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Goleva, Irina, Esteban C. Rubio Cadena, Nar B. Ranabhat, Caroline Beckereit, and Claus P. W. Zebitz. "Dietary effects on body weight of predatory mites (Acari, Phytoseiidae)." *Experimental and Applied Acarology* 66, no. 4 (August 2015): 541-553.
<https://dx.doi.org/10.1007/s10493-015-9920-5>.

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Dietary effects on body weight of predatory mites (Acari, Phytoseiidae)

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Abstract

Pollen is offered as alternative or supplementary food for predacious mites; however, it may vary in its nutritional value. Body weight appears a representative parameter to describe food quality. Thus, we assessed the body weight for adults of the generalist mites *Amblyseius swirskii*, *Amblydromalus limonicus*, and *Neoseiulus cucumeris* reared on 22, 12, and 6 pollen species, respectively. In addition, *A. swirskii* and *A. limonicus* was reared on codling moth eggs. In all mite species, female body weight was higher than that of males, ranging between 4.33 and 8.18 lg for *A. swirskii*, 2.56–6.53 lg for *A. limonicus*, and 4.66–5.92 lg for *N. cucumeris*. Male body weight ranged between 1.78 and 3.28 lg, 1.37–3.06 lg, and 2.73–3.03 lg, respectively. Nutritional quality of pollen was neither consistent among the mite species nor among sex, revealing superior quality of *Quercus macranthera* pollen for females of *A. swirskii* and *Tulipa gesneriana* pollen for males, *Alnus incana* pollen for females of *A. limonicus* and *Aesculus hippocastanum* pollen for males, and *Ae. hippocastanum* pollen for both sexes of *N. cucumeris*. The results are discussed against the background of known or putative pollen chemistry and mite's nutritional physiology.

Introduction

Limitation and quality of either primary, alternative or supplementary food plays a crucial role in development, longevity, and reproduction of predacious mites (Badii et al. 1990; Yao and Chant 1990; Momen 1994; Jung and Croft 2001; Williams et al. 2004; Hussein 2010; Walzer and Schausberger 2013).

Besides these descriptive parameters important for successful biocontrol, food quantity and quality also directly influences body size and biomass, which indirectly determines physical fitness. Smaller males are less competitive during courtship behaviour and less successful in mating compared to bigger ones (Walzer and Schausberger 2011, 2013, 2014). In predator–prey relations, disparity in body size and biomass determines success to subdue a prey (Sabelis 1981; Yao and Chant 1990; Walzer and Schausberger 2008, 2011; Reis et al. 2003). Body size and fitness also affect intraguild competition and result in shifts in species dominance and biocontrol efficacy when several predator species have been released (Polis and Holt 1992; Polis et al. 1989). However, body size, weight and life-table characteristics of phytoseiid mites differ considerably between species and within a species depending on quality of pollen, animal food, or artificial diets (McMurtry and Scriven 1966; Badii et al. 1990; Croft et al. 1999; van Rijn and Tanigoshi 1999; Vantornhout et al. 2004; Momen and El-Laithy 2007; Lorenzon et al. 2012; Goleva and Zebitz 2013; Vangansbeke et al. 2014a, b; Walzer and Schausberger 2014; Nguyen et al. 2014, 2015). However, information on body size or weight dependent on food quality is rare.

In our study, we assessed the significance of nutritional quality of different diets on body weight of the generalist mites *Amblyseius swirskii* Athias-Henriot, *Amblydromalus* (*Amblyseius*, *Typhlodromalus*) *limonicus* (Garman & McGregor) (both type III b), and *Neoseiulus cucumeris* (Oudemans) (type IIIe, according to McMurtry et al. 2013) (Acari: Phytoseiidae).

Materials and methods

Food sources

Pollen

Pollen of the following anemophilous plants were collected by shedding the flowers: birch (*Betula pendula* Roth), common cattail (*Typha latifolia* L.), Scots pine (*Pinus sylvestris* L.), common walnut (*Juglans regia* L.), Persian oak (*Quercus macranthera* Fisch. & C.A. Mey. ex Hohen.), European beech (*Fagus sylvatica* L.), hazelnut (*Corylus avellana* L.), Caucasian walnut (*Pterocarya fraxinifolia* (Lam.) Spach), common alder (*Alnus glutinosa* L.), grey alder (*Alnus incana* (L.) Moench), Japanese alder (*Alnus japonica* (Thunb.) Steud.), olive (*Oleae europaea* L.), castor bean (*Ricinus communis* L.), and maize (*Zea mays* L.). Pollen of the following entomophilous plants were collected using a brush: horse chestnut (*Aesculus hippocastanum* L.), princess tree (*Paulownia tomentosa* (Thunb.) Sieb. & Zucc.), sunflower (*Helianthus annuus* L.), apple (*Malus domestica* Borkh.), dog rose

(*Rosa canina* L.), rape (*Brassica napus* L.), christmas cactus (*Schlumbergera* sp. (Lem.)) hybrid, tulip (*Tulipa gesneriana* L.). All pollen were collected from pesticide-free plants in the field, dried for 2 days at room temperature and stored under -20°C until use in the experiments. Pollen of Scots pine was provided by Mr. H. Schneller (LTZ Augustenberg, Dept. of Plant Health and Product Quality). Except maize, sunflower, and *C. avellana* pollen (all collected in Straubing-Bogen, Bavaria, Germany), and common cattail pollen (supplied by Koppert, Berkel en Rodenrijs, The Netherlands), all pollens were collected on the campus of the University of Hohenheim.

Animal food

Codling moth [*Cydia pomonella* (L.) (Lepidoptera, Tortricidae)] eggs were collected daily from the oviposition substrate (polythene film) of adults of the laboratory stock and transferred to the experimental arenas by using a fine brush.

Mite rearing

Amblyseius swirskii and *N. cucumeris* were purchased from Sautter & Stepper (Ammerbuch, Germany), and *A. limonicus* was provided by Koppert. All species were kept in stackable plastic boxes covered with plastic lids and kept in an incubator at $25 \pm 1^{\circ}\text{C}$, 70–80 % relative humidity and L16:D8 h photoperiod. *Amblyseius swirskii* and *A. limonicus* were reared on *B. pendula*-pollen, and *N. cucumeris* on pollen of *M. domestica* (all offered ad libitum), to obtain eggs for the experiments.

Experimental set-up

All experiments were conducted in an experimental arena following Overmeer (1985) with slight modifications (Goleva and Zebitz 2013; Ranabhat et al. 2014). The sponges used by Overmeer as spacers, were replaced by petri-dishes placed between the plastic dish bottom and a black PVC plate. This PVC plate ($10 \times 15 \times 0.5$ cm) was divided into eight arenas of 2×2.5 cm for experiments with *A. swirskii* and *N. cucumeris*, and into six arenas of 2×3.5 cm for *A. limonicus*. Each arena was separated by moistened filter paper (Munktell and Filtrak, No. 3, Bärenstein, Germany) to supply the mites with water. A strip of insect glue (Heller Raupenleim—Brutonia, Schacht, Germany) mixed with citronella and castor oil, served as repellent to reduce loss of mites without exerting negative side-effects to the mites (Al-Shammery 2011). These experimental units were kept in a separate incubator at the same regimen as given for the stock rearing.

Newly laid eggs (≤ 16 h) were collected from the rearing plates and 5 eggs were transferred onto each small observation arena on the experimental plate. Pollen was offered ad libitum at larval hatch and replaced every second or third day, and codling moth eggs (≤ 24 h) were supplied daily, always removing the old food by a fine brush. Preimaginal development was assessed in 20 replicates (5 eggs/replicate) for each food source. Each test set was examined twice daily, once in the morning and once in the late afternoon, and the numbers of individuals in the respective developmental stages were recorded. Exuviae of the moulted stages were removed at each observation time.

To obtain a sufficient number of adults for subsequent analysis of body mass, the same procedure was followed in 40–80 replicates without assessing preimaginal development.

Freshly hatched males and females were randomly chosen from each treatment and killed in a deep-freezer at -20°C for 24 h for later assessment of body weight.

Adult fresh weight (AFW) was assessed on a micro-balance (Type UMX2 Automated-S Ultra-microbalance, Mettler Toledo, Gießen, Germany).

Statistical analysis

The obtained data were analyzed using JMP[®] 11.0.1 software (SAS Institute, Cary, NC, USA). Parametric data were analyzed by the following steps: (1) Generalized linear model (GLM-procedure), (2) oneway-ANOVA with subsequent Tukey–Kramer HSD-test at $\alpha = 0.05$, to compare the effects of independent parameters. F , df , and P values were corrected by Welsh-test if variance inhomogeneity was given following Bartlett's test.

The nonparametric mortality data were analysed by a Wilcoxon-test followed by a Wilcoxon-pairwise comparison and oneway-ANOVA with subsequent Tukey–Kramer HSD-test at $\alpha = 0.05$.

Predator species was used as additional factor in a GLM-analysis to compare the mortality, developmental time, and adult weight among the three species only in the treatments with identical pollen provision (*Ae. hippocastanum*, *B. pendula*, *R. communis*, *Schlumbergera* sp., *T. gesneriana*, *Z. mays*). Previously published mortality and development data for *A. swirskii* fed with these pollen have been taken from Goleva and Zebitz (2013). Adult weight data for *A. swirskii* fed with pollen of *B. pendula* and *Z. mays* have been taken from Goleva et al. (2014). Since 100 % preimaginal mortality occurred when *N. cucumeris* was fed with pollen of *R. communis*, and *A. limonicus* was offered pollen of *T. gesneriana*, these pollen were excluded for GLM-analysis for developmental time and adult weight. The respective statistical procedures, and statistical core data are provided in the legends of the tables.

Results

Preimaginal development and mortality

Preimaginal development and mortality of all mite species tested was affected by pollen food quality. However, the suitability of pollen as food was not consistent among the mite species (Table 1). *Ricinus communis* for example was a good food source for *A. limonicus* with a preimaginal mortality of 2.67 %, but *N. cucumeris* suffered from 100 % mortality (Ranabhat et al. 2014). On the other hand, pollen of *T. gesneriana* was a suitable food source for *N. cucumeris* with 12.6 % preimaginal mortality whereas mortality was medium for *A. swirskii* and completely unsuitable as food for *A. limonicus* (31.5 and 100 % preimaginal mortality, respectively). Compared to *A. swirskii* and *A. limonicus*, performance of *N. cucumeris* was inferior, except on pollen of *T. gesneriana*, when only the pollen offered to all three species was considered. In all species tested, preimaginal development of males was always faster than that of females.

Body weight

Adult body weight differed significantly between species, food offered and sex (Table 2). Females always had a higher biomass than males regardless of the food source. Depending

Table 1 Preimaginal mortality and developmental time of females and males (mean \pm SEM) of *Amblyseius swirskii* and *Amblydromalus limonicus* reared on different diets

Diet	N	Preimaginal mortality (%) ²	Females		Males		<i>df</i> ³	<i>P</i>
			Developmental time (days) ²		Developmental time (days) ²			
			N	Developmental time (days) ²	N	Developmental time (days) ²		
<i>Amblyseius swirskii</i>								
<i>Alnus glutinosa</i>	20	0 c	71	5.54 \pm 0.053 cd	26	5.08 \pm 0.036 cd	94 (corr.)	<0.0001
<i>A. incana</i>	20	0 c	74	5.32 \pm 0.050 de	19	5.29 \pm 0.096 c	91	0.80
<i>A. japonica</i>	20	0 c	82	5.82 \pm 0.055 c	18	5.50 \pm 0.162 bc	98	0.023
<i>Brassica napus</i>	20	0 c	69	5.17 \pm 0.034 e	24	5.02 \pm 0.021 cd	91 (corr.)	0.0002
<i>Corylus avellana</i>	20	5.0 \pm 2.46 bc	64	4.76 \pm 0.083 f	25	4.06 \pm 0.033 f	79 (corr.)	<0.0001
<i>Fagus sylvatica</i>	20	4.0 \pm 2.34 c	66	4.64 \pm 0.080 f	22	4.25 \pm 0.108 ef	86	0.013
<i>Juglans regia</i>	20	5.0 \pm 1.99 bc	68	4.06 \pm 0.020 g	24	4.0 \pm 0.030 f	90	0.12
<i>Malus domestica</i>	20	6.0 \pm 2.55 abc	56	5.20 \pm 0.035 e	24	5.13 \pm 0.045 c	78	0.25
<i>Oleae europaea</i>	20	0 c	64	5.31 \pm 0.056 de	35	5.01 \pm 0.014 cd	71 (corr.)	<0.0001
<i>Pterocarya fraxinifolia</i>	20	6.75 \pm 3.0 abc	58	4.27 \pm 0.046 g	29	4.14 \pm 0.042 f	85	0.077
<i>Quercus macranthera</i>	20	4.0 \pm 2.34 c	71	4.32 \pm 0.072 g	25	4.18 \pm 0.070 ef	73	0.16
<i>Rosa canina</i>	20	17.0 \pm 4.87 a	59	4.80 \pm 0.038 f	24	4.63 \pm 0.069 de	81	0.024
<i>Typha latifolia</i>	20	16.25 \pm 4.27 ab	43	11.14 \pm 0.190 a	34	10.53 \pm 0.222 a	75	0.039
<i>Cydia pomonella</i>	20	0 c	63	6.15 \pm 0.086 b	25	5.82 \pm 0.091 b	86	0.028
F (X ²)		5.8199 (69.3831)		295.0429 ¹		205.3067 ¹		
<i>df</i> (Wilcoxon-test)		13,266 (13)		13,332 ¹		13,123 ¹		
<i>P</i> (Wilcoxon-test)		<0.0001 (<0.0001)		<0.0001 ¹		<0.0001 ¹		
<i>Amblydromalus limonicus</i>								
<i>Aesculus hippocastanum</i>	19	13.42 \pm 3.46 d	30	6.03 \pm 0.041 def	45	5.59 \pm 0.066 cde	69 (corr.)	<0.0001
<i>A. glutinosa</i>	20	0 e	53	7.02 \pm 0.075 bc	47	6.67 \pm 0.101 a	98	0.0060
<i>A. incana</i>	20	0 e	71	5.99 \pm 0.046 def	29	5.38 \pm 0.095 def	98	<0.0001
<i>Betula pendula</i>	19	7.37 \pm 2.27 de	52	5.56 \pm 0.067 gh	31	5.03 \pm 0.022 f	62 (corr.)	<0.0001
<i>B. napus</i>	20	0 e	66	6.13 \pm 0.097 de	34	5.25 \pm 0.077 def	97 (corr.)	<0.0001

Table 1 continued

Diet	N	Preimaginal mortality (%) ²	Females		Males		<i>df</i> ³	<i>P</i>
			N	Developmental time (days) ²	N	Developmental time (days) ²		
<i>Helianthus annuus</i>	19	36.32 ± 5.07 c	23	7.22 ± 0.186 b	29	6.12 ± 0.135 b	50	<0.0001
<i>Paulownia tomentosa</i>	20	51.75 ± 5.80 b	26	6.19 ± 0.062 def	20	5.70 ± 0.142 bcd	26 (corr.)	0.0039
<i>Pinus sylvestris</i>	19	12.90 ± 3.18 de	54	5.17 ± 0.059 fg	24	5.10 ± 0.042 ef	75 (corr.)	<0.0001
<i>Ricinus communis</i>	20	0 e	61	6.20 ± 0.083 d	39	6.05 ± 0.120 b	98	0.31
<i>Schlumbergera</i> sp.	20	0 e	74	5.33 ± 0.059 h	26	5.00 ± 0 f	73 (corr.)	<0.0001
<i>Tulipa gesneriana</i>	20	100 a	–	–	–	–	–	–
<i>T. latifolia</i>	19	17.81 ± 4.0 d	27	9.83 ± 0.291 a	36	7.07 ± 0.173 a	43 (corr.)	<0.0001
<i>Zea mays</i>	20	0 e	64	6.70 ± 0.069 c	36	5.90 ± 0.071 bc	98	<0.0001
<i>Cydia pomonella</i>	20	0 e	67	5.79 ± 0.044 efg	31	5.50 ± 0.073 cdef	96	0.0006
F (X^2)		116.9774 (206.1541)		59.7256 ¹		41.2565		
<i>df</i> (Wilcoxon-test)		13,261 (13)		12,210 ¹		12,414		
<i>P</i> (Wilcoxon-test)		<0.0001 (<0.0001)		<0.0001 ¹		<0.0001		

¹ F, *df*, and *P* values were corrected by Welch-test if variance inhomogeneity was given following Bartlett's test

² Means within a column and within a phytoseid species followed by the same letter do not differ significantly (1-way ANOVA followed by Tukey–Kramer HSD-test: *P* < 0.05; non-parametric Wilcoxon-test followed by Wilcoxon pairwise comparison for preimaginal mortality: *P* < 0.05)

³ *P* of the bilateral *t* test for preimaginal development of females versus males; *df* were corrected if variance inhomogeneity was given following Bartlett's test

Table 2 Body weight (mean \pm SEM) of *Amblyseius swirskii*, *Amblydromalus limonicus*, and *Neoseiulus cucumeris* reared on different diets

Diet	Females		Males		df^2	P
	N	Body weight (μg)	N	Body weight (μg)		
<i>Amblyseius swirskii</i>						
<i>Aesculus hippocastanum</i>	48	5.69 \pm 0.062 efg	47	3.02 \pm 0.039 ab	81 (corr.)	<0.0001
<i>Alnus glutinosa</i>	37	5.32 \pm 0.108 gh	42	2.55 \pm 0.062 de	59 (corr.)	<0.0001
<i>A. incana</i>	49	5.75 \pm 0.079 defg	48	2.57 \pm 0.048 de	74 (corr.)	<0.0001
<i>A. japonica</i>	47	5.50 \pm 0.074 fgh	34	2.84 \pm 0.040 bcd	69 (corr.)	<0.0001
<i>Brassica napus</i>	50	6.19 \pm 0.072 cd	49	2.64 \pm 0.067 cde	93	<0.0001
<i>Corylus avellana</i>	63	4.33 \pm 0.143 i	62	1.95 \pm 0.097 ghi	109 (corr.)	<0.0001
<i>Fagus sylvatica</i>	47	6.10 \pm 0.083 cde	47	2.62 \pm 0.065 cde	83 (corr.)	<0.0001
<i>Juglans regia</i>	97	5.79 \pm 0.068 def	92	2.84 \pm 0.031 bc	138 (corr.)	<0.0001
<i>Malus domestica</i>	50	5.81 \pm 0.069 defg	47	2.12 \pm 0.027 gh	63 (corr.)	<0.0001
<i>Olaea europaea</i>	46	5.19 \pm 0.067 h	46	2.46 \pm 0.035 ef	69 (corr.)	<0.0001
<i>Pinus sylvestris</i>	42	5.63 \pm 0.061 efg	24	2.65 \pm 0.047 cde	60 (corr.)	<0.0001
<i>Pterocarya fraxinifolia</i>	62	5.74 \pm 0.121 defg	57	1.78 \pm 0.073 i	97 (corr.)	<0.0001
<i>Quercus macranthera</i>	55	8.18 \pm 0.109 a	56	1.93 \pm 0.060 hi	81 (corr.)	<0.0001
<i>Ricinus communis</i>	47	7.11 \pm 0.093 b	47	2.23 \pm 0.066 fg	82 (corr.)	<0.0001
<i>Rosa canina</i>	45	5.92 \pm 0.118 cdef	47	2.59 \pm 0.060 cde	65 (corr.)	<0.0001
<i>Schlumbergera</i> sp.	55	5.39 \pm 0.092 gh	50	2.82 \pm 0.061 bcd	91 (corr.)	<0.0001
<i>Tulipa gesneriana</i>	45	5.81 \pm 0.041 defg	49	3.28 \pm 0.049 a	91 (corr.)	<0.0001
<i>Typha latifolia</i>	60	5.18 \pm 0.081 h	25	2.56 \pm 0.036 cdef	75 (corr.)	<0.0001
<i>Cydia pomonella</i>	46	6.37 \pm 0.119 c	47	2.57 \pm 0.056 de	61 (corr.)	<0.0001
F ¹		56.8762		58.1193		
df ¹		18,345		18,305		
P ¹		<0.0001		<0.0001		
<i>Amblydromalus limonicus</i>						
<i>Ae. hippocastanum</i>	47	5.54 \pm 0.094 b	58	3.06 \pm 0.045 a	67 (corr.)	<0.0001
<i>A. glutinosa</i>	35	4.24 \pm 0.222 e	26	1.39 \pm 0.076 gh	42 (corr.)	<0.0001
<i>A. incana</i>	47	6.53 \pm 0.042 a	48	2.30 \pm 0.023 c	71 (corr.)	<0.0001
<i>Betula pendula</i>	47	5.29 \pm 0.082 bc	48	2.98 \pm 0.044 ab	71 (corr.)	<0.0001
<i>B. napus</i>	48	3.93 \pm 0.052 e	47	2.08 \pm 0.031 cde	77 (corr.)	<0.0001
<i>Helianthus annuus</i>	45	2.56 \pm 0.031 g	48	1.41 \pm 0.034 h	91	<0.0001
<i>Paulownia tomentosa</i>	49	3.22 \pm 0.063 f	49	1.93 \pm 0.056 de	96	<0.0001
<i>P. sylvestris</i>	45	4.09 \pm 0.073 e	49	1.67 \pm 0.052 fg	81 (corr.)	<0.0001
<i>R. communis</i>	29	4.98 \pm 0.105 cd	54	1.84 \pm 0.086 ef	81	<0.0001
<i>Schlumbergera</i> sp.	48	5.59 \pm 0.054 b	48	2.14 \pm 0.032 cd	77 (corr.)	<0.0001
<i>T. latifolia</i>	50	2.92 \pm 0.076 fg	49	1.37 \pm 0.051 h	85 (corr.)	<0.0001
<i>Zea mays</i>	45	5.51 \pm 0.032 b	48	1.97 \pm 0.031 de	91	<0.0001
<i>Cydia pomonella</i>	51	4.89 \pm 0.092 d	52	2.79 \pm 0.088 b	101	<0.0001
F ¹		720.4323		144.7645		
df ¹		12,215		12,227		
P ¹		<0.0001		<0.0001		

Table 2 continued

Diet	Females		Males		df^2	P
	N	Body weight (μg)	N	Body weight (μg)		
<i>Neoseiulus cucumeris</i>						
<i>Ae. hippocastanum</i>	50	5.92 \pm 0.081 a	48	3.03 \pm 0.036 a	70 (corr.)	<0.0001
<i>B. pendula</i>	49	4.66 \pm 0.058 d	47	2.73 \pm 0.034 b	75 (corr.)	<0.0001
<i>M. domestica</i>	49	4.78 \pm 0.054 cd	47	2.69 \pm 0.040 b	85 (corr.)	<0.0001
<i>Schlumbergera</i> sp.	47	4.97 \pm 0.057 c	48	2.99 \pm 0.054 a	91	<0.0001
<i>T. gesneriana</i>	47	5.27 \pm 0.065 b	48	3.02 \pm 0.055 a	93	<0.0001
<i>Zea mays</i>	50	4.76 \pm 0.060 cd	49	2.57 \pm 0.049 b	92	<0.0001
F^1		41.2054		19.2973		
df^1		5133		5131		
P^1		<0.0001		<0.0001		

Means within a column and within a phytoseiid species followed by the same letter do not differ significantly (1-way ANOVA followed by Tukey–Kramer HSD-test: $P < 0.05$)

¹ F , df , and P values were corrected by Welch-ANOVA-test because of variance inhomogeneity after Bartlett's test

² P of the bilateral t test for body weight of females versus males; df were corrected if variance inhomogeneity was given following Bartlett's test

on mite species and food, mean body weight varied widely in females between 4.12 μg for *A. limonicus* fed with *P. sylvestris* and 8.18 μg for *A. swirskii* fed with *Q. macranthera*, and in males ranging from 1.39 μg for *A. limonicus* fed with *A. glutinosa* to 3.68 μg for *A. swirskii* fed with *P. tomentosa*. Only *A. limonicus* females fed on *P. tomentosa*, *T. latifolia*, and *H. annuus* pollen had a low mean weight (3.19, 2.90, and 2.54 μg , respectively) similar or only slightly higher than the mean male body weight of the three species tested. Feeding *A. limonicus* with *T. gesneriana* and *N. cucumeris* with pollen of *R. communis* proved to be an unsuitable food for this mite species, resulting in 100 % preimaginal mortality.

Amblyseius swirskii female mean body weight ranged between 4.33 and 8.18 μg when fed with *C. avellana* and *Q. macranthera*, respectively, and that of males varied between 1.78 and 3.66 when fed with *P. fraxinifolia* and *P. tomentosa*, respectively. Thus, the best food resulted in a 2 \times higher body weight of both sexes compared to the poorest food source. Feeding on *C. pomonella* eggs as animal food source resulted in high mean body weights in both, females and males of *A. swirskii* and *A. limonicus*. However, some pollen had a higher nutritional value for the mite species than codling moth eggs (Table 2).

Although the number of pollen species tested was not the same, in contrast to *A. swirskii* the highest female and male mean body weight of *A. limonicus* (6.54 and 3.07 μg , respectively) was almost 2.5 \times higher when reared on the most valuable food compared to the weight obtained when fed with the poorest food. However, also in this species, the ranking of the different food sources was not consistent between females and males. The nutritional value of related *Alnus*-species differed between pollen species and also between *A. swirskii* and *A. limonicus* (Table 2). Feeding pollen of *T. gesneriana* led to 100 % preimaginal mortality, whereas for *A. swirskii* and *N. cucumeris* this pollen was a food source of good quality.

Due to the smaller number of pollen tested, body weight of female and male *N. cucumeris* showed few significant differences ranging between 4.7 and 5.92 μg for females and 2.55 and 3.04 μg for males when fed with pollens which were found also among the best food for both *A. swirskii* and *A. limonicus*.

The multiple ANOVA by GLM-analysis, with predator species as additional factor, revealed significantly different performances of the mite species when fed with identical pollen. Factor combinations of pollen with species or sex also resulted in highly significant interactions (Table 3).

Discussion

Biological parameters used to describe the quality of predators such as developmental time, mortality, fecundity, reproduction period, longevity, predation potential and body size are tools to estimate the suitability of different factitious prey species, alternative food, or an artificial diet for mass rearing of predators (Croft et al. 1999; Grenier and De Clercq 2003; van Lenteren 2003; Callebaut et al. 2004). Not only the physical fitness and longevity are, to a certain extent, dependent on body weight and energy availability, which are determined by food quality, but also reproduction-related parameters depend on female size. The total number of eggs per female *Phytoseiulus persimilis* Athias-Henriot was positively correlated with the size of females. Even in the F_1 -generation, the mean dorsal

Table 3 Analysis of variance (GLM: General Linear Model, normal distribution, link: identity, full module test, maximum-likelihood) of preimaginal mortality, developmental time, and adult weight of *Amblyseius swirskii*, *Amblydromalus limonicus*, and *Neoseiulus cucumeris*, with identical pollen provision (*Aesculus hippocastanum*, *Betula pendula*, *Ricinus communis*, *Schlumbergera* sp., *Tulipa gesneriana*, and *Zea mays*)

	N	df	X ²	P
Preimaginal mortality				
Full model	372	17	668.5525	<0.0001
Source				
Species		2	158.9547	<0.0001
Pollen		5	249.1534	<0.0001
Species \times pollen		10	525.0332	<0.0001
Developmental time				
Full model	947	15	986.7799	<0.0001
Source				
Species		2	600.3407	<0.0001
Pollen ¹		3	408.3027	<0.0001
Sex		1	75.6579	<0.0001
Species \times pollen		6	176.1114	<0.0001
Sex \times pollen		3	11.1382	0.011
Adult weight				
Full model	1168	15	2640.750	<0.0001
Source				
Species		2	22.6254	<0.0001
Pollen ¹		3	233.4645	<0.0001
Sex		1	2573.5409	<0.0001
Species \times pollen		6	223.3406	<0.0001
Sex \times pollen		3	51.1585	<0.0001

¹ Pollen of *R. communis* and *T. gesneriana* excluded

shield length of females was positively correlated with the size of the parental females (Walzer and Schausberger 2013, 2014).

The phytoseiid mite species differ in size (Collyer 1982; Beard 2001; Zhang 2003), which may bear the risk of misinterpretation of absolute body weight differences between species, because mean body weight is directly correlated with body length (Goleva et al. 2014). However, body size of *A. limonicus*, *N. cucumeris*, and *A. swirskii* do not differ so much, ranging between 0.37 and 0.40 mm (Zhang 2003), and a direct comparison of body weight of these species should be possible.

Although each pollen offered was accepted and consumed by the three phytoseiid species tested, the nutritional value was not consistent for the three species. For example, a highly valuable food for *A. swirskii* must not necessarily have the same quality for another phytoseiid species. Comparing the ranks of suitability and quality of the five pollen tested with all three mite species, pollen of castor bean ranked first and fifth in female weight of *A. swirskii* and *A. limonicus*, respectively, but was absolutely unsuitable for *N. cucumeris* suffering from 100 % preimaginal mortality (Ranabhat et al. 2014).

Sexual dimorphism in phytoseiid mites is well described (Collyer 1982; Beard 2001) and, thus, in all mite species tested, females were generally heavier than males when fed with the same food. However, the relative difference between female and male weight was not always the same. For example, males of *A. swirskii* fed with pollen of *A. hippocastanum* and *Q. macranthera* reached 55.8 and 23.6 % of the female weight. Nearly similar differences could be found for *A. limonicus* fed with *P. tomentosa* and *A. glutinosa*-pollen, where males gained a body weight of 61.1 and 32.8 % of the female weight, respectively.

It may be assumed that males and females have different nutritional demands, which could not served by some pollen, either due to a poor metabolisation or lack of nutrients. Pollen of *Ae. hippocastanum* had the highest nutritional quality for all three mite species tested. Inferior nutritional quality of *T. latifolia* pollen has been reported also by Vangansbeke et al. (2014a, 2014b) for *A. limonicus* females compared to animal prey, being the smallest when fed with *T. latifolia* pollen compared to that of females fed with *Ephestia kuehniella* Zeller eggs or *Artemia franciscana* Kellogg cysts. Also females of *A. swirskii* reached a low body weight only when fed with *T. latifolia* whereas other pollen or codling moth eggs had a superior food quality.

Although cattail pollen has often been attributed a high nutritional quality for predacious mites, our results indicate that cattail pollen either collected at different years and/or possibly handled differently differs in food quality. Furthermore, food quality for predacious mites differs among mite species in a direct comparison and not only after comparison of literature data (Nguyen et al. 2015).

The most striking differences in food quality were found for pollen of *R. communis* and *T. gesneriana*. Pollen of castor bean was a suitable food source only for *A. swirskii* and *A. limonicus*, whereas *N. cucumeris* suffered from 100 % preimaginal mortality (Ranabhat et al. 2014). On the other hand, *A. limonicus* could not develop into adults when reared on pollen of *T. gesneriana*. Only *A. swirskii* could develop when fed with both the pollen. Compared with *A. limonicus* and *N. cucumeris*, *A. swirskii* is adapted to a wider range of pollen as alternative food source.

The significant effects of single factors and factor combinations on preimaginal mortality, developmental time, and adult weight of mites fed with identical pollen indicate that, firstly, the nutritional value of a food source for a given mite species cannot be generalized and any food source has to be tested independently. Secondly, it can be concluded that the mite species are differently adapted to pollen, which may depend on a species-specific equipment of metabolizing enzymes or differences in their activity. A possible explanation

for differences in pollen suitability may be found in a better adaptation of mites to pollen of autochthonous plant species in the same area of distribution, e.g. *Q. macranthera*, *R. communis* and *A. swirskii*, which may explain the good nutritional quality of their pollen for this mite species. On the other hand, *N. cucumeris* as a litter-dwelling species should also be adapted to a wide range of food sources, such as decaying organic matter or small soil- and litter-inhabiting arthropod species.

Reviews on pollen chemistry mainly report average concentrations of nutrients, such as proteins, nitrogen, amino acids, lipids, carbohydrates, and sterols of few taxa (Todd and Bretherick 1942; Stanley and Linskens 1974; Rabie et al. 1983; Day et al. 1990; Roulston and Cane 2000; Patt et al. 2003; Somerville and Nicol 2006; Li et al. 2007; You et al. 2007; Campos et al. 2008).

Because of lacking detailed information on pollen chemistry and a very poor knowledge of mite's nutritional physiology, the nutritional value of pollen and digestive or metabolizing processes in mites can only be assumed. Also calculations of food digestibility and conversion indices as used for insect nutrition studies (Waldbauer 1968), are elusive in mites due to their small size and biomass. Indirect parameters, such as digestive efficiency estimated for mites by counting empty pollen grains (Flechtmann and McMurtry 1992), are not very helpful to discuss the nutritional value of pollen or other mite's food.

Whereas proteins, carbohydrates, amino acids and lipids can be taken *in toto* as nutrients and digestion and metabolism should be unproblematic for the phytoseiids, detoxification of secondary compounds in pollen, such as alkaloids, flavonoids, or saponins (Stanley and Linskens 1974; Bonvehi et al. 2001; Roth et al. 2008) depends on the equipment of the mite species or strains with metabolizing enzymes. Particularly the multifunctional oxidases (mfo), esterases, or glutathione-S-transferases, are known to be responsible for food adaptations in herbivorous insects or are generally involved in the detoxification of xenobiotics. Furthermore, pollen, like that of *Z. mays*, may contain quercetin, which is an effective protease-inhibitor, interfering with protein digestion and negatively affecting food conversion although a high protein content may suggest high suitability of a pollen as food source (Larsen 1971; Stanley and Linskens 1974; Barbehenn and Constabel 2011).

For a better understanding of phytoseiid nutrition, particularly on plant material, it is inevitable to know more about the chemical composition of pollen and the nutritional physiology of these mites.

Acknowledgments The authors are indebted to Greta Ott and Josef Schreiber for their help in pollen collection. This study was in part supported by a PhD grant from the European commission Erasmus Mundus External Cooperation Window (IAMONET-RU).

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