Running title: Host related pupal emergence in cactophilic flies

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*Original article*

**Pupal emergence pattern in cactophilic Drosophila and the effect of host plants**

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Abstract

_Drosophila buzzatii_ and _D. koepferae_ are sibling cactophilic species. The former breeds primarily on prickly pears (genus _Opuntia_) whereas the latter breeds on columnar cacti of the genera _Cereus_ and _Trichocereus_, although with certain degree of niche overlapping. We examined the interspecific differences in diurnal temporal patterns of adult emergence from puparia and evaluated whether this behavior is affected by rearing in the different cactus hosts available in nature. We detected important host-dependent genetic variation for this trait differentially affecting the emergence schedule of these species. Diurnal pattern of emergence time was directly correlated with developmental time and negatively correlated with adult wing size, suggesting that early emergences are at least indirectly correlated with increased fitness. We discussed our results in terms of their putative effects on fitness and the genetic-metabolic pathways that would be presumably affected by host’s nutritional-chemical differences.

Keywords: alkaloids; Cactus; circadian cycle; life history traits; phenotypic plasticity; pupae
Introduction

Arthropods are a predominant animal taxon in arid environments (Whitford, 1999). Despite the extreme temperatures and low humidity that might constitute severe stressful conditions for their physiology, these invertebrates have managed to adapt and thrive in desert habitats. The tendency for nocturnal/crepuscular activity patterns may prevail in these environments, since it allows avoiding exposure to extremely hot conditions. In this regard, the daily activity patterns of desert flies are a good example of temporal avoidance as an adaptation to the thermal stress (Dahlgaard et al., 2001). Some fly communities, including species of Drosophila, occur in arid environments (Markow & O’Grady, 2005; Oliveira et al., 2012). However, desiccation and temperature stress can significantly impact on them, even in mesic environments (Worthen et al., 1998; Worthen & Haney, 1999; Folguera et al., 2008). As with other holometabolous insects, adaptive mechanisms in response to stress are likely to vary across life stages. Adults may display avoidance of extreme temperatures by seeking refuge in cooler/warmer microhabitats (Junge-Berberovic, 1996; Feder et al., 2000), but larvae and pupae might be less able to spatially avoid thermal stress (Feder et al., 1997) forcing them to adapt through metabolic adjustment (Hoffmann & Parsons, 1991; Dahlgaard et al., 2001). Indeed, Coyne et al. (1983) have already suggested that the marked adaptive differences in thermal resistance observed in pupae (but not in adults) from different populations of Drosophila, are the result of the pupae’s inability for behavioral response (i.e. lack of a mechanism for mobility) to extreme temperatures.

The timing of daily activity plays an important role in stress-avoidance adaptations as many aspects of physiology and behavior are clock-controlled. There are numerous activities restricted to a particular part of the day or night in many insect species (reviewed in Saunders, 2002). For instance, mating presents two daily peaks of increased activity in natural populations of the cactophilic D.
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mojavensis Patterson (Krebs & Bean, 1991), one in the morning and one in the evening. Pupation and pupal emergence time display physiologic-related circadian rhythms as potential adaptations to avoid environmental stresses (Bartholomew, 1964; Saunders, 2002; Sørensen & Loeschcke, 2002). Although the phenomenon of insects emerging from the pupae following a diurnal rhythm was well established in the past century (e.g. Bliss, 1926; Pittendrigh, 1954; Bateman, 1955; Brett, 1955; Palmén, 1955; Bünning, 1958, Bakker & Nelissen, 1963), recent studies on the topic are rare or nonexistent for the vast majority of holometabolous groups.

The Drosophila repleta group has diversified in arid and semi-arid regions of the Americas due to the ability of several species to colonize necrotic tissues of cacti (Throckmorton, 1975; Durando et al., 2000). Cactophilic species are strongly associated with their host plants and show different degrees of specialization and niche width. Within this group, the D. buzzatii cluster constitutes a radiation occurring in the last 4.6 million years (Oliveira et al., 2012). This monophyletic group of at least seven species is mainly found in open xerophytic regions of South America (Manfrin & Sene, 2006). We studied the pair of sibling species D. buzzatii Patterson and Wheeler and D. koepferae Fontdevila and Wasserman, which co-occur in the arid Andean regions of western Argentina and Bolivia (Fontdevila et al., 1988). Drosophila buzzatii uses necrotic cladodes of prickly pears of the genus Opuntia as primary hosts, whereas D. koepferae exploits mainly columnar cacti of the genera Cereus and Trichocereus. Nonetheless, in the vast areas where both species occur in sympatry, a certain degree of overlap in host exploitation occurs, with the two species emerging from both resources despite maintaining a preference for their respective primary host (Hasson et al., 1992; Soto et al., 2012). Previous studies showed that traits associated to fitness were maximized when flies were reared in their primary hosts (Soto et al., 2008a,b, 2012, 2014; Hurtado et al., 2012). Developmental instability levels increased when flies of both species were reared in their respective secondary host (Soto et al., 2008b).
In contrast to abundant literature focused on morphological and life-history traits, studies addressing stress-avoidance traits and their ecological relevance are scarce for this group, despite the high amount of genetic variability known to be available to fuel the adaptive evolution of behavioral and physiological characters (Hoffmann, 1991; Boake, 1994; Soto et al., 2012). In this regard, the best known behaviors are host acceptance and oviposition preference (Fanara et al., 1999; Soto et al., 2012). Host acceptance assays revealed that both types of cactus are equally accepted by *D. buzzatii* and *D. koepferae* as egg-laying sites. In contrast, oviposition preference assays revealed that *D. buzzatii* clearly prefers its primary host, whereas for *D. koepferae* the pattern is less clear as similar quantities of eggs were found to be laid in both hosts’ tissues (Soto et al., 2012).

In the present study we determined, described and compared the daily patterns of adult emergence from puparia of *D. buzzatii* and *D. koepferae* in different cactus hosts. We evaluated whether the time of emergence of adults presents a plastic host-dependent pattern or is otherwise a canalized clock-controlled cycle (potentially related to exogenous predictable stress factor such as temperature). Additionally, we analyzed the existence of intraspecific genetic variation for this trait and its correlation with fitness-related traits.

**Materials and methods**

*Fly stocks and cactus collection*

Ten isofemale lines of each species were founded with flies collected in the Valle Fértil Natural Reserve, located in Northwestern Argentina (30°31′13″S, 67°34′05″W), where both *O. sulphurea* and *T. terscheckii* are available as cactus hosts. Rotting cladodes and fresh materials of both cacti were
collected for the preparation of ‘semi-natural’ rearing media. The fresh cactus material was stored at -20º C while the exudates from several necrotic tissues were maintained at 4º C in plastic containers with sterilized cotton caps, with the addition of 10 g of fresh cactus every two weeks. For the preparation of the ‘semi-natural’ media, pieces of fresh cactus of each species were mixed in a blender and 6 mL were poured into standard glass vials. Vials were then inoculated with 0.1 mL of the fermenting juice produced by the necrotic tissues (see Fanara et al., 1999 for details). Isofemale lines (lines hereafter) of each species were maintained in bottles with 30 mL of standard Drosophila instant medium (Carolina Biological Supply Company) until the onset of the experiments (two generations after collection). Laboratory rearing and experimental conditions were held constant at 25 ± 1º C with a 12:12h light/dark photoperiod.

Collection permits for both flies and cacti tissues were issued to IMS and JP by local authorities of Conservation Management and Protected Areas (Secretariat of Environment and Sustainable Development, San Juan, File N° 1300-0236-13).

Emergence time recording and traits scored

Drosophila buzzatii and D. koepferae larvae were reared in sets of vials prepared with O. sulphurea or T. terscheckii semi-natural media. We set two egg-collecting chambers per species, containing a petri dish with egg-laying medium (agar-agar with commercial yeast) and one hundred pairs of sexually mature flies. Petri dishes were removed 12 h later and inspected for the presence of eggs. The eggs were collected on the agar surface and then sterilized with 50 % clorox for 3 min (Fanara et al., 1999); batches of 100 eggs were placed on sterile agar and incubated for another 24 h to allow larval hatching. Batches of 30 first instar larvae were then collected and placed in culture vials containing 6 ml of one of the two alternative semi-natural cactus media (cactus hereafter). Larval...
placing was performed between 7 and 8 am h. We analyzed ten isofemale lines per *Drosophila* species, with four replicated vials initiated for each combination of line and cactus. Emerged flies were collected every 4 hours (at 8, 12, 16 and 20 h) during the diurnal period (i.e. Light hours in the photoperiod) and sexed under light CO₂ anesthesia.

Mean emergence time (ET) for each replicate was estimated by recording the number of emerged individuals in each collection interval, every day by a total of five days. Additionally, we scored three traits associated with the performance of genotypes in host exploitation: larval viability (LV), developmental time (DT) and adult wing size (WS). LV was scored for each vial as the proportion of adult survivors with respect to the number of larvae originally placed in the vial. DT was recorded as the time elapsed (in hours) from the moment in which first instar larvae were placed in the vials until the emergence of each adult fly. WS (as a proxy for body size) was scored following Soto et al. (2014) protocol. Briefly, right wings of adult flies of both sexes were removed and mounted on slides. Digital images of wings were obtained, 10 landmarks were placed along each wing and the centroid size (the square root of the sum of the squared distances of landmarks to the centroid of the configuration) was calculated.

*Data analysis*

The window of emergence from pupae encompassed six days although over 95% of all individuals usually emerged within the first five days. Thus, in order to avoid heavy tailed distributions, the individuals emerged on the sixth day were considered for LV analysis but treated as outliers and therefore excluded from the ET and DT analyses.
Regarding ET, as the response variable (number of emerged individuals) was measured as a count variable, the analyses were carried out using Generalized Linear Mixed Models (GLMM) with a Poisson distribution. To account for differences in viability, the total number of emerged individuals of the same sex from the same replica at the end of the experiment was used as covariable. Each Drosophila species was analyzed separately. Three fixed explanatory variables were considered: Cactus, Sex and Hour of emergence (integer covariate representing each collection interval), as well as their interactions.

After data transformation, the traits complied with ANOVA assumptions. LV scores were angularly transformed whereas DT and WS scores were log-transformed. Traits were analyzed by means of an ANOVA with Drosophila and Cactus (fixed categorical factors, each one with two levels) and Line (categorical random factor with 10 levels, nested in Drosophila) as explanatory variables. Additionally we performed intraspecific analyses consisting in two-way factorial ANOVAs with Cactus (fixed) and Line (random) as explanatory variables.

Correlations between ET and the other traits were tested for each line in both cacti by means of Pearson product moment correlation tests corrected for multiple tests. To assess the relative contributions of genetic and environmental sources of phenotypic variation, we included random intercept and slope models for Line and Replica (random factors). These designs are classic applications of the isofemale line technique for characterizing quantitative traits in natural populations (David et al., 2005) in which the Line-associated variation is an estimator of phenotypic (genetic) variation, the Cactus-associated variation estimates the phenotypic plasticity and the interaction between them indicates a genetic by environment interaction (G × E). In ET analysis, we performed intraspecific Poisson GLMMs using the same fixed explanatory variables, as well as Line.
and Replica as random factors. Statistical significances for the latter were tested through likelihood ratio tests, by successively dropping fixed terms and assessing their contribution to the model.

Analyses were performed in R environment (R Core Team, 2015) using the packages lme4 (Bates et al., 2014) and car (Fox & Weisberg, 2011).

Results

We recorded the emergence of 3085 total individuals (from which 26 adults emerged on the sixth day). Mean values of ET, LV, DT and WS for each breeding cacti are shown in Table 1.

**Emergence time**

Sexual differences in ET were absent in both species (Table 2). In the case of *D. buzzatti*, the proportion of emerged adults peaked late in the morning (collected at 12 h), whereas adults of *D. koepferae* revealed high proportions of emerged flies both at 8 and 12 h (Fig. 1). The interaction between Hour of emergence and Cactus was significant only in the case of *D. buzzatti*, revealing that the pattern of emergence differed between rearing hosts with individuals emerging earlier during the day when they are reared in *T. terscheckii* (Table 2). Genetic variation was detected in both species but was higher in *D. koepferae* (Line variance *D. buzzatti* = 0.006; Line variance *D. koepferae* = 0.015). Moreover, the Replicate factor (a proxy of environmental “noise”) explained a larger amount of total variation than the Line factor in both species, but was higher and only significant in *D. koepferae* (Replicate variance *D. buzzatti*...
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= 0.084; Replicate variance $D. koepferae = 0.313$). Thus, on average, random environmental variation was 18 times larger than genetic induced variability.

**Performance of genotypes in host exploitation: larval viability, developmental time and adult wing size**

The analysis of LV showed a *Drosophila* by Cactus significant interaction (Table 3). *Drosophila buzzatii* presented lower LV when reared in *T. terscheckii* (Post hoc Tukey test, $F_{1,120}=15.513, P < 0.01$) whereas no differences were detected for *D. koepferae* (Post hoc Tukey test, $F_{1,120} = 0.001, P = 0.983$) (Fig. 2). Additionally, important variation among lines within *Drosophila* species was also detected (Fig. 2). Thereby no significant Cactus by Line interaction was observed in general or intraspecific analyses suggesting the nonexistence of variation of reaction norms among genotypes (Table 3). Regarding the variance components, we observed extremely differing patterns between species. Although neither species showed significant $G \times E$ interaction, *D. buzzatii* displayed low levels of phenotypic variation attributable to among-genotypes variation, whereas variation among lines accounted for 38% of the overall LV variation in *D. koepferae* (Fig. 2).

On average, both species developed faster (lower DT) in *T. terscheckii* but as for LV, the difference was more marked in *D. buzzatii* (Fig. 2). This behavior was not entirely consistent among lines within species, indicating substantial amounts of host-dependent genetic variation segregating in the populations (significant Cactus by Line interaction, Table 3). Host cacti influence on *D. buzzatii*’s DT, but also an important $G \times E$ interaction was detected indicating significant amounts of variation in phenotypic plasticity (39% of total phenotypic variation; Fig. 2). *Drosophila koepferae*’s mean DT on the other hand, seemed rather impervious to changes in rearing host. Nevertheless, an important
variation among the genotypes was observed for this trait, with the Line factor accounting for 19% of total phenotypic variation (Fig. 2).

Regarding WS, *D. koepferae* presented bigger wings than its sibling. In a pattern opposite to that of DT, *D. buzzatii* displayed size variation among lines but not host-dependent phenotypic plasticity whereas for *D. koepferae* there was an evident variability among genotypes across hosts (Table 3, Fig. 2).

**Correlations among traits**

Both *Drosophila* species presented mean Emergence times significantly correlated with developmental time and wing size of adults but not with larval viability (Table 4). The daily-belated genotypes of both species displayed longer developmental times throughout the experiment (a seemingly trivial result but that discards the scenario of flies emerging mainly in the afternoon of the first day of emergence and in the morning of subsequent days). Also, both species showed smaller wing sizes as adults. Finally, whereas *D. buzzatii* had similar pattern of correlations between traits independently of the cactus, *D. koepferae* presented a host-dependent pattern of correlations (Table 4).

**Discussion**

The temporal pattern of emergence is regarded as an important life history trait in holometabolous insects inhabiting regions where, such as deserts, environmental conditions are highly variable reaching potentially stressful levels with lethal values for many organisms (Hoffmann & Parsons,
In the case of flies, after emergence from puparia, adults are vulnerable and unable to immediately take off. Flies expend a couple of hours extending their wings and hardening their cuticle before being able to fly. During this critical period, they have limited mobility and are under potentially higher risk of predation and or desiccation. Therefore, the emergence schedule should be an adaptive trait highly linked with local environmental conditions. In the present study we have established that emergence events are not randomly distributed during the day as both species exhibit an early daytime emergence. In natural (i.e. collection site) conditions, this is when milder and moister environmental conditions prevail (AccuWeather, 2015). Our results are in agreement with previous observations in *D. pseudoobscura* Frolova which emerges from the puparia close to dawn when the relative humidity of the air is at its height. In fact it has been established that the maximum eclosion’s success in this species occurs during dawn (Pittendrigh, 1958). Bakker and Nelissen (1963) found that for *D. melanogaster* Meigen, emergence is highest between 4 and 8 o’clock in the morning. However, the eclosion’s success along humidity and temperature gradients in cactophilic species remains undescribed.

The number of individuals emerging during the night was negligible, as the flies first scored in the morning were still in their puparia at 7 h AM when the record began (IM Soto, personal observation) and according to our capture records at the collection site, *D. buzzatii* and *D. koepferae* are more active in the two to three hours following sunrise and the hours preceding dusk. In this regard, the next step is to confirm these observations in both natural conditions and experimental setups, and extend them to other related species inhabiting xeric environments.

Studies of natural populations in the field and under laboratory conditions have shown that *D. buzzatii* and *D. koepferae* differ in their preferences regarding oviposition sites (Soto et al., 2012) and higher viabilities, faster developing times and increased mating success for both species were
observed when they were reared in their respective primary hosts (Soto et al., 2008a; Hurtado et al., 2012). Here we enlarged the list of traits in which host-dependent phenotypic plasticity is displayed by *D. buzzatii* whereas *D. koepferae* showed a more canalized behavior as previously observed for viability, developmental time (Soto et al., 2008a,b, 2012, 2014), starvation resistance, oviposition preference (Soto et al., 2012) and genital morphology (Soto et al., 2007). As a performance-related trait, time of pupal emergence was positively correlated with developmental time and negatively correlated with adult wing size. Previous results, in *D. melanogaster*, have shown that food uptake affects puparium formation and emergence time (Bakker, 1959). Thus, for cactophilic species, variation in larval density (as in field rots where densities may be much higher) might produce results different than those observed in the present study. Larval density used in our experiments (30 larvae per vial) has proven to be optimal for different fitness related traits (i.e., it does not change results obtained using lower larval densities; Fanara et al. 1999) and yet was sufficient to elicit a host-dependent response. More stressful conditions and the assessment of a reaction norm to emergence time remain untested.

Similar correlations between emergence time and developmental time and adult size have been observed in *D. melanogaster* (Bakker & Nelissen, 1963). Delayed development and small adult size are considered indicators of low performances (Norry et al., 2001; Cortese et al., 2002). These correlations would indicate that, within hosts, early emergences are at least indirectly, if not directly, correlated with increased fitness. Regarding the developmental time-wing size correlation, our results showed that this negative correlation, expected in *Drosophila* species in general (Bakker & Nelissen, 1963; Norry et al., 2001; Cortese et al., 2002), was not observed in most cases except for *D. koepferae* bred in *O. sulphurea*. It is interesting to note that the patterns of correlation between traits in *D. koepferae* changed with breeding resources, unlike *D. buzzatii*. This may affect the evolution of different strategies of adaptation to heterogeneous breeding resources.

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D. buzzatii showed and interesting variation in the time of emergence from pupae between cactus hosts while D. koepferae tended to be more resilient (a pattern previously observed on other traits; Soto et al., 2007; Soto et al., 2008b; Soto et al., 2014). Previous observations could be considered in the context of the present results. First, it is known that the nutritional quality of food has profound effects on the circadian rhythms of many organisms (Panda et al., 2002; Froy, 2009). In fact, in Drosophila, correlations between the circadian clock and development time have been observed, with the latter depending in turn on the substrate quality (Walkiewicz & Stern, 2009; Yadav & Sharma, 2013). In the present case, O. sulphurea is a cactus host richer in sugar and fat content respect to T. terscheckii (Padro & Soto, 2013; Carreira et al., 2014), which also harbors higher diversity of cactophilic microorganisms and yeasts in its necrotic tissues (Mongiardino Koch et al., 2015). Therefore, the experimental substrates are nutritionally different and could be a key factor conditioning the time spent in pupal stage, thus affecting ET as we know it affects development time (Soto et al., 2008b, Soto et al., 2014).

Cactus hosts also display extremely different contents of secondary metabolites (terpenes and alkaloids). There is substantial empirical evidence in insects showing pronounced modifications of behavioral, morphological, biochemical and physiological traits in response to secondary plant compounds (Fogleman, 2000; Narberhaus et al., 2005; Padró et al., 2014; Agrawal & Weber, 2015). In particular, alkaloids have a wide spectrum of pharmacological effects, including the alteration of circadian rhythms (Onishi et al., 2012a, b). Psychotropic drugs have been observed to affect the circadian rhythm of locomotor activity in insects, which along with the mescaline serotonin binding receptor emphasize the possible implication of neurotransmitters pathways affecting the emergence time via the central nervous system (Cymborowski & Muszyńska, 1974; Cymborowski, 1998; Aghajanian & Marek, 1999; Nishinokubi & Tomioka, 2000; Yuan et al., 2005). On the other hand, the presence of high concentrations of alkaloids compromise metabolism via detoxification pathways. In

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this sense, *T. terscheckii* is naturally rich in mescaline and close-related to phenylethylamine alkaloids with psychotrophic properties (Reti & Castrillon, 1951; Corio *et al.*, 2013). Previous studies showed that *D. buzzatii* but not *D. koepferae* suffered the effects of increasing doses of *Trichocereus*’ alkaloids (Soto *et al.*, 2014).

Therefore, direct and indirect mechanisms modulating the circadian clock depending on the alkaloid-molecular target could be involved in the present case. For instance, in *Drosophila*, it has been widely established the implication of the cytochrome P-450 inducible enzymes family in the metabolism of cactus alkaloids, whose activity in turn can affect circadian rhythms (Danielson *et al.*, 1995; Matzkin *et al.*, 2006; Bono *et al.*, 2008; Froy, 2009; Pan *et al.*, 2009). Recently, it has been proved that the same enzymes are differentially expressed in *D. buzzatii* and *D. koepferae* when exposed to alkaloids (De Panis *et al.*, 2016). In this sense, the genomic expression profile in cactophilic *Drosophila* has been observed to be largely plastic during development responding to different cactus hosts, causing pervasive changes beyond the expected specific chemical-stress responses and comprising genes directly related to circadian cycles (Matzkin *et al.*, 2006; Etges *et al.*, 2015, De Panis *et al.*, 2016).

In summary, host plant differentially affect daily emergence patterns in the studied species, which nonetheless showed a strong fixed pattern of early eclosion during the day. The fact that this behavior correlates with the moister/cooler environmental conditions of the day suggest the overwhelming relevance of physical conditions during emergence time adaptation. Further field studies in natural populations should be performed in order to test these hypotheses and to assess the ecological implications of different emergence strategies.

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Table 1. Means corresponding to emergence time (ET, mean hour of daily emergence from puparia), larval viability (LV, estimated as the proportion of original larvae emerged as adults), developmental time (DT, in hours) and wing size (WS, log centroid size) of isofemale lines of *D. buzzatii* and *D. koepferae* reared in alternative cacti. Standard errors are reported in parentheses.

| *Drosophila* species | Cactus       | ET     | LV     | DT      | WS     |
|---------------------|--------------|--------|--------|---------|--------|
| *D. buzzatii*       | *O. sulphurea* | 11.63 (0.23) | 0.75 (0.03) | 296.24 (2.29) | 39.56 (0.3) |
|                     | *T. terscheckii* | 11.49 (0.24) | 0.59 (0.03) | 272.15 (1.75) | 39.55 (0.3) |
| *D. koepferae*      | *O. sulphurea* | 10.88 (0.17) | 0.61 (0.03) | 279.25 (1.87) | 39.74 (0.07) |
|                     | *T. terscheckii* | 10.30 (0.18) | 0.62 (0.03) | 275.00 (2.37) | 39.71 (0.07) |
Table 2. Intraspecific analyses of deviance of emergence time (Proportion of emerged adults). Df: degrees of freedom

| Source of variation | $\chi^2$ value | Df | P-value | $\chi^2$ value | Df | P-value |
|---------------------|----------------|----|---------|----------------|----|---------|
| Hour                | 37.397         | 1  | ***     | 48.586         | 1  | ***     |
| Cactus              | 3.363          | 1  | 0.067   | 0.289          | 1  | 0.59    |
| Sex                 | 1.219          | 1  | 0.269   | 1.172          | 1  | 0.278   |
| Cactus by hour      | 3.864          | 1  | *       | 0.258          | 1  | 0.612   |
| Sex by hour         | 0.842          | 1  | 0.359   | 0.034          | 1  | 0.852   |
| Cactus by sex       | 0.235          | 1  | 0.628   | 0.292          | 1  | 0.589   |
| Cactus by sex by hour | 0.025     | 1  | 0.875   | 1.014          | 1  | 0.314   |

Df: degrees of freedom; * P< 0.05; *** P< 0.001

Table 3. Inter and intraspecific mixed ANOVAs for larval viability, developmental time and wing size.

| Source of variation | Larval viability | Developmental time | Wing Size |
|---------------------|------------------|--------------------|-----------|
| Effect              | Df | MS | F | Df | MS | F | Df | MS | F |

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|                |                  |                  |                  |                  |                  |                  |                  |
|----------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| **Both**       |                  |                  |                  |                  |                  |                  |                  |
| **Drosophila** | **Drosophila**   | Fixed            | 1                | 0.141            | 1.72             | 1                | 2001             | 5.82*            | 1                | 1136             | 6.40*            |
|                | **Cactus**       | Fixed            | 1                | 0.234            | 9.49**           | 1                | 8028             | 30.27***         | 1                | 0.014            | 4.08             |
|                | **Drosophila**   | **by Cactus**    | Fixed            | 1                | 0.259            | 10.46**          | 1                | 3937             | 14.85**          | 1                | 0.01             | 0.35             |
|                | **Line**         | **(Drosophila)** | Random           | 18               | 0.082            | 3.31**           | 18               | 343              | 1.29             | 18               | 0.178            | 51.19***         |
|                | **Cactus**       | **by Line**      | **(Drosophila)** | Random           | 18               | 0.025            | 1.27             | 18               | 265              | 1.95*            | 18               | 0.003            | 2.35**           |
|                | **Error**        |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |
|                |                  | Fixed            | 1                | 0.019            |                  |                  |                  |                  |                  |                  |                  |                  |
| **D. buzzatii**| **Cactus**       | Fixed            | 1                | 0.493            | 20.86**          | 1                | 11605            | 28.68***         | 1                | 0.004            | 3.08             |
|                | **Line**         | Random           | 9                | 0.043            | 1.81             | 9                | 267              | 0.66             | 9                | 0.351            | 307.17***         |
|                | **Cactus**       | **by Line**      | **(Drosophila)** | Random           | 9                | 0.024            | 1.1              | 9                | 405              | 3.50**           | 9                | 0.001            | 0.54             |
|                | **Error**        |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |
| **D. koepferae**| **Cactus**       | Fixed            | 1                | 0.001            | 0.01             | 1                | 360              | 2.87             | 1                | 0.012            | 2.04             |
|                | **Line**         | Random           | 9                | 0.121            | 4.67*            | 9                | 419              | 3.34*            | 9                | 0.005            | 0.80             |
|                | **Cactus**       | **by Line**      | **(Drosophila)** | Random           | 9                | 0.026            | 1.46             | 9                | 126              | 0.8              | 9                | 0.006            | 6.92***          |
|                | **Error**        |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |                  |

Df: degrees of freedom; MS: mean squares. * P< 0.05; ** P< 0.01; *** P< 0.001.
Table 4: Correlation patterns. Pearson correlation coefficients among emergence time (ET) and fitness related traits: larval viability (LV), developmental time (DT) and wing size (WS). Values correspond to rearing in both hosts: *Opuntia sulphurea* (above diagonal) and *Trichocereus terscheckii* (below diagonal). Asterisks denote significant correlations ($P < 0.05$).

|       | LV    | DT    | WS    | ET    |
|-------|-------|-------|-------|-------|
| LV    | 0.355*| -0.219*| 0.158 |       |
| DT    | 0.141 | 0.345*| 0.524*|       |
| WS    | 0.044 | 0.109 | 0.303*|       |
| ET    | 0.107 | 0.339*| -0.285*|       |

Figure 1. Emergence time. Total number (and proportion from the total) of adults emerged in each cactus host in the four-hour periods of diurnal collection (Light grey: *O. sulphurea*; Dark grey: *T. terscheckii*).
Figure 2. Larval viability, developmental time and wing size displayed by each *Drosophila* species reared in both cacti hosts. In the bottom, the percentage of variance explained by random sources of variation is shown for each life history trait.
