L., *Adalia bipunctata* L. (Coleoptera: Coccinellidae) and *Orius insidiosus* (Say) (Hemiptera: Anthocoridae), on two apple tree (*Malus domestica* Borkh) aphids which were used as a prey, *Aphis pomi* DeGeer and *Dysaphis plantaginea* Passerini (Hemiptera: Aphididae). In laboratory conditions, small clear plastic cages (12x12x6 cm) were used. The upper open side was covered by muslin cloth (0.06 mm) as described by Deligeorgidis *et al*. (2011; 2013) [8, 9].

Each predator species was fed separately by the two aphid species in the cages in order to avoid interactions (Deligeorgidis *et al*., 2013) [9]. Aphids in the cages were kept on apple tree leaves (cultivar Red Chief). All cages were held in fully controlled environment at a temperature of 26 ± 3°C, 66 ± 2% relative humidity (RH) and 16h light: 8h dark photoperiod with intensity of light 9000 Lux. One single female predator was introduced into each cage and corresponded to a prey number of 10, 15, 20, 25, 30 aphid individuals per cage· survivor of prey was observed each day. Eight replications were used for each treatment (predator/prey ratio) for all predators and aphids species in an experimental scheme: 3 predators x 2 aphids x 5 predator/prey ratio x 8 replications, and also 10 control cages in absence of predators were also used for each of the two prey species with 10, 15, 20, 25 or 30 aphids per cage, where no mortality was observed for the test period (Deligeorgidis *et al*. (2011; 2013) [8, 9]. The adult female predators used, were starved for 24h before the introduction into the cages. Experimental application and model implementation were based on Deligeorgidis *et al*. (2005a; 2005b; 2011) [6, 7, 8] findings. Means, standard deviations and mean errors were computed from original data (Deligeorgidis *et al*. (2005a; 2005b; 2011) [6, 7, 8]. Mean predatory effect and aphid escapes (as the difference between total prey number and aphids consumed by the predator) were also calculated and a correlation model was applied (adapted from Deligeorgidis *et al*., 2005a; 2005b) [6, 7].

Artificial intelligence model was based on machine learning open software WEKA 3.8.4 (University of Waikato). Classification was based on J48 tree classifier algorithm and four classes were determined by users (FULL for high efficiency of predators, SAT for satisfactory efficiency,
GOOD for limited efficiency and, NO for very low efficiency, as determined in previous research work of Deligeorgidis *et al*. 2005a; 2005b; 2011) [6, 7, 8]. C4.5 (or J48) is an algorithm used to generate a decision tree developed by Ross Quinlan (Panigrahi & Borah, 2018). C4.5 is an extension of Quinlan's earlier ID3 algorithm. The decision trees generated by C4.5 can be used for classification, and for this reason, C4.5 is often referred to as a statistical classifier. Main classes were distinguished by the WEKA software and the visual relations between main attributes (predator and prey species at different aphid populations) were also calculated. First-time classification is used to train the basic algorithm how to handle future data and how to create new classes within the limits set. Algorithm re-evaluated original model on a projection to 1/40 predator/prey proportion for *A. bipunctata* on *A. pomi*. New data for evaluation was retrieved from a special cage at 1/40 predator/prey proportions. In any case original data were used and the parameters used were the default selection.

3. Results

Killed prey (*A. pomi* και *D. Plantaginea*) by the three predators *C. septempunctata*, *A. bipunctata* and *O. insidiosus*, are presented in three respective three tables (1, 2 and 3). In general, all predators consumed greater numbers of *A. pomi* than *D. plantaginea* as shown in the general means, which are 16.35, 15.75 and 13.475 for *A. pomi* and the three predators respectively, and 15.375, 14.975 and 11.50 for *D. plantaginea* and the three predators respectively. More detailed, in case of predator/prey ratio 1/10, all the aphids were consumed except in case of the predator *O. insidiosus*, where some aphids escaped.

The upper limit of consumption (effective predation) was determined for the most effective predator, *C. septempunctata*, where 182 in total aphid individuals were consumed for all replications and the mean was 22.75 at 1/30 predator/prey ratio. General means were found at 16.35 and 15.375 for the two aphid species consumed by *C. septempunctata*.

Also, three figures (1, 2 and 3) present the predation model of the three predators, where it is clearly shown a linear model with high correlation coefficients (over 0.97 and in some cases almost 1, statistically significant at 0.01 level). Escapes to consumed individuals showed a crossing point only in the case of *O. insidiosus*.

Figure 4 presents classification of data instances for all ratio and predators/prey, in J48 tree classifier algorithm. The precision of machine learning process reached 80% (number of correctly classified instances %), especially for highly efficient cases (FULL, SAT, GOOD) based on F-metrics. Figure 5 presents visualization of data between predator/prey proportions (1/10, 1/15, 1/20, 1/25, 1/30) and efficiency of predation distribution, while Figure 6 presents the relation of efficiency of predation between the two kind of aphids *Aphis pomi* and *Dysaphis plantaginea* (distribution of all cases). Figure 7, presents the main model for *Aphis pomi*, with a limit of 16.375 individuals that may be consumed by the probable predators (tested in this research). Figure 8, presents possible predation curve after re-evaluation of original model on a projection to 1/40 predator/prey proportion for *Adalia bipunctata* on *Aphis pomi*. It is possible that after 1/25 to 1/30 linear curve is distorted in a second-degree model.

Table 1: Predatory effect of female adult *Coccinella septempunctata*, on female adults of *Aphis pomi* and *Dysaphis plantaginea*, under controlled conditions.

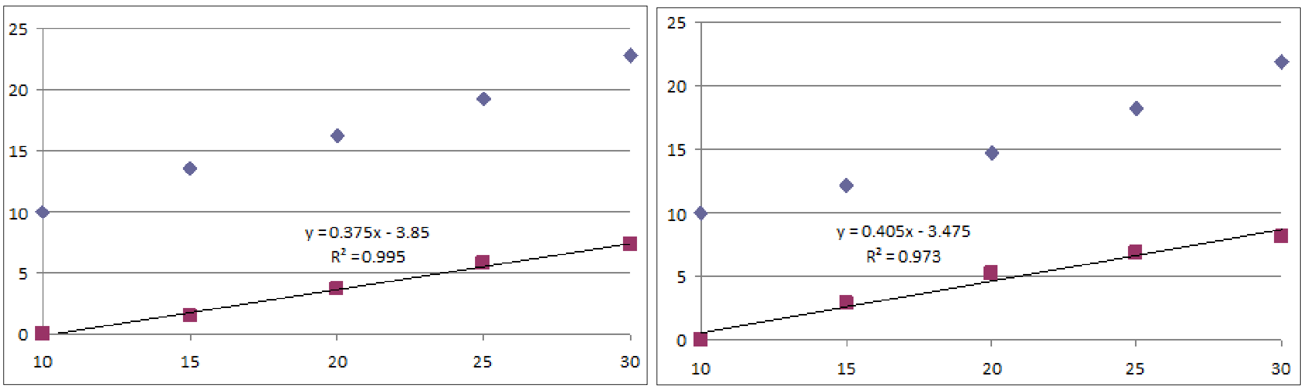
	No of Aphis pomi consumed										**No of Dysaphis plantaginea consumed**									
Predator/prey ratio	**Replications**								**Sum**	**Mean**	**Replications**								**Sum**	**Mean**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**			**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**		
1/10	10	10	10	10	10	10	10	10	80	10±0	10	10	10	10	10	10	10	10	80	10±0
1/15	13	13	14	14	14	14	13	13	108	13.5±0.35	10	13	12	12	12	13	12	13	97	12.125±0.18
1/20	15	16	16	17	17	16	17	16	130	16.25±0.25	16	14	15	15	14	14	15	15	118	14.75±0.25
1/25	18	19	20	20	18	19	20	20	154	19.25±0.23	18	17	18	19	18	19	18	18	145	18.125±0.32
1/30	22	22	23	24	22	23	22	24	182	22.75±0.29	22	23	21	22	22	21	23	21	175	21.875±0.41
General mean										16.35										15.37
All means at each column are statistically significant, compared at level 0.05, comparisons between all General means showed significant differences at level 0.05																				

Table 2: Predatory effect of female adult *Adalia bipunctata*, on female adults of *Aphis pomi* and *Dysaphis plantaginea*, under controlled conditions.

	No of Aphis pomi consumed										**No of Dysaphis plantaginea consumed**									
Predator/prey ratio	**Replications**								**Sum**	**Mean**	**Replications**								**Sum**	**Mean**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**			**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**		
1/10	10	10	10	10	10	10	10	10	80	10±0	10	10	10	10	10	10	10	10	80	10±0
1/15	13	12	13	13	12	13	12	13	101	12.625±0.18	11	13	12	12	12	13	12	13	98	12.25±0.18
1/20	15	16	15	15	16	17	16	16	126	15.75±0.25	15	15	14	14	14	14	15	16	117	14.625±0.25
1/25	18	18	20	18	18	19	18	20	149	18.625±0.32	17	16	17	18	18	16	18	18	138	17.25±0.31
1/30	23	22	22	20	20	22	22	23	174	21.75±0.41	22	22	20	20	22	20	20	20	166	20.75±0.37
General mean										15.75										14.975
All means at each column are statistically significant, compared at level 0.05, comparisons between all General means showed significant differences at level 0.05																				

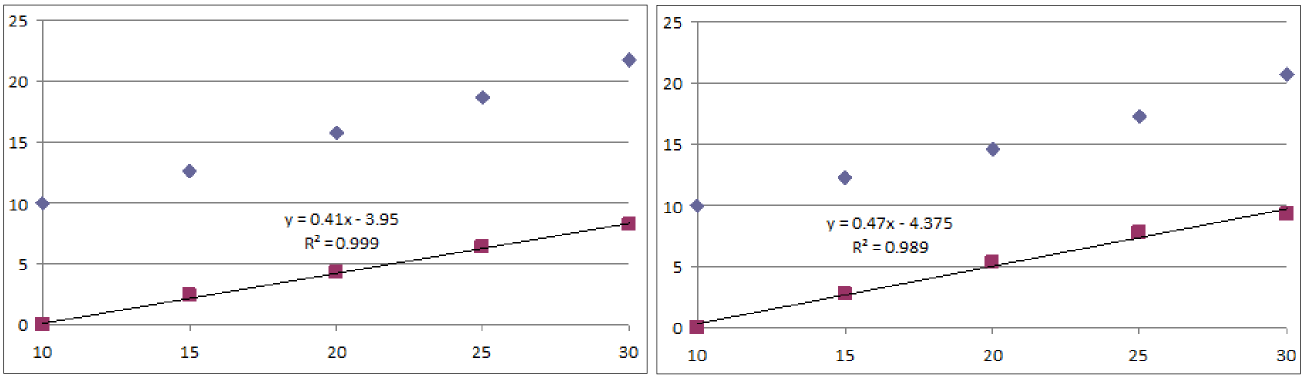
Table 3: Predatory effect of female adult *Orius insidiosus*, on female adults of *Aphis pomi* and *Dysaphis plantaginea*, under controlled conditions.

	No of Aphis pomi consumed										**No of Dysaphis plantaginea consumed**									
Predator/prey ratio	**Replications**								**Sum**	**Mean**	**Replications**								**Sum**	**Mean**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**			**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**		
1/10	9	9	10	9	9	10	9	10	75	9.375±0.18	10	10	9	9	9	9	8	9	73	9.125±0.22
1/15	11	10	12	12	12	13	12	12	94	11.75±0.31	10	9	9	9	11	12	10	12	82	10.25±0.45
1/20	15	14	14	15	14	14	15	13	114	14.25±0.25	12	12	11	11	12	13	11	12	94	11.75±0.25
1/25	16	16	15	14	16	16	16	16	125	15.625±0.26	12	13	14	12	12	14	12	13	102	12.75±0.31
1/30	17	17	16	15	16	17	17	16	131	16.375±0.26	14	13	15	13	15	12	15	12	109	13.625±0.46
General mean										13.475										11.50
All means at each column are statistically significant, compared at level 0.05, comparisons between all General means showed significant differences at level 0.05																				



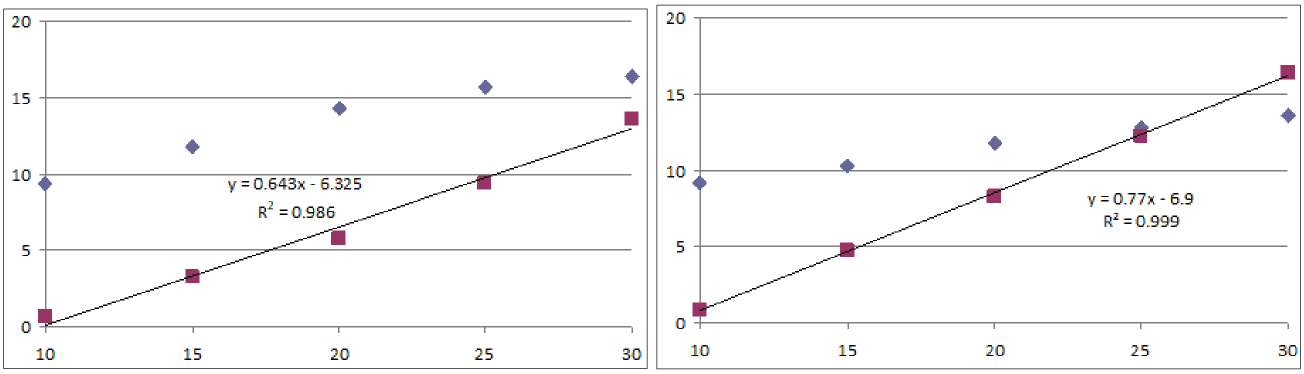
(a) (b)

Fig 1: Mean predatory effect (upper dots) and escapes (lower dots and line) for female adult *Coccinella septempunctata*, on female adults of *Aphis pomi* (A) and *Dysaphis plantaginea* (B), under controlled conditions. Linear model adapted from Deligeorgidis *et al*. (2005a, b) [6, 7]



(a) (b)

Fig 2: Mean predatory effect (upper dots) and escapes (lower dots and line) for female adult *Adalia bipunctata*, on female adults of *Aphis pomi* (A) and *Dysaphis plantaginea* (B), under controlled conditions. Linear model adapted from Deligeorgidis *et al*. (2005a, b) [6, 7]



(a) (b)

Fig 3: Mean predatory effect (upper dots) and escapes (lower dots and line) for female adult *Orius insidiosus*, on female adults of *Aphis pomi* (A) and *Dysaphis plantaginea* (B), under controlled conditions. Linear model adapted from Deligeorgidis *et al*. (2005a, b) [6, 7]

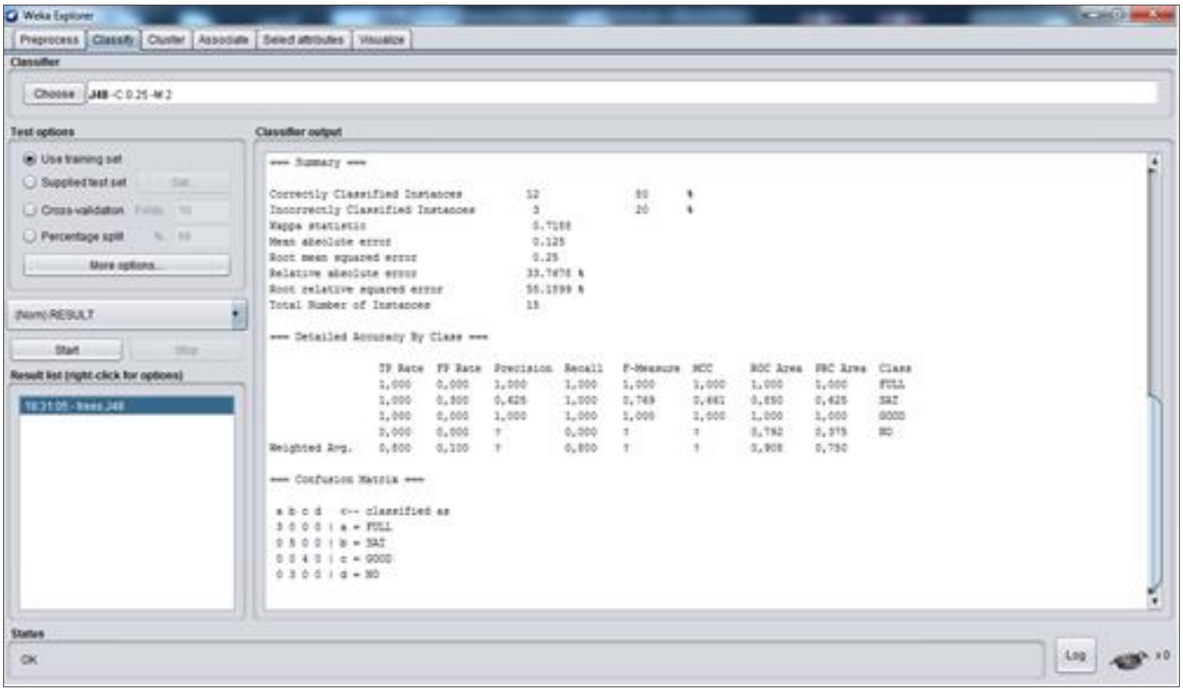


Fig 4: Classification of data instances for all species and predators/prey ratio, in J48 tree classifier algorithm

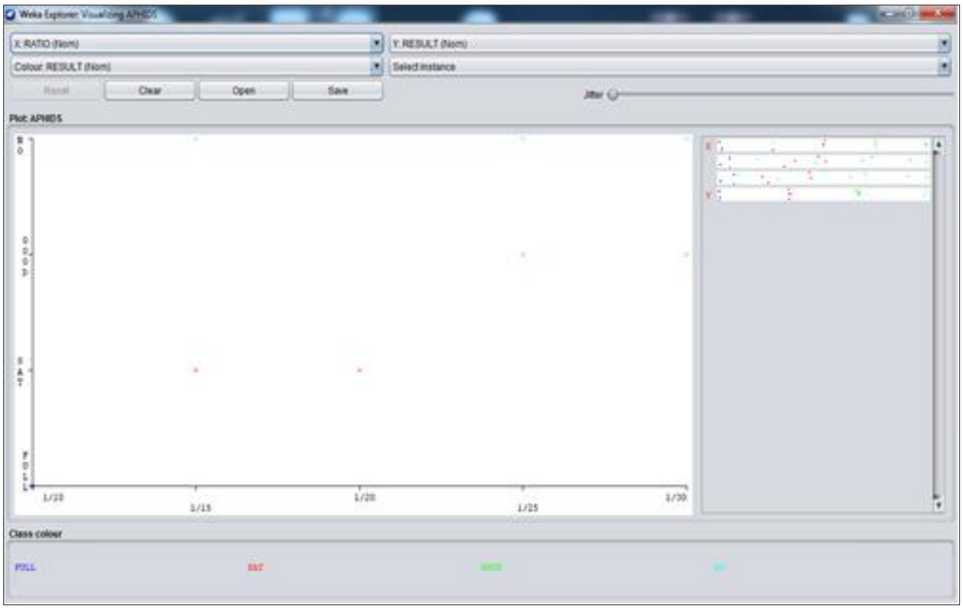


Fig 5: Graphic visualization of data between predator/prey proportions (ratio 1/10, 1/15, 1/20, 1/25, 1/30) and efficiency of predation (FULL, SAT, GOOD, NO)

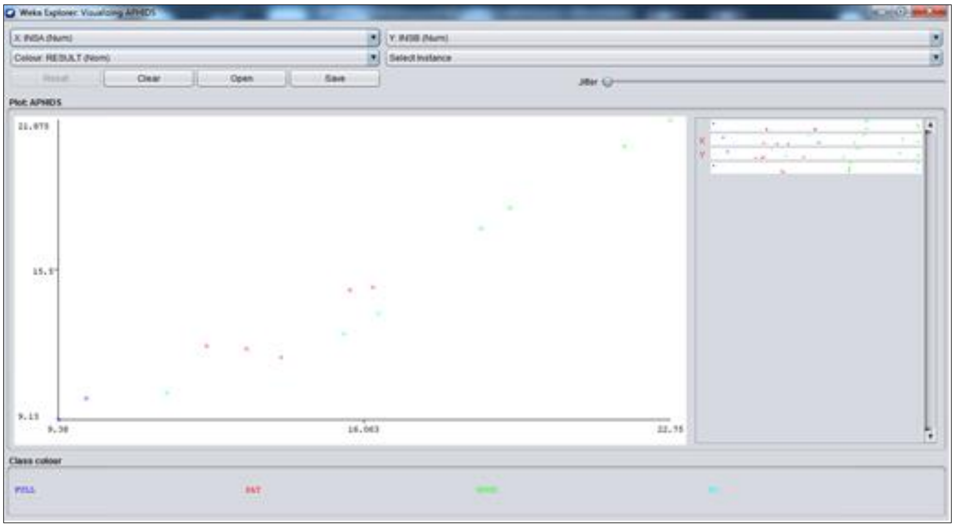


Fig 6: The relation of efficiency of predation between the two kind of aphids *Aphis pomi* (horizontal axis) and *Dysaphis plantaginea* (vertical axis)

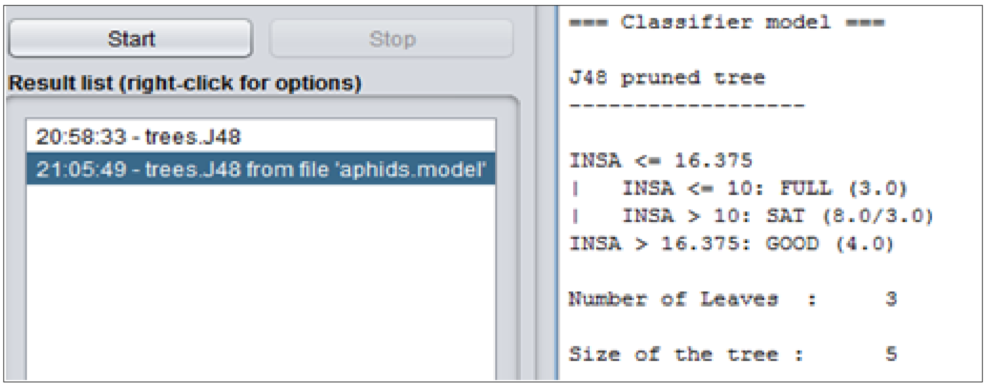


Fig 7: The main model for *Aphis pomi*, with individuals that may be consumed by the probable predators

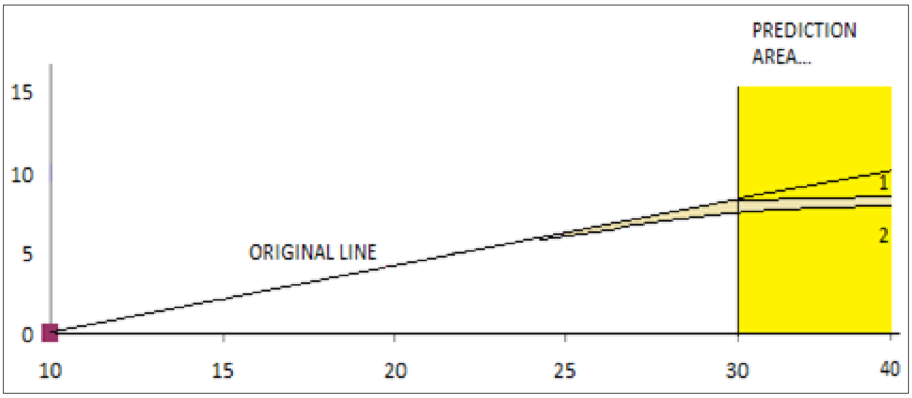


Fig 8: Possible predation curve after re-evaluation of original model on a projection to 1/40 predator/prey proportion for *Adalia bipunctata* on *Aphis pomi* original straight line (curve), 1 = predicted line, 2 = distorted original curve

4. Discussion

Initially, based on previous research data (Frazer & Gill, 1981; Losey & Denno, 1998; Deligeorgidis *et al*., 2005a; 2005b; 2011) [11, 22, 6, 7, 8], authors consider two main factors to explain predators' behavior: a) the predator's failure because aphids are escaping, b) hunger satiation of each predator species. Regarding the first factor, in case of greater populations of aphids, individuals may escape by higher production of alarm pheromone (Losey & Denno, 1998) [22] and thus survive by dropping away in the cage or hiding until hunger of the predator is satiated. The second factor is based on hunger satiation, resulting in aphids' individuals ignored by the predator (Frazer and Gill, 1981) [11]. These two factors were described previously by a second-degree model (Deligeorgidis *et al*., 2005a; 2005b; 2011) [6, 7].

From our dataset, the equation describing predatory effect of *C. septempunctata* on *A. pomi*, was linear: y=0.375x-3.85, also linear was the equation describing predatory effect of *C. septempunctata* on *D. plantaginea*, y=0.405x-3.475, indicating high efficiency without any indication of hunger satiation according to Deligeorgidis *et al*. (2005a; 2005b; 2011) [6, 7] and previous work of Losey & Denno (1998) [22], who depicted that there are two main parameters for efficient predation, individual hiding/escaping and hunger that is satisfied at a certain level of consumption, depending mainly on the predator/prey ratio. The parameters escape ability and hunger satiation, usually form a second-degree model as mentioned in the research works above, but in our data set the model seems to be linear.

The linear equation describing predatory effect of *A. bipunctata* on *A. pomi*, was y=0.41x-3.95 and the also linear equation describing predatory effect of *A. bipunctata* on *D. plantaginea*, was y=0.47x-4.375. The linear equation describing predatory effect of *O. insidiosus* on *A. pomi*, was y=0.643x-6.325 and the also linear equation describing predatory effect of *O. insidiosus* on *D. plantaginea*, was y=0.77x-6.9.

Comparing these equations, in case *O. insidiosus* the slope was greater, indicating less effective predation Deligeorgidis *et al*. (2005a, 2005b) [6, 7] and greater numbers of escapes of aphid individuals. The two coccinelid species and especially *C. septempunctata*, were more effective predators. Escapes to consumed individuals curves showed a crossing point only in the case of *O. insidiosus* indicating also that many aphids may escape, especially in the case of *D. plantaginea*, where even in the predator/prey ratio 1/25 escapes reached consumed individuals. In case of *O. insidiosus* and *A. pomi*, this may happen (as a projection) at a predator/prey ratio 1/40, according to the schemes.

The preference of predators on *A. pomi*, may be attributed to less capability to hide and escape, or some small differences in size, or even taste (Deligeorgidis *et al*., 2005a; 2005b; 2011) [6, 7]. Effective predation of *C. septempunctata*, is also ensured by the greater numbers of aphid individuals consumed and many researchers reported similar results (Triltsch & Roßberg 1997; Deligeorgidis *et al*., 2005a; 2005b; 2011) [38, 6, 7]. The choice of a predator species must be a result of extensive testing on the prey because differentiation of predatory effect is common to coccinellids and depends on the environmental conditions and also on the locality of a species.

Machine learning process on our dataset is considered satisfactory (Witten & Frank, 2005) [40] because 80% of correctly classified instances were able to train the selected tree classifier algorithm J48. The produced model was saved for future use on newly produced data. Data distributions showed that non-satisfactory predation was found between the various cases and satisfactory predation was determined in the middle values. According to the model, efficient predation (EP) found between the following limits in predator/prey ratio: 1/10≤EP<1/30, with a limit of 16.375 *A. pomi* individuals that may be consumed by the probable predators tested. In the same way, Kalamatianos *et al*. (2018) [20] set the threshold for *Bactrocera oleae* (Gmelin), (Diptera: Tephritidae) infestations of economic importance. Re-evaluation of original model showed that after 1/25 to 1/30, linear curve is distorted in a second-degree model as described by Deligeorgidis *et al*. (2005a, 2005b) [6, 7], indicating hunger satiation after 1/30 predator/prey proportion for coccinellids on *A. pomi*. This distortion seems to be over 10% and is considered significant.

5. Conclusions

Concluding, all predators showed no indications of hunger satiation until the predator/prey ratio 1/30. The two coccinellid species and especially *C. septempunctata*, were more effective predators than *O. insidiosus*. The machine learning model derived from current data set was saved for future data assessment on efficiency of predators. It is possible that after 1/30 predator/prey ratio, hunger satiation may appear. Nevertheless, the linear model is applicable until 1/30 predator/prey ratio. Furthermore, a neural stochastic network may be used for prognostic projection on different predator/prey ratios.

6. References

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