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RESEARCH

Antibiosis in small grain cereals against the rose-grain aphid, *Metopolophium dirhodum* (Hemiptera: Aphididae)

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Abstract Resistance against aphids is an integrated pest management tactic that enhances the economic and environmental sustainability of cereal production. The aim of our study was to assess the degree of antibiosis against *Metopolophium dirhodum* (Walker) (Hemiptera: Aphididae), one of the most important cereal aphids in temperate regions, in two lines of small grain cereals bred in the Crop Research Institute (CRI) of Prague: spring wheat, *Triticum aestivum* L. cv. 'Rufia', and germplasm of durum wheat, *Triticum turgidum* ssp. *durum* (Desf.) van Slageren 'TTD40363', under controlled laboratory conditions. Resistant spring wheat cultivar ('Libertina') and highly susceptible spring barley (*Hordeum vulgare* L. cv. 'Sebastian') were used for reference. The responses of *M. dirhodum* to each line and population growth projections were determined according to the age-stage, two-sex life table theory. We found that Rufia was susceptible and TTD40363 was rather resistant to *M. dirhodum*. The projected population sizes after 35 days were ~ 41,000 individuals in spring wheat Rufia and ~ 12,000 in durum wheat TTD40363, which is within the range delimited by the reference cultivars (4,000 in the highly resistant spring wheat Libertina and 77,500 in highly susceptible spring barley Sebastian). This study provides new data on small grain cereal resistance to aphids. An age-stage, two-sex life table approach was used to assess resistance to aphids on durum wheat and barley for the first time.

Keywords Crop resistance · Susceptibility to pests · Durum wheat · Barley · Spring wheat · Life table · Population growth

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Introduction

Small grain cereals, mainly wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.), are highly important crops for human nutrition (e.g., flour, malt), animal feed and technical (e.g., bioethanol, starch) purposes. For example, the average global annual wheat production over past 10 years reached over 760 million metric tons, and barley added another 147 million metric tons (USDA, 2024). Assuring sustainable growth of small grain cereals that includes effective crop management is therefore the main goal of today's agriculture. Aphids (Hemiptera: Aphididae) are significant pests of small grain cereals and cause harm by direct feeding and viral transmission (van Emden & Harrington, 2017; Zhang et al., 2022). Together with *Sitobion avenae* (Fabricius) and *Rhopalosiphum padi* (Linnaeus), *Metopolophium*

dirhodum (Walker) is one of the most economically important aphids on small grain cereals in temperate regions of Europe (van Emden & Harrington, 2017). Rose-grain aphid preferentially feeds on cereal leaves, where it can form large colonies when conditions are suitable (Honek, 1991). Yield losses caused by aphids can be substantial and exceed 60% under massive infestation (Papp & Mesterhazy, 1993). Aphids are typically controlled by pesticides, which pose considerable risks to the environment and human health. To safeguard environmental and food safety, complementary pest control measures are needed to decrease the reliance of conventional crop production on insecticides.

One promising direction for reducing pest populations in crops, which at the same time can potentially lower insecticide use, is adopting cultivars with increased resistance to pests (Birch et al., 2011; Quisenberry & Schotzko, 1994; Radchenko et al., 2022; Smith & Clement, 2012). Resistance to insects can be manifested as antixenosis (the plant is not attractive to the herbivore), antibiosis (the insects do not perform well on the plant) and tolerance (the plant tolerates the infestation by a pest so the yield is not affected) (Smith & Clement, 2012). While the antixenotic qualities of the plant are assessed based on olfactory, visual, tactile and gustatory cues (Hu et al., 2016; Smith & Clement, 2012), antibiosis is determined by nutritional quality of the plant (Chandrasekhar et al., 2018; Karley et al., 2002; Lin et al., 2021), morphological characters of the infested organ, such as trichome density or cuticular thickness (Saska et al., 2021a) or physiological responses to damage, such as sieve element occlusion (Walker, 2022). Antibiosis negatively affects insect performance and fitness-related traits, such as survival and reproduction (e.g., Saska et al., 2021a), and represents one of the important interfaces between plant (crop) defense and the herbivore (pest) attack.

Multiple examples are available from field conditions, showing that crops with increased resistance to certain diseases or pests exhibited less damage and required fewer pesticide applications (Pingali & Gerpacio, 1997; Harris, 2001; Brewer et al., 2019; El Bouhssini et al., 2021). Additionally, plant resistance can affect higher trophic levels. Cai et al. (2009) found that cumulative parasitism by aphids was greater on resistant than on susceptible wheat cultivars. It is therefore important to continue evaluating crop cultivars and germplasms for natural resistance against pests, including aphids. This line of research should also include other species of *Poaceae*, such as minor cereals of the genus *Triticum*, which are globally less agronomically important but can be very important locally for agricultural production. Additionally, these species or lines have served or may serve in the future as donors of genes in small grain cereal breeding programs (McIntosh, 1998; Mondal et al., 2016; Aradottir & Crespo-Herrera, 2021), which further accentuates the need to study them in regard to their resistance or susceptibility to aphids. For example, we recently showed, over the whole life cycle of the rose-grain aphid, that some emmer wheat (*T. turgidum* ssp. *dicoccum* (Schrank ex Schübler) Thell.) cultivars were comparably more susceptible to aphids than cultivars of spring wheat, which resulted in highly significantly faster population growth in emmer wheat compared to spring wheat (Platkova et al., 2020). Other study that investigated aphid response to minor small grain cereals (Chandrasekhar et al., 2018) found after 4 days that *R. padi* produced significantly more offspring on *T. turgidum* ssp. *dicoccoides* (Körn. ex Asch. & Graebn.) Thell. compared to *T. turgidum* ssp. *durum* (Desf.) van Slageren.

The Crop Research Institute (CRI), Prague, Czech Republic, has a long tradition in breeding cereals (Prasil et al., 2011) and resistance assessment to pathogens (Chrpova et al., 2021), but these lines have rarely been evaluated in terms of resistance to aphids (Havlickova, 1997). The principal aim of this study is therefore to assess using the age-stage, two-sex life table (Chi et al., 2020, 2023) the level of antibiosis against the rose-grain aphid (*M. dirhodum*) in two selected lines, one durum and one bread wheat, that have been recently bred in the CRI. Although there is available literature on cereal resistance/susceptibility to aphids (barley: e.g., Ma & Bechinski, 2009; Descamps & Sanchez, 2011; Gao & Liu, 2013; Puterka et al., 2013; Mornhinweg & Armstrong, 2023; durum wheat: e.g., Migui & Lamb, 2006, 2007; Elek et al., 2013; Chandrasekhar et al., 2018; Shavit et al., 2018; Batyrshina et al., 2020a; wheat: e.g., Havlickova, 1997; Saska et al., 2016, 2021a, 2023; Platkova et al., 2020; Lin et al., 2021), we are not aware of any publication that used the age-stage, two-sex life table approach for aphids on barley and durum wheat.

Materials and methods

Host plant cultivars

This study used four lines of small grain cereals as host plants for *M. dirhodum*. The test lines were germplasm of *T. turgidum* ssp. *durum* 'TTD40363' and *T. aestivum* cv. 'Rufia'. Durum wheat (*T. turgidum* ssp. *durum*) is widely grown in the arid Mediterranean region and Middle East, where it is an important crop used for making couscous, bulgur, pasta, pizza and different types of bread. 'Rufia' is a newly bred cultivar of bread wheat registered for commercial use in 2021 that has red kernels due to its high content of flavonoids and anthocyanins, which makes it noteworthy from a human nutritional point of view. The productive spring wheat cultivar 'Libertina' was used as a reference since our previous work found that this line was resistant to *M. dirhodum* (Platkova et al., 2020). The productive spring barley *Hordeum vulgare* cv. 'Sebastian' was used as another susceptible reference. Seed material was obtained from the Genebank of the CRI (Table 1; https://grinczech.vurv.cz/gringlobal/search.aspx).

Plant cultivation

Experimental plants were prepared under laboratory conditions. Seeds were sown in garden soil in pots (0.25 L) after pre-germination in the dark at 20 °C for 2 days. Ten seeds per pot were sown in fully saturated soil and grown at room temperature.

Aphids

We chose *M. dirhodum* as the aphid model species because it is one the most important aphid species infesting small grain cereals with a cosmopolitan distribution (van Emden & Harrington, 2017). This species infests only leaves and is capable of transmission BYDV virus (van Emden & Harrington, 2017). Infestation rate of 10 aphids/tiller causes a 6% loss of yield (Niehoff & Stäblein, 1998). Aphid material was provided by the long-term (>20 years) parthenogenetic laboratory culture maintained in the CRI of Prague on young (growth stages 2–3 leaves, before the onset of tillering) winter wheat plants, cultivar 'Butterfly'. The culture is maintained in greenhouse under natural photoperiod (8L:16D in winter and 16L:8D in summer) and temperature regulated to 20 ± 1 °C.

Life table study

The data collection was carried out in climatic chambers under a constant temperature of 21 ± 1 °C and a long-day photoperiod (16 h light/8 h dark). Eight pots per cultivar, containing seedlings enclosed in clear polyethylene tubes to prevent aphids escaping, were infested with ten adult wingless virginoparae each. These aphids were removed the next day, whereafter the number of neonates was reduced to ten per pot (thus one aphid per plant) to balance the initial population numbers. Every day, the number of aphids, instars, and newly born offspring were counted in

Table 1 Characterization of wheat cultivars used in the life table study with the rose-grain aphid, *Metopolophium dirhodum* (Walker) (https://grinczech.vurv.cz/gringlobal/search.aspx)

Description	*Triticum aestivum* cv. Libertina	*Triticum aestivum* cv. Rufia	*Triticum turgidum* ssp. *durum* TTD40363	*Hordeum sativum* cv. Sebastian
Country of origin	Czech Republic	Czech Republic	Czech Republic	Denmark
Level of certification[1]/ holder	CPG/Selgen a.s	PO/Crop Research Institute	Advanced breeding line/ Crop Research Institute	CPG/ Sejet Planteforaedling I/S
Baking quality	A	C	to be determined	NA
Yield potential	high	low	to be determined	high
Plant height	short	medium	to be determined	medium
Earing	medium	late	to be determined	medium to late
Inclination to lodging	low	low	to be determined	low to medium
Resistance to fungal diseases	high	medium	to be determined	medium to high

[1] CPG—Community Plant Guarantee (EU level); PO – National registration

each pot and recorded, and the neonate nymphs were removed. The data collection thus represented the "group design" sensu Chang et al. (2016), meaning that the development and reproduction was followed at the level of a group, or cohort, of aphids in one pot. The aphids were transferred to different young plants every week due to space restrictions and to simplify manipulation (Akca et al., 2015; Saska et al., 2021a). Data were collected until the last aphid of the initial cohort died (approximately six weeks).

Analysis

The level of antibiosis was assessed using the age-stage, two-sex life table theory (Chi, 1988; Chi & Liu, 1985; Chi et al., 2020, 2023). Age-stage, two-sex life table theory provides an optimum tool for such assessment because unlike the traditional female-based life table, it considers uneven development rates among individuals as well as the contribution of both sexes to the population (not relevant in the case of parthenogenetic aphid populations) and makes predictions of population build-up possible (Chi et al., 2020, 2023). It is also more accurate than simplified methods for population growth rate estimation (Saska et al., 2021a).

The life-table data were processed and analyzed using the TWOSEX-MSChart program (Chi, 2023a). Table 2 lists the procedures that were followed to determine the population characteristics and life table. A paired bootstrap test was used to compare treatments (Mou et al., 2015; Wei et al., 2020), and 100,000 bootstraps were used to estimate the standard errors (SEs) of the parameters (Polat Akkopru

Table 2 Population parameters used in the age-stage, two-sex life table analysis. The equations come from (Chi, 1988; Chi & Liu, 1985), unless stated otherwise. The SEs of the parameters were estimated using 100,000 bootstraps (Polat Akkopru et al., 2015)

Parameter and equation	Explanation
$s_{xj} = \frac{n_{xj}}{n_{01}}$	Age-stage specific survival rate (s_{xj}); x is age from birth [d], j is the stage[1]. Thus, n_{xj} is the number of individuals who survived to age x and stage j. n_{01} is the initial number of new-born aphids with which the experiment was started
$l_x = \sum_{j=1}^{\beta} s_{xj}$	Age-specific survival rate (l_x); β is the total number of life stages
$f_{xj} = \frac{N_x}{n_{xj}}$	Age-stage specific fecundity (f_{xj}); N_x is the number of nymphs produced at age x
$m_x = \frac{\sum_{j=1}^{\beta} s_{xj} f_{xj}}{\sum_{j=1}^{\beta} s_{xj}}$	Age-specific fecundity (m_x)
$R_0 = \sum_{x=0}^{\infty} \sum_{j=1}^{\beta} s_{xj} f_{xj} = \sum_{x=0}^{\infty} l_x m_x$	Net reproductive rate (R_0) [offspring individual^{-1}]. Note that $R_0 = F\left(\frac{n_f}{n_{01}}\right)$, where F is mean fecundity [offspring], n_f is the number of individuals who reached the female stage f and n_{01} is the initial number of individuals at the beginning of the life table study
$\sum_{x=0}^{\infty} e^{-r(x+1)} l_x m_x = 1$	Intrinsic rate of increase (r) [d^{-1}] estimated by using the iterative bisection method and the Euler-Lotka equation with the age indexed from 0 (Goodman, 1982)
$\lambda = e^r$	Finite rate of increase (λ) [d^{-1}]
$T = \frac{lnR_0}{r}$	Mean generation time (T) [d]
$e_{xj} = \sum_{i=x}^{\infty} \sum_{y=j}^{\beta} s_{iy}'$	Life expectancy (e_{xj}) [d]; s_{iy}' is the probability that an individual of age x and stage j can survive to age i and stage y by assuming that $s_{iy}' = 1$ (Chi & Su, 2006)
$v_{xj} = \frac{e^{r(x+1)}}{s_{xj}} \sum_{i=x}^{\infty} e^{-r(x+1)} \sum_{y=j}^{\beta} s_{iy}' f_{iy}$	Reproductive value (v_{xj}) [offspring] (Tuan et al., 2014)
$\phi_{j,t} = \log\left(\frac{n_{j,t+1}+1}{n_{j,t}+1}\right)$ $\approx \log\left(\frac{\lambda n_{j,t}}{n_{j,t}}\right) = \log\left(\frac{\lambda n_{total,t}}{n_{total,t}}\right) = \log\lambda$	Growth rate of each stage between two consecutive days, where t is time (Huang et al., 2018). As a population approaches stable age stage distribution, all stages ($n_{j,t}$) and the total population ($n_{total,t}$) will increase at the finite rate, λ

[1]Here as a stage we mean the phase of development delimited by moulting. In the case of parthenogenetic generations of aphids, there would be five stages—four nymphal instars and the female stage

et al., 2015). The population growth starting with 10 individuals was projected in the program TIMING-MSChart (Chi, 2023b), following the method of Huang et al. (2018) (Table 2). Following Huang et al. (2018), the 95% confidence intervals (CIs) of the predicted population size after 35 days were determined, which is a usual time when populations of *M. dirhodum* achieve stable age-stage distribution under control conditions (Saska et al., 2023). This is important because when stable age-stage distribution is achieved, population sizes do not fluctuate, which makes the comparison across treatments more reliable (Saska et al. 2024). Also, this period of time represents a realistic time window during which *M. dirhodum* population can be present in the crop in central Europe (Honěk et al., 2018). A paired bootstrap test was used to compare the expected population numbers after 35 days (Mou et al., 2015; Wei et al., 2020).

Results

Aphid life table

The host species and cultivars affected the life table and population parameters of *M. dirhodum* (Fig. 1; Table 3). The survival rates during the nymphal stage were rather high on barley (94%) but significantly lower on *Triticum* hosts (69–78%; Fig. 1a). The age-stage specific survival rates (s_{xj}) demonstrated that, due to the variations in the duration of development of particular stages, the nymphal stage overlapped with the adult stage (Supplementary Fig. S1). Although the development times of *M. dirhodum* were generally rapid (ca. 7.5–8.5 days on average), there were significant differences across all the hosts (Fig. 1b), being shortest on barley and longest on Libertina. The females lived significantly longer on Rufia than on barley and Libertina (Fig. 1c), while the total longevity was significantly different only between Libertina and Rufia, the former exhibiting the shortest mean longevity of the hosts included in this study (Fig. 1d).

Reproduction was also affected by the plant host. The reproduction period was shortest on barley and longest on Rufia (Fig. 1e), and the remaining differences between the hosts were not significant. The differences in fecundity were prominent among the hosts. The lowest fecundity was observed on Libertina, followed by barley and durum wheat, and the highest was found on Rufia (Fig. 1f), with the difference between the two extremes being nearly two-fold (Table 3). The age-specific survival rates (l_x), age-specific fecundity (m_x), net maternity ($l_x m_x$) and age-stage-specific life expectancy (e_{xj}) for each treatment are shown in the Supplementary Figs. S2-S3. The highest age-stage reproductive value (v_{xj}) was estimated to occur at ages of 9 (Rufia) to 11 (Libertina) days (Supplementary Fig. S4).

The values of the intrinsic rate of increase, r, and finite rate of increase, λ, pointed to rapid population growth of *M. dirhodum* under all treatments (Table 3). The lowest r and λ values were observed for Libertina, followed by durum wheat and Rufia, and the highest were observed for barley, while differences in both r and λ were significant for all hosts (Fig. 1g-h). The reproduction rates R_0 were lowest on Libertina compared to the remaining hosts (Fig. 1i) (Table 3). The generation time T was shortest for barley, intermediate for Rufia and longest for Libertina and durum wheat (Fig. 1j), and the difference between T on barley and on durum wheat was 2.2 days (Table 3).

The population growth curves (on a logarithmic scale) approached linearity after approximately 40 days (Fig. 2a) for all hosts, which suggests that the aphid populations had reached a stable age-stage distribution. The stable stage distributions were nearly identical for all treatments, as the populations consisted of $89.76 \pm 0.44\%$ nymphs and $10.24 \pm 0.44\%$ females. The growth curves notably differed across the treatments (Fig. 2a). The projected population sizes after 35 days significantly differed among all hosts (Fig. 2b), and the overall pattern of the differences resembled those of r and λ (Fig. 1g-h). The projected population sizes after 35 days were greatest for barley (77,589 individuals), followed by Rufia (41,225) and durum wheat (11,776), and the lowest population size was predicted for Libertina (4,051) (Fig. 2b).

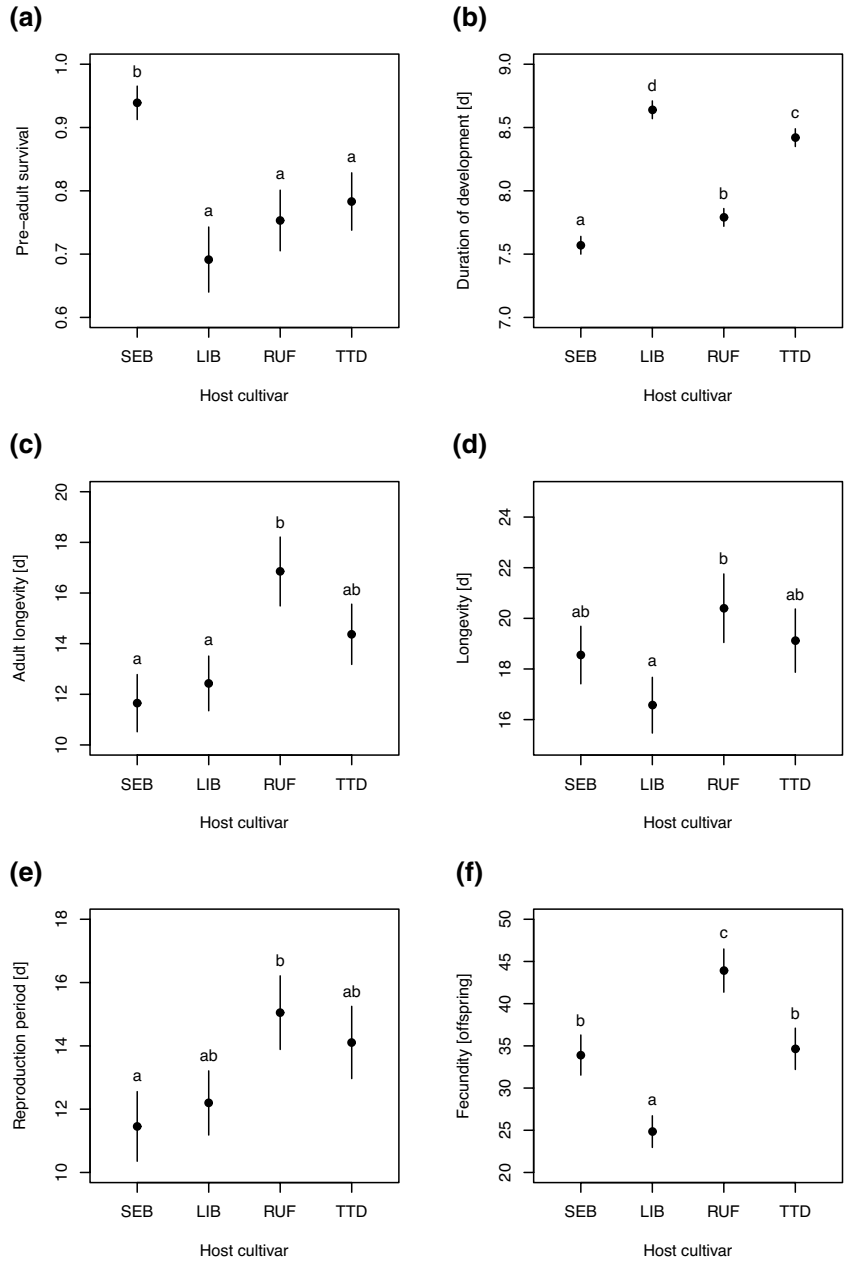


Fig. 1 Life table and population growth parameters for *Metopolophium dirhodum* reared on four small grain cereal hosts: SEB—*Hordeum vulgare* 'Sebastian', LIB—*Triticum aestivum* 'Libertina', RUF—*T. aestivum* 'Rufia', TTD—*T. turgidum* ssp. *durum* 'TTD40363'. The vertical bars represent the standard errors (SEs) of the means estimated from 100,000 bootstraps. Treatments assigned the same letters did not differ significantly from each other (paired bootstrap test). The values ± SEs of all parameters can be found in Table 3

Discussion

In this experiment, we evaluated two lines of small grain cereals bred in the CRI for antibiosis against aphids. We found that the spring bread wheat Rufia was a highly susceptible host for *M. dirhodum*, while the durum wheat germplasm TTD40363 presented only a mild level of antibiosis. We confirmed our previous results that the spring wheat cultivar Libertina shows a high level of antibiosis (Platkova et al., 2020). The host most susceptible to *M. dirhodum* in this study was spring barley Sebastian, on which the aphid population after 35 days was ca. 19 times greater than on Libertina.

Here we used the age-stage, two-sex life table approach (Chi et al., 2020, 2023), which provides an opportunity to predict population growth of a population under given conditions. Such predictions are

Fig. 1 (continued)

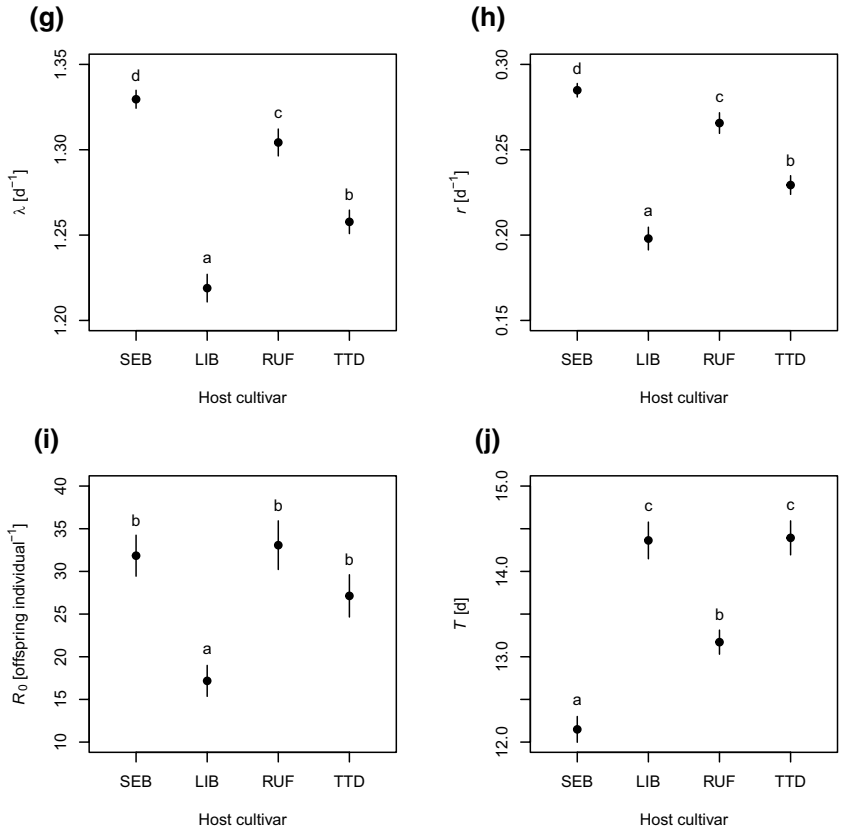


Table 3 Life table parameters (means ± s.e) of *Metopolophium dirhodum* reared on four small grain cereal cultivars. S.e. were estimated with bootstrapping (100,000 resamplings). Numbers in brackets report the sample size. The same letters within the rows indicate values that were not significantly different from each other based on a paired bootstrap test

Parameter	*Hordeum vulgare*	*Triticum aestivum*	*Triticum aestivum*	*Triticum turgidum* ssp. *durum*
	Sebastian	Libertina	Rufia	TTD40363
Duration of development [d]	7.57 ± 0.07 (77) a	8.64 ± 0.07 (56) d	7.79 ± 0.07 (61) b	8.42 ± 0.07 (65) c
Survival	0.94 ± 0.03 (82) b	0.69 ± 0.05 (81) a	0.75 ± 0.05 (81) a	0.78 ± 0.05 (83) a
Fecundity [offspring]	33.91 ± 2.38 (77) b	24.84 ± 1.87 (56) a	43.92 ± 2.56 (61) c	34.65 ± 2.45 (65) b
Reproduction days [d]	11.45 ± 1.10 (77) a	12.20 ± 1.01 (56) ab	15.05 ± 1.16 (61) b	14.11 ± 1.14 (65) ab
Adult longevity [d]	11.65 ± 1.13 (77) a	12.43 ± 1.08 (56) a	16.85 ± 1.36 (61) b	14.37 ± 1.19 (65) ab
Total longevity [d]	18.55 ± 1.14 (82) ab	16.57 ± 1.10 (81) a	20.40 ± 1.35 (81) b	19.12 ± 1.25 (83) ab
r [d^{-1}]	0.2849 ± 0.0040 (82) d	0.1980 ± 0.0067 (81) a	0.2656 ± 0.0060 (81) c	0.2293 ± 0.0055 (83) b
λ [d^{-1}]	1.3296 ± 0.0053 (82) d	1.2189 ± 0.0081 (81) a	1.3043 ± 0.0079 (81) c	1.2578 ± 0.0069 (83) b
R_0 [offspring individual^{-1}]	31.84 ± 2.40 (82) b	17.17 ± 1.81 (81) a	33.07 ± 2.85 (81) b	27.13 ± 2.47 (83) b
T [d]	12.15 ± 0.15 (82) a	14.36 ± 0.22 (81) c	13.17 ± 0.14 (81) b	14.39 ± 0.20 (83) c

useful because in practice slower population growth results in achieving the economic thresholds later, if ever. Also, slower population growth provides wider time window for natural enemies to effectively regulate the populations of pests. Thus, conditions that assure slower population growth of a pest, such as

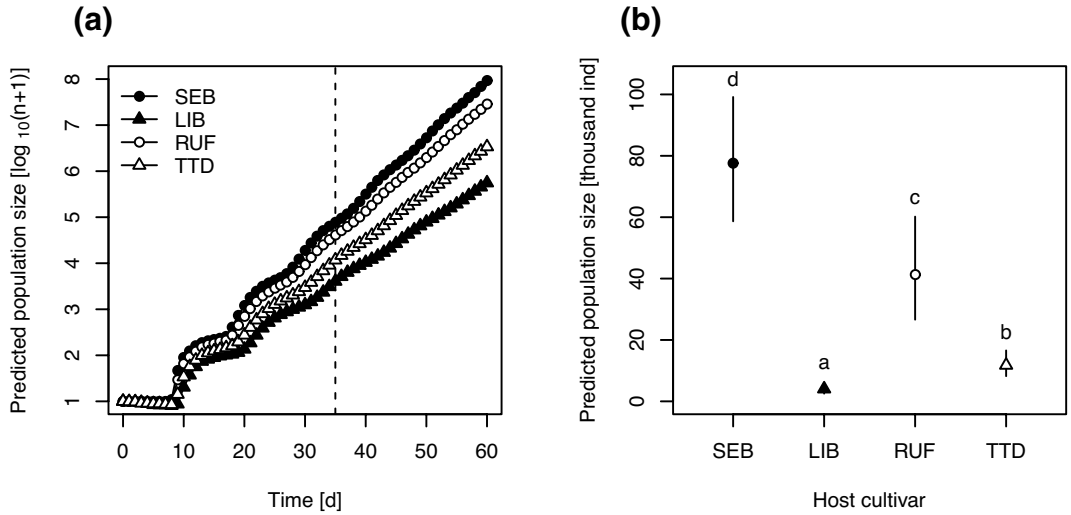


Fig. 2 Population projections (log10[n + 1]) for *Metopolophium dirhodum* reared on four small grain cereal hosts. The projections are based on the age-stage, two-sex life table theory. **a** Predicted courses of population growth. The relationships between time for d ≥ 35 (after the stable age-stage distribution was reached, dashed vertical line) and the population sizes for the individual treatments are as follows. *Hordeum vulgare* 'Sebastian', SEB: $(\log_{10}[n+1]) = 0.5163 + 0.1244d$, *Triticum aestivum* 'Libertina', LIB: $(\log_{10}[n+1]) = 0.6229 + 0.0851d$, *T. aestivum* 'Rufia', RUF: $(\log 10[n+1]) = 0.5329 + 0.1156d$, *T. turgidum* ssp. *durum* 'TTD40363', TTD: $(\log_{10}[n+1]) = 0.5707 + 0.0992d$. Note that the slopes are equal to specific values of $\log_{10}(\lambda)$. **b** Projected population sizes ± 95% confidence intervals after 35 d. The vertical bars show the 95% confidence intervals that were calculated according to Huang et al. (2018). Treatments assigned the same letters did not differ significantly from each other (paired bootstrap test)

growing more resistant cultivar of a crop, may result in postponing or reducing the number of insecticide applications in practical farming (Pingali & Gerpacio, 1997; Harris, 2001; Brewer et al., 2019; El Bouhssini et al., 2021), which is a desired outcome of this or similar research.

Durum wheat resistance against aphids has been investigated in several previous studies, and multiple aphid species were included: *Diuraphis noxia* Kurdjumov (Assad, 2002; Formusoh et al., 1992; Marimuthu & Smith, 2012), *Rhopalosiphum padi* (Linneaus) (Alsuhaibani, 1996; Batyrshina et al., 2020a; Elek et al., 2013; Migui & Lamb, 2007; Shavit et al., 2018, 2022), *R. maidis* (Fitch) (Chandrasekhar et al., 2018; Jasrotia et al., 2022), *Sitobion avenae* (Fabricius) (Migui & Lamb, 2007; Shavit et al., 2018) and *Schizaphis graminum* (Rondani) (Alsuhaibani, 1996; Migui & Lamb, 2007; Shavit et al., 2018). To date, no study has explicitly targeted the resistance of durum wheat against *M. dirhodum*. This study provides the first assessment of aphid–plant interactions based on an age-stage, two-sex life table for any durum wheat line but also for the rose-grain aphid. Other studies assessed durum wheat infestation in the field (Batyrshina et al., 2020b; Pons et al., 1989, 1993; Sigsgaard, 2002), of which Pons et al. (1989) and Sigsgaard (2002) also reported on this aphid species. Available studies documented high variation in resistance across multiple durum wheat cultivars (Assad, 2002; Formusoh et al., 1992). In our study, we found that the durum wheat germplasm TTD40363 presented a rather high level of antibiosis to *M. dirhodum*, as the projected population size after 35 days reached nearly 12,000 individuals, which is ca. three times more than in the most resistant spring wheat Libertina but 6.5 times less than in the most susceptible barley cultivar. Thus, this particular germplasm is a promising one for future breeding regarding its antibiotic performance against aphids.

Bread wheat has received much more research interest concerning resistance to aphids, and several studies have used the age-stage, two-sex life table theory to assess the antibiosis of various lines against aphids (Lin et al., 2021; Platkova et al., 2020; Saska et al., 2021a, 2023). Based on the values of the finite rates of increase, λ, Rufia appeared

to be the most susceptible to *M. dirhodum* out of the 13 lines evaluated to date (Li et al., 2023; Lin et al., 2021; Platkova et al., 2020; Saska et al., 2023). In other cultivars, the values of λ estimated in a similar temperature range of ca. 20–22 °C ranged from 1.2189 to 1.2860 d^{-1}, which translates to 4,000–26,000 aphids after 35 days (predation/parasitism/diseases and host plant quality changes not considered). For Rufia, the predicted population size after 35 days was 41,000. Growing this cultivar will thus require additional measures to control this aphid species. As the level of antibiosis may differ against particular species of aphids even in the same cultivar (Shavit et al., 2018), generalizing this conclusion to other aphid species requires caution.

The next step in this research is to more closely examine the mechanisms of antibiosis or susceptibility to aphids at the structural—waxiness, trichome density and cuticular thickness – (van Emden & Harrington, 2017; Saska et al., 2021b; Singh et al., 2021) and molecular (Chandrasekhar et al., 2018; Kosova et al., 2022; Marimuthu & Smith, 2012; Shavit et al., 2022) levels as well as the antixenotic potential (Hu et al., 2016) of the promising lines, to enhance the results of this study for application in breeding for resistance to aphids and other herbivorous pests. Given that some aphid species are able to develop biotypes resistant to plant anti-herbivore responses (Botha, 2021), this work will probably never end, however it is still highly relevant given that any pesticide application saved due to increased plant resistance against aphids (or other pests) will make the food production safer and more sustainable.

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Data availability Data underlying this research are available with authors upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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