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Master Thesis

與蝶同行？
城市人行道作為紋白蝶屬蝴蝶棲地之評估

Walk with butterflies?
Evaluating urban sidewalks as habitat for *Pieris* butterflies

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本論文係温彞禎君（R03B21005）在國立臺灣大學生態學與演化生物學研究所完成之碩士學位論文，於民國109年7月27日承下列考試委員審查通過及口試及格，特此證明

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摘要

現今都市佔地快速增加，評估其作為生物棲地的可能性漸趨重要。以往研究多關注公園等人為模擬自然之區域，較少探討更典型的都市環境（如人行道）。因此本研究想知道都市廣布的人行道（如臺北市人行道約 940 公里，佔近 1%土地面積）所提供的生態棲地價值。我們探討：(1)人行道是否能作為野生生物（如紋白蝶屬蝴蝶）的合適棲地？(2)人行道上的生物與非生物環境如何影響野生生物的表現？我們的研究包含以下五個實驗：

(1) 為了解食草資源分布，每月調查人行道上可供紋白蝶幼蟲利用的食草量。
(2) 為比較紋白蝶利用人行道與自然棲地的情況，在蝶季中每日調查樣區食草上的卵與幼蟲族群量。
(3) 為瞭解人行道及自然棲地中非生物環境因素（如溫度）對紋白蝶幼蟲的影響，分別在人行道與自然棲地中飼養臺灣紋白蝶幼蟲，量測其存活率及發育速度。
(4) 為進一步了解人行道環境溫度（平均高溫及溫度起伏）對紋白蝶的影響，本研究利用實驗室生長箱模擬人行道與自然棲地環境（溫度設定分別模擬人行道日夜溫度變化、人行道固定日夜均溫、野外日夜溫度變化），並於各模擬環境下飼養臺灣紋白蝶幼蟲，量測其存活率及發育速度。
(5) 為比較人行道與自然棲地的生物因素（如捕食率與人類活動）對紋白蝶存活率之影響，本研究在人行道與自然環境放置蝶卵及假幼蟲，觀察其受干擾情形。

此外，本研究亦利用實地觀測資料，建立使用氣象資料預測人行道溫度的方法，以及使用人行道上臺灣紋白蝶幼蟲體長來推估齡期之轉換方法。

2016 至 2018 年之研究結果顯示，人行道上具有紋白蝶的食草資源（實驗 1 與 2），

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且紋白蝶在生長季節時的確利用人行道作為棲地。非生物環境因素實驗顯示，相較於野外棲地，人行道上的紋白蝶幼蟲有類似甚至較高的存活率，以及較快的發育速度，暗示人行道可以是比野外環境更好的棲地（實驗 3）。在實驗室生長箱的溫度模擬實驗亦顯示相同結果，佐證人行道的高溫環境可以加速紋白蝶幼蟲的生長（實驗 4），並且此加速現象主要因為人行道較高的平均溫度，而非較大的溫度起伏。生物因素部分，相比野外棲地，人行道上的蝶卵受到的捕食壓力較小，然而幼蟲受到較多人類活動干擾（實驗 5）。綜合以上研究結果，我們認為都市環境如人行道，是被低估但重要的野生動物棲地（例如紋白蝶），因此我們建議都市管理者進行生態調查，並以更好的管理方式增進都市的生態價值。

關鍵字：都市生態系、人行道、棲地品質、鱗翅目、紋白蝶、白粉蝶、緣點白粉蝶

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Abstract

Global urbanization has rapidly increased urban areas. Studies have evaluated urban environment (e.g., parks) as habitat for wildlife; however, few studies have examined the role of urban sidewalks as wildlife habitat. Given that sidewalks are a common component of cities worldwide (e.g., about 900 km long or 1% area in Taipei city), this study investigated (a) whether sidewalks in an international city (e.g., Taipei) can be suitable habitat for wildlife (e.g., *Pieris* butterflies), and (b) how the abiotic and biotic factors on sidewalks affect wildlife performance. Our study included these five experiments (Exp.):

(1) To evaluate the food resource on Taipei sidewalks, this study conducted monthly surveys on the host plants of *Pieris* in Taipei sidewalk vs. field habitats.

(2) To examine whether *Pieris* butterflies inhabit sidewalks, this study conducted daily surveys on *Pieris* density on sidewalks during *Pieris* seasons.

(3) To compare how the abiotic factors (mainly temperature) of sidewalks and field

doi:10.6342/NTU202003180

habitats affect *Pieris* performance, this study raised *Pieris* larvae on caged plants in both sidewalk and field habitats.

(4) To further examine the effect of average temperature, temperature fluctuation, and other abiotic factors on *Pieris* larval performance, this study raised *Pieris* larvae in laboratory cage experiments, which simulated sidewalk and field habitat temperatures (i.e., sidewalk-fluctuating, sidewalk-fixed and field-fluctuating temperature regime).

(5) To compare how the biotic factors (predation and human disturbance) of sidewalk and field habitats affect the survivorship of *Pieris* eggs and larvae, this study placed *Pieris* eggs and larval decoys in sidewalk and field habitats.

Furthermore, this study created conversion criterion of larval body length into larval stage, and of weather temperatures into sidewalk temperatures.

The results of year 2016 – 2018 showed that *Pieris* and host plants did inhabit sidewalks (Exp. 1 and 2). *Pieris* larvae had similar survivorship in sidewalk and field habitats. *Pieris*

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larvae developed faster in sidewalk than field habitats (Exp. 3). The results of survivorship and development rate suggest that sidewalk could be as good as or even better than field habitats in terms of *Pieris* larval performance. The faster development under sidewalk temperature regime was also confirmed in laboratory experiments (Exp. 4). Moreover, the accelerated development on sidewalks was mainly due to high average temperature instead of temperature fluctuation (Exp. 4). Finally, *Pieris* on sidewalks faced a lower predation pressure on eggs but higher human disturbance on larvae (decoys), compared to those in the field (Exp. 5). Taken together, our results suggest that urban sidewalks, while underappreciated, can serve as an important habitat for wildlife such as *Pieris* butterflies. Therefore, this study encourage city managers to investigate and improve the ecological value of urban areas.

Key word: urban ecosystem, sidewalk, Lepidoptera, habitat quality, *Pieris*, *Pieris canidia, Pieris rapae*

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doi:10.6342/NTU202003180

doi:10.6342/NTU202003180

Content of tables

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doi:10.6342/NTU202003180

Content of figures

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Introduction

Urban area has become an important habitat for wildlife under global urban expansion

Global urbanization has resulted in a rapid expansion in urban areas. For example, urban land cover by 2030 is predicted to be nearly three times as large as that in 2000 (Seto et al. 2012), with nearly 60% people living in urban area (Grimm et al. 2008). Urbanization is one of the most importance threat to biodiversity worldwide (Ricketts and Imhoff 2003), such as changing the distribution and abundance of wildlife around the world (Hill et al. 2001). In addition, habitat fragmentation due to urbanization can significantly affect the migration and survival of species populations (Lande 1987, Collingham and Huntley 2000, Warren et al. 2001, Travis 2003).

On the other hand, urban area offer unique and various habitat types that foster a diverse group of species (Niemelä 1999). This could makes cities valuable shelters for species that can survive urban environment. For example, urban habitat supported 35 % of rare carabid species in Britain (Eversham et al. 1996), buffering the loss of butterfly diversity in surrounding reserves (Kadlec et al. 2008). Therefore, as urban expansion continues, it becomes more and more important to evaluate wildlife performance in urban area.

The role of sidewalks as wildlife habitat is overlooked

Sidewalks are a typical and representative urban environment, but its role as wildlife habitat has been unclear. Sidewalks can occupy a large area of a city: paved surface (roads, parking areas and sidewalks) in four metropolitan areas of USA covered 29% - 36% area of the cities (Akbari and Rose 2008); roads and sidewalks covered a third of urban land in Hamburg, Germany (Transport 1977). Sidewalks or roadsides have been suggested to serve as habitat for diverse wild plants and animals (Way 1977, Van der Sluijs and Van Bohemen 1991, Seiler 2001), and offer valuable shelters and corridors that facilitate wildlife movement in heavily exploited landscapes (Bennett 1991, Forman 1995, Seiler 2001).

While sidewalks represent a large portion of urban areas and provide potential habitats for wildlife, as described above, there have been a lack of rigorous studies evaluating the role of sidewalks as wildlife habitat (e.g., a comparison with field habitat) and the effect

doi:10.6342/NTU202003180

of abiotic and biotic factors of sidewalks on wildlife performance. Current studies on highly urbanized areas (e.g., sidewalks) are limited (Gilbert 2012), and a large proportion of urban ecological studies has focused on areas other than sidewalks (e.g., city gardens) (Hardy and Dennis 2010, Matteson and Langellotto 2012, 陳家豪 2015).

Urban environmental trait: abiotic factors

Although the role of evaluate urban sidewalks as wildlife habitat remains unclear, it is well known that some abiotic factors in urban environment are hostile for wildlife. For example, cities often have high levels of light and ultraviolet light (Heisler and Grant 2000). Cities also have many artificial building materials and human activities, creating heat islands effect and air pollution (Tsai and Cheng 2004). In addition, urban soils are typically characterized by scarcity, compaction, and drought and special composition. (Benvenuti 2004).

High temperature is among the most obvious traits in urban environment (Johnson et al. 1974, Svensson and Eliasson 2002). The literature indicates that urban environments and artificial materials can influence heat exchange and lead to high surface temperature

doi:10.6342/NTU202003180

(Taha 1997, Yokohari et al. 2001). Among different types of urban environment, urban sidewalks can have higher day and night temperature, compared to nearby natural environment and other parts of the city (Taha 1997).

To understand the effect of abiotic factors (e.g., high temperature) of urban environment on wildlife, we should consider whether the effect is life stage specific. This concern is supported by studies where high temperature increases the development rate of insects (e.g., Lepidoptera) in a stage-specific manner (Petersen et al. 2000, Kingsolver and Gomulkiewicz 2003, Whitney-Johnson et al. 2005, Esperk 2006, Folguera et al. 2010, Despland 2017, Banahene et al. 2018). Besides development rate, insect survivorship under temperature influence varies with stage (Wang et al. 2004). Therefore, exploring the effect of urban temperature on wildlife may need to delve into stage-specific response in wildlife.

Examining urban temperature effect should also consider the effect of temperature fluctuation because mean temperature may not fully reflect the impacts of temperature on species (Sheldon and Dillon 2016). Ectotherm development rate is a nonlinear function of temperature (Sharpe 1977). Jensen's inequality indicate that, for a nonlinear function, the average result of inputs may not equal to the result of average inputs (Ruel and Ayres 1999). Therefore, development rate under a temperature fluctuation regime may be different from that under a constant temperature regime, although these two regimes share the same mean. This is generally accepted as the rate summation effect or Kaufmann effect (Bryant et al. 1999).

In fact, increased daily temperature variability (without a change in mean temperature) reportedly resulted in higher rates of development (Taylor and Shields 1990, Brakefield Paul and Mazzotta 2002), lower rates of mortality (Brakefield Paul and Mazzotta 2002, Mironidis 2014) and other changes in specific life stages (McDermott Long et al. 2017). Therefore, accurate prediction of insect performance under temperature gradients should be based on temperature fluctuation model (Hagstrum and Milliken 1991, Worner 1992, Fantinou et al. 2003).

Urban environmental trait: biotic factors

Besides abiotic factors, some biotic factors such as resource abundance, predation

doi:10.6342/NTU202003180

pressure and human disturbance may affect wildlife performance on sidewalks. Regarding resource, plants (e.g., weeds) growing on urban roads and roadsides may provide wild herbivores food resources. The quality of urban or suburban host plants for herbivores could be low due to the lack of soil nutrients, or high due to the pollution (Riemer et al. 1989).

Regarding predation pressure, urban area may serve as “safe zones” for some wildlife species because of the lack of natural predators (Tomialojc 1982). For example, birds in some urban areas were less stressed by predators than those in the field and therefore had a higher species diversity and population size (Noske 1998, Gering and Blair 1999, Sorace 2002, Eötvös et al. 2018). However, the opposite results have been reported as well (Thorington and Bowman 2003, Jokimäki et al. 2005). In the case of insects, the urban effect on their predation pressure remains to be explored. What we have known is that insect (butterfly) survivorship should be determined by bird and arthropod predation (Baker 1970, Schmaedick and Shelton 2012, Kozlov et al. 2017), along with rainfall (Harcourt 2012), viruses (Harcourt 2012) and parasites (Parker 1970, Hamilton 1979). For example, butterfly eggs are attractive to many arthropod predators (Oberhauser et al.

doi:10.6342/NTU202003180

2015, Hermann et al. 2019). In the study of *Pieris rapae*, arthropod predators may lead to 56% larval mortality (Ashby 1974). Specifically, eggs and larvae (up to 3rd instar) were hunted by wolf spider, *Phalangium opilio*, ladybug and Syrphidae (Ashby 1974, Schmaedick and Shelton 2012). Later instars may be consumed by ants (Jones 1987).

Human disturbance can have a negative effect on wildlife in urban areas. For example, human interference reduced the foraging time of urban birds (Valcarcel and Fernández-Juricic 2009). Human disturbance such as trampling may also reduce insect survivorship on urban sidewalks (Senzota 2012, Ciach et al. 2017), although rigorous studies are needed.

Study system: *Pieris* butterflies on urban sidewalk

To understand (a) whether sidewalks are an important, but overlooked, habitat for wildlife, and (b) how the abiotic and biotic factors on sidewalks affect wildlife performance, we focus on the *Pieris* butterflies and their host plants on sidewalks in Taipei, Taiwan.

Some butterflies, such as the *Pieris* butterflies, frequently appear in cities, although urban

doi:10.6342/NTU202003180

areas are generally not suitable habitat for many species (für Naturschutz 1987),. *Pieris* butterflies are common pollinators and have a mobility to move a great distance for resource in an urban matrix (Jones et al. 1980, Matteson and Langellotto 2012). Adult *Pieris* are opportunistic polyphagia nectar users, so they can take advantage of the spotty nectar plants in highly build-up areas of cities (Hardy and Dennis 1999).

Previous studies focused on the emergence of *Pieris* adults in urban (Munguira and Thomas 1992, Matteson and Langellotto 2012). But did not address where these butterflies originally came from urban areas. Some studies have speculated that these *Pieris* adults immigrated from nearby agricultural and forested habitats (Altermatt 2012). However, whether urban functions as a sink or source for *Pieris* butterflies has not been tested.

Aims and hypothesis

To understand whether sidewalks in urban area can be suitable habitat for wildlife (e.g., Pieris butterflies), and how the abiotic and biotic factors on sidewalks affect wildlife performance, we aimed to answer the following questions and test related hypotheses.

Question 1: Do Pieris inhabit sidewalks?

Aim 1 Survey the host plant resource of *Pieris* larvae on sidewalks (Exp.1 Field survey: host plant density).

Hypothesis 1 There are host plants (Brassicaceae) of *Pieris* larvae on sidewalk.

Aim 2 Survey the population dynamics of *Pieris* on sidewalks (Exp. 2 Field survey: *Pieris* egg and larval density).

Hypothesis 2 *Pieris* eggs and larvae are found on sidewalks, indicating that *Pieris* use urban sidewalks as habitat.

Question 2: Can sidewalks be suitable habitat for Pieris?

We defined "suitable habitat" here as a habitat where *Pieris* can have survivorship and

doi:10.6342/NTU202003180

development rate that are at least similar to those in *Pieris* natural habitat (field habitat).

Aim 3 Compare how the abiotic factors (mainly temperature) of sidewalk and field habitats affect *Pieris* larval performance (Exp. 3 Sidewalk cage experiment: larval performance in sidewalk microenvironment).

Hypothesis 3 Given that some abiotic factors in urban environment are hostile for wildlife, most *Pieris* larvae cannot tolerate the abiotic regime (e.g., high temperature) of sidewalks, resulting in lower survivorship on sidewalks.

Hypothesis 4 However, given that urban sidewalks have higher temperature than the field, the *Pieris* larvae surviving on sidewalks will have accelerated development rates and reach smaller adult sizes.

Hypothesis 5 Given that temperature effects on insect survivorship and development rate reportedly varied with life stage, the difference in larval performance between sidewalk and field habitats varies with instar stage.

Aim 4 Further explore the effect of average temperature, temperature fluctuation, and other abiotic factors on larval performance (Exp. 4 Laboratory cage experiment: larval performance under sidewalk temperature regime).

Hypothesis 6 Given that the high and extreme temperature on sidewalks may create a stressful environment to *Pieris*, the high temperature and large temperature fluctuation on sidewalks will reduce *Pieris* survivorship.

Hypothesis 7 Given that high temperature reportedly increased the development rate of insects, the high average temperature on sidewalk will accelerate the development rate of *Pieris* larvae and result in smaller adult sizes.

Hypothesis 8 Given that increased daily temperature variability reportedly increased *Pieris* development rate, the large temperature fluctuation on sidewalk will accelerate the development rate of *Pieris* larvae and result in smaller adult sizes.

Hypothesis 9 Temperature aside, other abiotic factors on sidewalks negatively affect the performance of *Pieris* larvae.

Aim 5 Compare how the biotic stress (e.g., predation and human disturbance) of sidewalk and field habitats affect the survivorship of *Pieris* eggs and larvae (decoys) (Exp. 5 Field manipulation experiment: survivorship on eggs and caterpillar decoys)

Hypothesis 10 Given that sidewalks may have fewer insect predators, compared to the field, sidewalk habitat will have a lower egg predation pressure from natural enemies (e.g., ants), thus resulting in a higher egg survival rate on sidewalks.

Hypothesis 11 Given that human disturbance has been reported to negatively affect wildlife in urban areas, human disturbance (e.g., trampling) will reduce the survivorship of *Pieris* larvae (decoys) on sidewalks.

The concept map for this study is in Figure 1.

*Previous studies had report that *Pieris* larvae had lower survivorship in 25°C and 30°C than 20°C consistent temperatures. Sidewalks may have temperature higher than 25°C. Therefore, we predicted that the high temperature and temperature fluctuation on sidewalks would reduce *Pieris* survivorship in our Hypothesis 6.

Materials and methods

Study System

Pieris spp.

Pieris canidia and *P. rapae* (Lepidoptera: *Pieridae*) are common butterflies in lowland Taiwan (李大維 2006, 2010). They widely distribute in the field in Taiwan (Huang 2000). These two *Pieris* species are both active from late autumn to spring in low land Taiwan. Population outbreaks of eggs, larvae and adults appear in March and April in Taipei (林正鴻 2015). *Pieris* larvae have five development stages from 1st to 5th instar (named as stage 1 to 5 in this study), followed by pupation and eclosion to butterflies. Larvae of the two *Pieris* consume Brassicaceae plants and a few related families (Chew and Renwick 1995, 林柏昌 2008).

Our study focused on both *P. rapae* and *P. canidia* populations on sidewalks, and further studied the immature stage of *P. canidia*. As an important agricultural pest worldwide, the immature stage and living conditions of *P. rapae* have been well studied. However, the immature stage of *P. canidia*, a native *Pieris* species in Taiwan, remains understudied.

A previous study has reported that the native *P. canidia* was more competitive than the exotic *P. rapae* on *Rorippa indica* plants, a common sidewalk weed in Taiwan (林正鴻 2015).

Rorippa Spp.

Rorippa indica (L.) Hiern is a perennial plant which belongs to Brassicaceae. *R. indica* is a common weed and host plant of *Pieris* larvae. In addition to growing in field habitat, *R. indica* could be observed on urban sidewalks worldwide (Uchida et al. 2014), and is widely distributed on Taiwan's sidewalks (林柏昌 2008, 徐玲明 2009, 鐘明哲 2011, 徐玲明 2019).

Taipei city sidewalk

Studies have suggested that sidewalk cracks can offer habitat for plants, including the host plants of *Pieris* butterflies, (e.g., *R. indica*) (Uchida et al. 2014). There were 939,745 meters long and 2,527,900 m^2 of goverment-builed sidewalks in 2015 in Taipei, Taiwan (Figure 2) (Department of Budget Accounting and Statistics 2015). Given that the area of Taipei City was 271,799,700 m^2 (Department of Civil Affairs 2019), sidewalk covered

0.93% area of Taipei City.

Exp. 1 Field survey: host plant density

Experimental design

To understand the temporal and spatial variations in host plants, we surveyed plants monthly on Taipei sidewalks from December 2015 to January 2017. Detailed survey period is provided in Table 1.

Procedure

We first marked all sidewalks in Taipei city (data collected from (Department of Budget Accounting and Statistics 2015)). After weighting each sidewalk by its length, we randomly selected 60 sites from these sidewalks (Table 1, Figure 3). A sampling quadrat in each sidewalk site (two meters long with variable width (Figure 4a) were then surveyed monthly for plant species and the plant abundance of each species. To estimate the plant abundance, we recorded the length of sidewalk cracks occupied by each species of plants (Figure 4b). Note that our methods may record more than two meters long of plant abundance in each two-meters long quadrat. The plant abundance data would be used to

doi:10.6342/NTU202003180

estimate the host plant abundance available to *Pieris*.

Exp. 2 Field survey: *Pieris* egg and larval density

Experimental design

To examine whether *Pieris* butterflies use host plants on sidewalks, we surveyed (a) egg density on host plants, (b) larval density on host plants, and (c) proportion of host plants utilized by ovipositing females. To do so, we conducted daily field surveys in sidewalk habitat in spring *Pieris* season (peak season for *Pieris* egg, larval and adult densities in Taipei) in Taipei. We also did so in field habitat to make a comparison with sidewalk habitat. Detailed survey period is listed in Table 3.

Procedure: Egg and larval density

Due to extensive manpower required (0.5 - 1 hours/day per site), we surveyed egg and larval density in two to four sites in sidewalk habitat and one site in field habitat in *Pieris* breeding seasons in 2016, 2017, and 2018. We haphazardly labeled *R. indica* plants in each site and counted number of *Pieris* eggs and larvae (*P. canidia* and *P. rapae*) daily on each of the labeled plants. To understand the condition of larvae, we recorded their body

doi:10.6342/NTU202003180

length, which was later used to estimate larval stage based on the conversion criterion in Table 4. The method of establishing the conversion criterion is in the Appendix A: Larval stage identification.

Procedure: Proportion of host plant utilized by ovipositing females

R. indica plants (n = 12 - 20) were haphazardly selected and examined in three sites each in sidewalk and field habitats. We recorded whether these plants contained *Pieris* eggs or not once during *Pieris* season (April and May) in 2016.

Exp. 3 Sidewalk cage experiment: larval performance in sidewalk microenvironment

Experimental design

To test how the abiotic factors of sidewalk and field habitats affect *Pieris* larval performance, we raised *Pieris* and monitored their performance in sidewalk and field habitats from eggs to eclosion in *Pieris* breeding seasons in 2016, 2017, and 2018. Detailed experimental information is provided in Table 5.

doi:10.6342/NTU202003180

Procedure

P. canidia adults were collected at National Taiwan University (NTU) campus in Taipei, Taiwan (25.0173405N, 121.5397518E), and allowed to lay eggs on *R. indica* plants (collected from the NTU campus grassland) in the laboratory. We then cut a square of a leaf (0.25 cm^2) with one egg on top and attached it to a leaf of each experimental *R. indica* plant. In total, three squares (three eggs) were placed on one potted *R. indica* plant. A mesh fabric cage was then used to cover each plant before being moved to sidewalk and field habitats. New plants would replace the old ones that were finished by larvae. Photos of experiment procedures and site examples are presented in Figure 5. We examined *Pieris* larvae daily and recorded their body length and life state. Larvae stage was later estimated based on the conversion criterion in Table 4. We also recorded the body weight and forewing length of *Pieris* adults after they emerged.

Exp. 4 Laboratory cage experiment: larval performance under sidewalk temperature regimes

Experimental design

To further investigate the effect of average temperature, temperature fluctuation, and

doi:10.6342/NTU202003180

other abiotic factors on the development of *Pieris* larvae, we conducted the laboratory cage experiment using growth chambers to simulate sidewalk-fluctuating, field fluctuating and sidewalk-fixed temperatures (Table 6).

Procedure

We prepared *P. canidia* and *R. indica* similarly to the procedure of Exp. 3. We installed mini weather loggers (iButton) in sidewalk and field habitats to collect real temperature/humidity data during 2018 *Pieris* season (the same time period as Exp. 3) (Figure 6, Figure 7). The settings of sidewalk-fluctuating, field-fluctuating, and sidewalk-fixed temperature treatments (Figure 8a) were based on the real temperature data (Figure 7a) and described as below:

(1) ***Sidewalk-fluctuating temperature:*** This treatment group simulated the within-day variation in temperature in the sidewalk habitat (mean = 25.10°C, range in 21.3°C - 31.9°C).

(2) ***Field-fluctuating temperature***: This treatment group simulated the within-day

variation in temperature in the field habitat (mean = 22.35°C, range in 20.3 - 24.7°C).

(3) ***Sidewalk-fixed temperature***: This treatment group simulated the mean temperature in the sidewalk habitat, with fixed day and night temperature. (27.1°C and 22.7°C, respectively)

We installed weather loggers inside growth chambers to monitor how well these chambers would simulate our temperature settings. The results were positive (Figure 8b). The mean squared error between the real growth chamber temperatures and our temperature settings were 23.518 degree^2 (sidewalk-fluctuating), 7.622 degree^2 (field-fluctuating) and 14.740 degree^2 (sidewalk-fixed). The relatively humidity was all controlled at average 67.70 ± 3.07% (mean ± SD).

We examined *Pieris* larvae daily and recorded their body length and life stage. Their head width was recorded daily from half replicates to help determine developmental stages. After eclosion, the body weight and forewing length of adults were recorded. Other procedure was the same as that in Exp. 3.

doi:10.6342/NTU202003180

Larval stage identification

In order to investigate the stage-specific performance in larvae, we established a criterion for the conversion of *P. canidia* larva body length to stage (Table 4). This criterion was used in Exp. 2, Exp. 3 and Exp. 4. A conventional method to determine the stage of *Pieris* larva is to measure their head width. However, it was difficult to measure head width accurately in our field survey. To establish and assess the criterion, we used the correlation among head width data, body length data, and larval stage data from Exp. 4. The details are given in Appendix A: Larval stage identification.

Sidewalk microenvironment temperature measurement and prediction

To better understand the sidewalk microenvironment where caterpillars live, we established a formula for estimating the temperature on sidewalks based on general meteorological monitoring data.

The ground truth temperature data were averaged from our environmental monitoring by iButton data loggers (WatchDog B102 Temp/RH Logger, Spectrum Technologies) in typical Taipei sidewalk sites (Figure 3). The general meteorological monitoring data were downloaded from the Central Weather Bureau Observation Dara Inquire System. The detailed procedure is provided in Appendix B: Sidewalk temperature prediction. We then built this formula to predict sidewalk temperature:

$$\begin{aligned}&\textbf{Predicted sidewalk temperature}\\&\qquad = -\mathbf{0.454036} + \mathbf{1.022215} \times \textbf{CWB temperature} + \mathbf{1.492239} \times \textbf{Global radiation}\end{aligned}$$

The CWB temperature and Global radiation represent the temperature and global radiation in general meteorological monitoring data, respectively. This formula was used to estimate the temperature on sidewalks in *Pieris* season.

Effective cumulative temperature (cumulative degree-days)

To explore the underlying mechanism for the temperature effect on larval development over different treatments and years, we calculated the effective cumulative temperature received by larvae. Since the threshold of developmental temperature of *P. canidia* was not studied, we used the threshold of *P. rapae*, a closely related species of *P. canidia* (鄭秋玲 2003). The temperatures larvae experienced in the sidewalk cage experiment were based on our predicted sidewalk temperature (see the section of "Sidewalk microenvironment temperature measurement and prediction"), the temperatures in the laboratory cage experiment were based on our temperature setting for each treatment group (growth chamber).

Exp. 5 Field manipulation experiment: survivorship on eggs and caterpillar decoys

Experimental design

To understand how biotic factors (predation and human disturbance) of sidewalk and field habitats affect the survivorship of *Pieris* eggs and larvae, we deployed *Pieris* eggs and caterpillar decoys in sidewalk and field habitats for a one-day test.

Procedure

To prepare *Pieris* eggs, we collected *P. canidia* adults at NTU campus, and harvest the eggs they laid in the laboratory. Only 1-day old eggs were used for this study to avoid hatching during the experiment. Caterpillar decoys were made by clay (faber castell clay colored with crayons). The model size was close to the average of real caterpillars (11mm long and 2mm in diameter, 50 mg clay/decoy, size averaged data from Exp. 2 Field survey:

doi:10.6342/NTU202003180

Pieris egg and larval density) (Figure 9). This experimental design was referenced from a previous study (Roslin et al. 2017). Eggs and decoys were placed on wild *R. indica* in three sidewalk sites and two field sites and checked for survivorship and damage after 24 hours. Detailed information is listed in Table 8.

Statistical analysis

All analyses were conducted using R studio version 1.1.414 (RStudio Team 2016) with R version 3.1.3 - "Smooth Sidewalk" (R Core Team 2015) and R version 3.6.3 - “Holding the Windsock” (R Core Team 2020).

Exp. 2 *Pieris* egg and larva density

Pieris egg and larval density were analyzed by Generalized linear mixed model (GLMM) zero-inflated Poisson method (using glmmTMB library in R(Brooks et al. 2017)), with habitat as a fixed effect, and site and plant individual as random effects. Observation day for each plant individual was also included to account for temporal autocorrelation. Oviposition rate was analyzed with Fisher’s exact test for count data.

Exp. 3. Larval performance in sidewalks microenvironment & Exp. 4. Larval performance under sidewalk temperature regime

We used GLMM to examine the effect of abiotic factors of sidewalk and field habitats on *Pieris* performance (using lme4 library in R (Bates et al. 2014)). Larvae growth period and stage-specific survival rate were analyzed with habitat, developmental stage, year and the two-way interactions as fixed effects, and site, pot and individual as random effects.

Larval survival rate was calculated, and the overall survival curves were analyzed by Kaplan-Meier method, and were compared using Log rank test and Gehan-Breslow test (Gehan's generalized Wilcoxon test) (using survival and coin library in R (Hothorn et al. 2006, Therneau 2015)).

To examine the effect of abiotic factors on *Pieris* adult body weight and forewing length, we used Linear mixed model (LMM) with habitat, year and sex as fixed effects, and site and pot as random effects (for body weight, pot was the only random effect).

To further examine the effect of temperature on larval development, we used LMM to examine the effective cumulative temperature, with developmental stage, year and the two-way interactions as fixed effects, site, pot and individual as random effects.

Considering heterogeneity, non-normality and a small sample size of data, the *post hoc* analyses were all conducted using Kruskal-Wallis test (growth period and adult butterflies performance) and Fisher's exact test for count data (survival rate).

Exp. 5. Mortality on caterpillar decoys and eggs

Survival rate was analyzed by Fisher's exact test for count data.

doi:10.6342/NTU202003180

Results

Microenvironment on sidewalks habitat

The temperature of sidewalk microenvironment (predicted by our measurement and the Central Weather Bureau data, as Appendix B) and meteorological weather in *Pieris* breeding season in Taipei was reported in Table 9 and Figure 10. On average, sidewalks had higher mean temperature (26.14°C) than the weather (25.17°C). Sidewalks also had a higher temperature variability (SD) (4.96°C) and a larger temperature range (27.35°C) than the weather (4.02°C and 22.33°C). While the maximum temperatures on sidewalks (41.44 °C) were substantially higher than the weather (22.33 °C), the minimum temperature on sidewalks (14.10°C) was slightly lower than the weather (14.23°C). Sidewalk had a higher day mean temperature (28.30°C) than the weather(26.68°C).

Exp. 1 Field survey: host plant density

We found a fair amount of food resource for *Pieris* larvae on sidewalks (Figure 11a), supporting our Hypothesis 1. In *Pieris* breeding season (April and May, 2016), we observed total 72.88 meters long (April) and 72.44 meters long (May) of plants biomass on our 60 study sites (each included a 2m sidewalk). The Brassicaceae plants, host plants of *Pieris* spp. larvae, were 4.51, 4.72 and 2.90 meters long in March, April and May, respectively mainly composed of *Rorippa* spp. and *Cardamine* spp (Table 10, Figure 11). Given that Taipei City had 940 kilometers long of sidewalks, the Brassicaceae plants were estimated to inhabit 37 kilometers long on the sidewalks of Taipei in April.

Exp. 2. Field survey: *Pieris* egg and larval density

Eggs and larvae

Pieris eggs and larvae were found in the breeding season of 2016, 2017 and 2018 on sidewalks (Figure 12 and Figure 13), supporting our Hypothesis 2 that *Pieris* species use urban sidewalks as habitat. The number of eggs and larvae varied with sites and years in both sidewalk and field habitats (Figure 12), but no difference between sidewalk and field except 2016. In 2016 larval density was lower on sidewalk than field ($P = 0.001$, Table 11, Figure 13).

Larvae development stages

In agreement with our Hypothesis 2 that *Pieris* species use sidewalks as habitat, *Pieris* larvae of various developmental stages (1^{st} to 5^{th} instar) were found on sidewalks, comparable to the field habitat (Figure 14). Furthermore, the proportion of older larvae on sidewalks increased over time during the breeding season of 2016-2018, hinting that *Pieris* larvae had an ability to tolerate the extreme high temperature on sidewalks. Overall, the results suggest that *Pieris* species could complete its life cycle on sidewalks.

Oviposition rate

Consistent with our Hypothesis 2, *Pieris* adults laid eggs on 31.6% ± 9.27% (mean ± SE) of host plant on sidewalks. This percentage was lower than the 76.9% ± 6.40% (mean ± SE) in field habitats ($P < 0.0001$, Figure 15).

Exp. 3 Sidewalk cage experiment: larval performance in sidewalk microenvironment

Survivorship

For cumulative survival rates, *P. canidia* larvae on sidewalks overall had similar survivorship as those in the field (Table 12, Figure 16a), contrary to part of our Hypothesis 3. Surprisingly in 2016, sidewalks even supported higher survival rate, suggesting that

doi:10.6342/NTU202003180

sidewalks could service as good habitat for *Pieris*. For stage-specific survivorship, no difference was observed between sidewalk and field habitats. However, egg stage had lower survivorship than other stages in 2017.

Growth period

Compared to field habitat, sidewalk habitat reduced the *P. canidia* growth period from egg to eclosion in three years of experiments (19.8 ± 0.27 days, 21.4 ± 0.38 days and 25.8 ± 0.33 days in sidewalk habitat, and 22.3 ± 0.37 days, 22.2 ± 0.29 days and 27.7 ± 0.56 days in field habitat in 2016, 2017 and 2018, respectively, mean ± SE) (Figure 18, Table 15a). It supports our Hypothesis 4 that abiotic microenvironment on sidewalk accelerated *P. canidia* development. Specifically, this acceleration occurs mainly in the larval period instead of pupal period, although accelerated pupal stage on sidewalks was observed in 2016.

We further examined each instar stage of the larval period and found no interaction between habitat treatment and instar stage (Table 15a). In other words, the acceleration on sidewalk over field habitat was not instar stage specific, different from Hypothesis 5.

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Pieris adults body size (weight and forewing length)

P. canidia larvae raised on sidewalks overall reached smaller adult body sizes than those in the field (*P* < 0.001 and 0.007 for body weight and forewing length, respectively) (Figure 21, Figure 22, Table 18), consistent with our prediction in Hypothesis 4. The adult body weight of male *P. canidia* was 46.3 ± 3.73 mg, 43.5 ± 1.13 mg and 48.6 ± 4.35 mg on the sidewalks, and 62.0 ± 5.95 mg, 56.0 ± 2.79 mg and 57.5 ± 4.55 mg in the field in 2016, 2017 and 2018, respectively (mean ± SE). The adult body weight of female *P. canidia* was 38.4 ± 1.89 mg, 40.9 ± 3.67 mg and 47.0 ± 2.32 mg on sidewalks, and 50.9 ± 3.04 mg, 54.0 ± 3.14 mg and 56.6 ± 4.43 mg in the field in 2016, 2017 and 2018, respectively (mean ± SE). Male *P. canidia* on sidewalks were lighter than those in the field in 2017 (*P* = 0.007). Female *P. canidia* on sidewalks were lighter than those in the field in 2016 and 2017 (*P* = 0.007 and 0.0339, Figure 21b).

The forewing length of male *P. canidia* was 24.6 ± 0.60 mm, 25.9 ± 0.31 mm and 25.6 ± 0.66 mm on sidewalks, and 26.4 ± 0.72 mm, 25.5 ± 0.53 mm and 26.7 ± 0.40 mm in the field in 2016, 2017 and 2018, respectively (mean ± SE). The forewing length of female *P. canidia* was 23.9 ± 0.44 mm, 23.1 ± 0.63 mm and 25.1 ± 0.45 mm on sidewalks, and

25.1 ± 0.66 mm, 25.2 ± 0.44 mm and 26.4 ± 0.57 mm in the field in 2016, 2017 and 2018, respectively (mean ± SE). While male *P. canidia* on sidewalks showed no difference from those in the field, female *P. canidia* on sidewalks had shorter forewings than those in the field in 2017 (*P* = 0.034)

Exp. 4 Laboratory cage experiment: larval performance under sidewalk temperature regimes

Survivorship

For cumulative survival rates, *P. canidia* larvae had similar survivorship under sidewalk-fluctuating, field-fluctuating and sidewalk-fixed temperature treatments (Figure 16a, Table 12), rejecting our Hypothesis 6 that high temperature and temperature fluctuation on sidewalks will reduce *P. canidia* survivorship. Specifically, the similar survival curves between sidewalk-fluctuating and field-fluctuating temperature treatment groups indicate that high average temperatures did not reduce the survival rate of *P. canidia* larvae. In addition, the similar survival curves between sidewalk-fluctuating and sidewalk-fixed temperature treatment groups suggest that larger temperature fluctuation would not reduce survival rate of *P. canidia* larvae.

The cumulative survival rates were also similar between Exp. 3 2018 (sidewalk cage experiment) and Exp. 4 (laboratory cage experiment) (Figure 16b). Since these two experiments shared similar temperature regimes, the result indicates that abiotic factors other than temperature on sidewalks habitat did not reduce *P. canidia* survivorship, compared to that in field habitat, not supporting our Hypothesis 9.

For stage-specific survival rates, *P. canidia* larvae had similar survivorship at each stage under sidewalk-fluctuating, field-fluctuating, and sidewalk-fixed temperature treatments in our laboratory cage experiment (Figure 17a, Table 13a), consistent with the results in cumulative survivor rates.

The stage-specific survival rates also showed no difference between Exp. 3 2018 (sidewalk cage experiment) and Exp. 4 (laboratory cage experiment), except the *P. canidia* on sidewalk habitat had a higher survivorship in pupal stage than *P. canidia* in other treatment groups (P = 0.035, Figure 17b, Table 13). This result did not support our Hypothesis 9 that abiotic factors other than temperature on sidewalks reduce the performance of *Pieris* larvae.

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Although our study did not aim to compare the variation in survivorship across life stages, the stage-specific survival rates from egg to eclosion showed that pupal stage had lower survivorship than other stages in Exp. 4 (*P* = 0.008, 0.008 and < 0.0001, Figure 17, Table 14).

Growth period

The larvae under sidewalk temperature treatments (both fluctuation and fixed) showed a shorter growth period (from egg to eclosion) than those under the field-fluctuating temperature treatment (24.1 ± 0.59 days under sidewalk-fluctuating treatment, 24.2 ± 0.47 days under sidewalk-fixed treatment and 28.7 ± 0.56 days under field-fluctuating treatment (mean ± SE)) (Figure 18a, Table 15b, Table 15d), supporting our Hypothesis 7 that high average temperature accelerated the development rate of *P. canidia* larvae. This laboratory cage result was consistent with the sidewalk cage result (Exp. 3), further confirming the positive effect of higher temperature on *P. canidia* development. Regarding stage-specific development, larvae under sidewalk temperature treatments (both fluctuating and fixed) developed faster (i. e., shorter growth period) than those under field-fluctuating temperature treatment in the 1st, 4th, 5th instar, and pupal stage

(Figure 18).

We found no interaction effect between temperature regime and stage in Exp.4 (Table 15b). In other words, the accelerated development under sidewalk over field temperature regime was not instar stage specific.

The larvae under the sidewalk-fluctuating and sidewalk-fixed temperature treatments had similar overall growth periods (Figure 18a, Table 15d), rejecting our Hypothesis 8 that larger temperature fluctuation would accelerate the development rate more.

Comparing Exp. 3 2018 and Exp. 4 concludes that abiotic factors other than temperature led to a lower larval development rate in sidewalk than field habitat, supporting our Hypothesis 9. Specifically, *P. canidia* larvae on sidewalk habitat (sidewalk cage experiment 2018 (Exp. 3)) generally had longer growth periods (worse performance) than those under sidewalk-fluctuating temperature treatment group (laboratory cage experiment (Exp. 4)) (Figure 19, Table 15e). If we assume that the acceleration of development rate caused by temperature and other abiotic factors can add up, the growth

doi:10.6342/NTU202003180

performance can be expressed as the following:

$$T_{sidewalk} + O_{sidewalk} < T_{sidewalk-fluctuating} + O_{sidewalk-fluctuating} \quad \textbf{(1)}$$

Where T and O represent the acceleration effect of temperature and other abiotic factors. Given that the sidewalk habitat and the sidewalk-fluctuating temperature treatment group shared similar temperatures (2), the acceleration effect due to other abiotic factors in sidewalk habitat should be less than that under sidewalk-fluctuating temperature treatment (3).

$$T_{sidewalk} = T_{sidewalk-fluctuating} \quad \textbf{(2)}$$

$$O_{sidewalk} < O_{sidewalk-fluctuating} \quad \textbf{(3)}$$

P. canidia larvae in field-fluctuating temperature treatment group (Exp. 4) generally had longer growth periods than those in field habitat (2018 Exp. 3). This can be expressed as the following:

$$T_{field-fluctuating} + O_{field-fluctuating} < T_{field} + O_{field} \quad \textbf{(4)}$$

Given that these two treatment groups shared similar temperatures (5), the acceleration effect due to other abiotic factors under field-fluctuating temperature treatment should be less than that under field habitat (6).

doi:10.6342/NTU202003180

$$T_{field-fluctuating} = T_{field} \tag{5}$$

$$O_{field-fluctuating} < O_{field} \tag{6}$$

Laboratory growth chamber had consist abiotic environment except temperature (7).

$$O_{laboratory} = O_{sidewalk-fluctuating} = O_{field-fluctuating} \tag{7}$$

Therefore, combing the equations (3), (6) and (7) leads to this result:

$$O_{sidewalk} < O_{laboratory} < O_{field} \tag{8}$$

Based on the result, the abiotic conditions (other than temperature) in field habitat were better than those in laboratory and then in sidewalk habitat for *P. canidia* development rate.

Pieris adults body size (weight and forewing length)

Sidewalk-fluctuating, field-fluctuating and sidewalk-fixed temperature treatments did not affect *P. canidia* body weight (Figure 21 and Table 18) and forewing length (Figure 22) in both male and female butterflies in (Exp. 4), not supporting our body size prediction in Hypothesis 7 and Hypothesis 8.

Exp. 5 Field manipulation experiment: survivorship on eggs and caterpillar decoys

Eggs on sidewalks had a marginally significant higher survivorship than those in the field (P = 0.059, Table 19, Figure 23), consistent with our Hypothesis 10 that sidewalk habitat reduces the predation pressure from natural predators. However, caterpillar decoys faced higher disturbance on sidewalks (P = 0.020, Table 19, Figure 23). The examples of caterpillar decoys damaged by sweeping and human tramping were shown in Figure 24, supporting our Hypothesis 11 that human disturbance (e.g., trampling) reduce the survivorship of *Pieris* larvae (decoys) on sidewalks. In addition to human disturbance, we also observed ant biting and other animals behavior (Figure 24).

Discussion

Summary

This study has these main findings:

(1) Sidewalks of Taipei city had food resource for *Pieris* larvae (supporting Hypothesis 1).

(2) *Pieris* larvae inhabited urban sidewalks (supporting Hypothesis 2).

(3) *Pieris* larvae survived the abiotic environment of sidewalks, with survivorship similar to that in field habitat (rejecting Hypothesis 3).

(4) *Pieris* had accelerated development rates and reached smaller adult sizes in sidewalk than field habitat (supporting Hypothesis 4).

(5) The difference in *Pieris* larvae performance between sidewalk and field habitats did

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not vary with instar stage (rejecting Hypothesis 5).

(6) The high temperature and large temperature fluctuation on sidewalks did not reduce the survivorship of *Pieris* larvae (rejecting Hypothesis 6).

(7) The high average temperature on sidewalks accelerated the development rate of *Pieris* larvae, although it did not result in smaller adult sizes (partially supporting Hypothesis 7).

(8) The large temperature fluctuation on sidewalks did not affect the development rate of *Pieris* larvae and body size of *Pieris* adults (rejecting Hypothesis 8).

(9) Temperature aside, other abiotic factors on sidewalks negatively affected the development rate, but not the survivorship, of *Pieris* larvae (partially supporting Hypothesis 9).

(10) *Pieris* eggs faced lower predation pressure in sidewalk than field habitat (supporting

Hypothesis 10).

(11) *Pieris* larvae experienced more human disturbance and lower survivorship in sidewalk than field habitat (supporting Hypothesis 11).

The overall comparison of sidewalk and field habitats is provided in Table 20.

Pieris butterflies inhabit urban sidewalks

Our experiment 1 and 2 revealed that sidewalks fostered *Pieris* larvae and their host plants, suggesting that urban sidewalks could function as wildlife habitat. Specifically, our survey result in Exp. 1 has demonstrated that the sidewalks of Taipei city contain a sizable amount of host plant resources (Brassicaceae, mainly *Rorippa* spp. and *Cardamine* spp.) for *Pieris* larvae (e.g., 37 km of host plants), supporting our Hypothesis 1. The host plant abundance peaked from March to May, which coincided with the *Pieris* butterfly's breeding season. Our survey in Exp. 2 found *Pieris* eggs and larvae on sidewalks, supporting our Hypothesis 2 that *Pieris* use sidewalks as habitat. The 4st and 5th instar larvae were observed on the sidewalks, suggesting that *Pieris* species could complete their life cycle on sidewalks. Taken together, our results suggest that the abiotic environment and human interference on sidewalks does not stop butterfly larvae from using sidewalks as a habitat. Furthermore, widely connected sidewalks with host plants resources could even serve as movement corridors to help wildlife (e.g., butterflies) spread through urban areas (Bennett 1991, Gilbert 2012).

While *Pieris* butterflies used sidewalk as a breeding habitat, the oviposition rate of *Pieris* on host plants (*R. indica*) was lower in sidewalk than field habitat (32% vs. 77%). The lower oviposition rate might be due to lower *Pieris* density or more scattered host plants in urban areas. That being said, our results still clearly support the observation that butterflies have the mobility to utilize these scattered tiny resources in urban area (Hardy and Dennis 1999, Matteson and Langellotto 2012).

Sidewalks are overlooked but suitable habitat for *Pieris*

Abiotic factors on sidewalks

Our temperature measurement in Exp. 3 (Figure 7) and prediction (Table 9, Figure 10) demonstrated that the mean temperature, day mean temperature, maximum temperature and temperature range were higher on sidewalks than those in the field or those measures by typical weather station. The results are consistent with the stereotype of urban heat. The heat resource could come from cars and the city's mechanical systems (Svensson and Eliasson 2002). Moreover, the artificial surface materials absorb heat from solar radiation (Oke et al. 1989, Yokohari et al. 2001) and reduce water available for evapotranspiration (Taha 1997, Raupp et al. 2010).

Different from previous studies that focused on air temperature in urban areas (Svensson and Eliasson 2002), our survey methods did measure the temperature close to the ground of sidewalks. In other words, our temperature sensors also recorded the sensible heat transformed from the solar radiation by road surface material (Oke et al. 1989, Yokohari et al. 2001). Therefore, our method could better reflect the temperature of real microenvironment experienced by *Pieris* larvae on sidewalks, compared to the meteorological station data.

Similar or higher survivorship in sidewalk vs. field habitats (abiotic regime)

Pieris survivorship under the abiotic regime of sidewalks was similar to or better than that in the field (Exp. 3, Figure 16), rejecting our Hypothesis 3 and suggesting that sidewalks could function as a wildlife habitat with similar or even higher quality than field habitats. The results here hint that *Pieris* larvae can survive the abiotic factors on sidewalk such as high temperature, large temperature fluctuation, pollution, etc. Each topic is discussed below.

Base on the similar *Pieris* survivorship between sidewalk-fluctuating and field-fluctuating temperature treatment groups (Exp. 4) and between sidewalk habitat and field habitat (Exp. 3), our study suggests that the average high temperature on sidewalks would not reduce *Pieris* survivorship, rejecting our Hypothesis 6. Previous study found the survivorship of *P. rapae* larvae before pupal stage under constant temperature 20°C, 25°C and 30°C were 93%, 77% and 40%, respectively (Chen and Su 1982). The mean temperature in our sidewalk-fluctuating and field-fluctuating temperature treatment groups were 25.10°C and 22.35°C (representing a higher and lower mean temperature regime), resulting in 53.6% and 56.7% *P. canidia* larval survivorship before pupal stage, respectively. Therefore, the degree of temperature increase in sidewalk over field habitats may not be significant enough to reduce survivorship.

The lack of high temperature effect on *Pieris* survivorship, as described above, is different from a previous study where high temperature (an increase by 10°C every day) decreasing survivorship of *Pieris napi* (Bauerfeind and Fischer 2014). An explanation for our results could be that *P. canidia* on sidewalks were exposed to higher temperatures mainly during the day but not at night (Figure 7 and Figure 10). Therefore, while experiencing 35-40°C high temperature for a short time period during daytime, *Pieris* larvae may be able to recover after that and during evening to avoid increasing mortality (Figure 6). Another possible explanation is that *P. canidia* larvae could reduce the effect of high temperature by hiding under plant leaves that provide shading and cooling through transpiration.

Base on the similar survivorship between *Pieris* larvae in sidewalk-fluctuating and sidewalk-fixed treatment groups, our study suggests that the large range of daily temperature fluctuation on sidewalks would not reduce *Pieris* larval survivorship, rejecting our Hypothesis 6. This result is consist with a previous study where an increase in daily temperature variation from Δ7°C to Δ12°C did not reduce *Pieris* survivorship (Bauerfeind and Fischer 2014), Our within-day temperature variation was set at Δ4.4°C (22.7 – 27.1°C) for sidewalk-fixed temperature treatment and Δ10.6°C (21.3 - 31.9°C) for sidewalk-fluctuating temperature treatment. Our survivorship result suggests that *Pieris* larvae can tolerate the degree of temperature fluctuation set in our study.

Higher development rate in sidewalks vs. field habitats (abiotic regime)

The result of higher development rate on sidewalks suggests that sidewalks could be an even better habitat for *Pieris* than the field. Faster development rate is generally beneficial to insects because it can reduce the time period during which caterpillars are exposed to predation and parasitism (Feeny 1976, Price et al. 1980, Benrey and Denno 1997) or allow more generations a year (Pollard and Yates 1994, Virtanen and Neuvonen 1999, Kiritani 2006, Gomi et al. 2007). Specifically, *Pieris* larvae developed faster on the sidewalk than in the field (Exp. 3, Figure 18), supporting our Hypothesis 4. Because the acceleration of development rate was also observed in our laboratory cage experiments (i.e., higher rate in sidewalk-fluctuating and sidewalk-fixed over field-fluctuating temperature groups in Exp. 4), higher temperature, instead of other abiotic factors, should be mainly responsible for the faster development in sidewalk than field habitats.

Furthermore, the high average temperature, instead of high temperature fluctuation, on

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sidewalks may be the key factor accelerating the development rate of immature *Pieris*. This because Exp. 4 showed that *Pieris* larvae under sidewalk-fluctuating and sidewalk-fixed temperature treatments had similar development rate, which was higher at under field-fluctuating temperature treatment. Therefore, one can conclude that high mean temperature, instead of temperature fluctuation, is the mean factor leading to the accelerated development. Although it is unclear why the effect of temperature fluctuation was minimum, a study hints that *P. rapae* can feed and grow efficiently over a wide range of temperatures (Kingsolver 2000).

Although we argue that the faster development rate on sidewalks is beneficial to *Pieris*, we do not rule out a potential cost of this faster development. Higher temperatures are usually expected to accelerate development but reduce body weight (Angilletta Jr and Angilletta 2009). This temperature-size rule leads to “hotter is smaller” (Atkinson 1994, Angilletta and Dunham 2003). In fact, we observed smaller adult butterflies in sidewalk than field habitats in Exp. 3. This may be because the higher temperature on sidewalk had a stronger effect on development rate than growth rate, thereby affecting the final-stage body size (van der Have and de Jong 1996). We, however, did not see the smaller adult

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size under sidewalk temperature treatment in Exp. 4. The different results between Exp. 3 and Exp.4 may due to the lack of extreme temperature in Exp. 4. Although the temperature regime on sidewalks (Exp. 3) and under sidewalk-fluctuating treatment (Exp. 4) seemed to have similar average temperature and within-day temperature fluctuation (Figure 7a and Figure 8b), short-time extreme temperature on sidewalks in Exp. 3 may be missing in Exp. 4 becaure we averaged temperatures over many days for Exp. 4 (Figure 6, Figure 7a). For example, the highest temperature in Exp. 4 was set at to 31.9°C, although there were some days with peak temperature higher than 35-40°C during daytime on sidewalks (Figure 6). The short-time extreme high temperature may play an important role in reducing *Pieris* adult body size on sidewalks (Exp. 3). Another possible explanation for the different results on body size between Exp. 3 and Exp. 4 might be because the small sample size in Exp. 4 provided limited statistical power.

The cost of smaller body size could be reflected on fertility. For example, larger male *P. napi* butterflies may provide females more nutrition at mating to increase their fertility (Wiklund and Kaitala 1995, Stjernholm and Karlsson 2000) and could perform better in sperm competition (Bissoondath and Wiklund 1997). Female body weight in *P. rapae* is

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linearly related to lifetime egg production (Jones et al. 1982). Therefore, smaller *Pieris* body size under the faster development on sidewalks may place a potential cost on reproduction.

We further examined how higher temperature benefited *Pieris* development based on the concept of degree day. Because insects need enough heat energy to develop to the next stage, higher temperature often shortens insects' developmental period, which can be described by the equation below (Ikemoto and Takai 2000):

$$(DT) = k + tD$$

D represents the duration of development (days); T represents the temperature under which an insect individual is raised; t indicates the development threshold temperature, and k is the effective cumulative temperature in this equation. Based on the equation, we examined the effective cumulative temperature for *Pieris* in Exp. 3.

Contrary to the common view that a species expresses similar degree-days under different

doi:10.6342/NTU202003180

environmental conditions (Damos and Savopoulou-Soultani 2012), the effective cumulative temperatures required by *Pieris* to reach certain life stages varied with years (Figure 20, Table 16 and Table 17). Specifically, the egg and pupal stages required different effective cumulative temperatures in each of the three years of this study; the larval stage (2nd, 4th and 5th instar) required less effective cumulative temperature in 2016 than in other years. These results raise a concern that degree days required by insects may depend on years, which feature different environmental conditions and affect insect development differently. In contrast, the effective cumulative temperature required by *Pieris* to reach certain life stages was consistent between different laboratory temperature treatments in Exp. 3. Given that each growth chamber provide similar, if not identical environment, our results suggest that similar environmental conditions may be a prerequisite for predicting insect development based on a stable effective cumulative temperature.

Our results in *Pieris* development rate do not support the findings from previous studies, which showed a stage-specific beneficial effect of higher temperature on insect development rate (Petersen et al. 2000, Kingsolver and Gomulkiewicz 2003, Whitney-

doi:10.6342/NTU202003180

Johnson et al. 2005, Esperk 2006, Folguera et al. 2010, Despland 2017, Banahene et al. 2018). In our study, the accelerated development of *Pieris* under higher temperature (e.g., sidewalk temperature regime) occurred generally in each life stage, reject our Hypothesis 5. This implies that climate warming (higher temperature) may place similar impact on the development of *Pieris* species across different life stages.

The biotic factors on sidewalks

While sidewalk habitat provides *Pieris* butterflies similar or better abiotic conditions compared to field habitat (e.g., similar/better survivorship and development rate), it provides mixed biotic conditions to *Pieris*. For instance, *Pieris* eggs had a higher survivorship in sidewalk than field habitats, but caterpillar decoys faced higher human disturbance in sidewalk than field habitats. The higher egg survivorship on sidewalks could be due to the lack of predators on sidewalks. Arthropod predators such as ants and spiders could prey on butterfly eggs and larvae (Schmaedick and Shelton 2012, Oberhauser et al. 2015, Hermann et al. 2019). In our study system, ants have been observed to feed on and carry *Pieris* eggs in field habitat. Since spider and ant populations are heavily influenced by local environmental factors (Philpott et al. 2014), the harsh

doi:10.6342/NTU202003180

environment of sidewalks may repel these predators and therefore increase *Pieris* egg survivorship. On the other hand, sidewalks could have a higher human disturbance that reduces the "survivorship" of *Pieris* caterpillar decoys. We observed that most of the caterpillar decoys on sidewalks were damaged or displaced by human interference, such as trampling, sweeping and weeding.

The strength and weakness of this study

This study helps advance our understanding of wildlife (*Pieris*) habitat in typical urban environment, by conducting both field survey and cage experiments, and examining the effect of temperature (average and fluctuation) on *Pieris* performance. Surprisingly, the habitat quality of sidewalks for *Pieris* could be similar to or better than that of the field, highlighting the importance of urban areas as wildlife habitats. This study also reveals similar effects of high temperature on *Pieris* larval performance across different life stages, hinting that climate warming could impact each stage of arthropod development. In addition, this study has established conversion criterion of body length into larval stage, and of weather temperatures into sidewalk temperatures. These conversion criterion should benefit future studies of urban sidewalks and butterflies.

This study has some limitations. For example, while this study is based on empirical experiments and should be able to reflect the reality, it could have more replicates to improve statistical power. In addition, this study examined the effects of abiotic and biotic factors separately. Although abiotic and biotic factors could interactively affect *Pieris* performance. Finally, this study did not examine the fitness of adult butterflies raised form sidewalk vs. field habitats.

doi:10.6342/NTU202003180

Conclusions

This study discovered that (1) sidewalks in Taipei city fostered *Pieris* larvae and their host plants, (2) *Pieris* larvae in sidewalk habitat performed similarly or better, compared to those in field habitat, (3) high average temperature, rather than large temperature fluctuation or other abiotic factors, was the key factor contributing to the accelerated development rate of *Pieris* larvae on sidewalks, and (4) *Pieris* faced lower egg predation but higher human disturbance in sidewalk vs. field habitats (Table 20).

Overall, this study suggests that sidewalks are important or even high quality habitat for some wildlife. Therefore, we recommend urban managers to adjust their management approaches to make urban more wildlife friendly (e.g., avoid mowing during *Pieris* peak season on sidewalks). As insect populations are declining globally (van Klink et al. 2020) and urban areas are increasing continuously, urban areas may play a more and more important role in providing wildlife refuge to inhabit or corridors to facilitate wildlife migration. Urban areas may also support wildlife populations (e.g., pollinators) that provide important ecosystem services to urban systems and adjacent suburban areas. Therefore, we encourage city managers to investigate and improve the ecological value

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of urban areas.

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Figures and tables

Table 1 Survey sites of Exp. 1

Sixty survey sites of Exp. 1 Field survey: host plant density. All coordinates were presented in the decimal degrees (DD) format.

Site	Longitude	Latitude	Site	Longitude	Latitude	Site	Longitude	Latitude
1	121.52754	25.09561	21	121.53667	25.0607	41	121.50856	25.14189
2	121.52012	25.09333	22	121.55434	25.08233	42	121.51313	25.14287
3	121.50895	25.0909	23	121.5213	25.03867	43	121.49031	25.14162
4	121.53074	25.10859	24	121.50638	25.03165	44	121.56733	25.05796
5	121.5254	25.1007	25	121.51729	25.02682	45	121.55668	25.05952
6	121.51519	25.05027	26	121.5094	25.03056	46	121.55478	25.0603
7	121.51414	25.05151	27	121.51457	25.04602	47	121.55255	25.05304
8	121.51678	25.05347	28	121.60328	25.08041	48	121.56074	25.07086
9	121.54606	25.02864	29	121.57209	25.08247	49	121.56962	25.04578
10	121.54574	25.0377	30	121.59654	25.06136	50	121.55786	25.04414
11	121.54661	25.02385	31	121.58589	25.06558	51	121.567	25.03041
12	121.53803	25.03303	32	121.598	25.07336	52	121.55937	25.02106
13	121.54599	25.02825	33	121.57549	25.05307	53	121.57086	25.0348
14	121.54856	25.03643	34	121.59577	25.07847	54	121.60047	25.05125
15	121.54565	25.03105	35	121.57304	25.08297	55	121.60977	25.05493
16	121.52266	25.05084	36	121.55089	25.00062	56	121.60239	25.05771
17	121.52691	25.04734	37	121.54861	24.99872	57	121.60695	25.05705
18	121.54159	25.04476	38	121.56476	24.99055	58	121.49785	25.0294
19	121.53826	25.06225	39	121.57211	24.99159	59	121.50425	25.03986
20	121.55158	25.08364	40	121.50431	25.14047	60	121.49622	25.03675

Table 2 Experimental information of Exp. 1

Experimental information of Exp. 1 Field survey: host plant density. The survey periods were given.

Year	Month	Start day	End day
2015	12	2015/12/23	2015/12/29
2016	1	2016/1/12	2016/1/20
2016	2	2016/2/23	2016/3/1
2016	3	2016/3/20	2016/3/28
2016	4	2016/4/20	2016/5/13
2016	5	2016/5/19	2016/6/8
2016	6	2016/6/27	2016/7/4
2016	7	2016/7/27	2016/8/6
2016	8	2016/9/3	2016/9/12
2016	9	2016/10/13	2016/10/28
2016	10	2016/10/30	2016/11/7
2016	11	2016/12/12	2016/12/21
2016	12	2016/12/31	2017/1/15
2017	1	2017/1/31	2017/2/14

Table 3 Experimental information of Exp. 2

Experimental information of Exp. 2 Field survey: *Pieris* egg and larval density.

(a) Population survey

	2016		2017		2018	
	4/8 -5/31		3/24 - 5/22		3/27 - 5/29	
Treatment	Sidewalk	Field	Sidewalk	Field	Sidewalk	Field
Site	4	1	2	1	3	1
Plant	110	15	61	4	75	9
Plant × Day	3353	284	1217	195	2536	410

(b) Host plant utilization by ovipositing females

	Sidewalk site			Field site		
	A	B	C	X	Y	Z
Plant	20	20	20	20	12	20

Table 4 Body length to stage conversion criterion

This conversion criterion was used to estimate the stage of *P. canidia* larvae by their body length. The method of establishing this conversion criterion is in the Appendix A: Larval stage identification.

	Upper limit of body length in stage (mm)				
Temperature treatment	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Sidewalk-fluctuating	3.23	6.08	9.30	16.07	26.71
Field-fluctuating	3.76	6.08	9.30	16.07	26.71
Sidewalk-fixed	3.60	6.08	9.30	16.07	26.71

Table 5 Experimental information of Exp. 3

Experimental information of Exp. 3 Sidewalk cage experiment: larval performance in sidewalk microenvironment.

	2016		2017		2018	
	4/29 -5/26		5/30 - 6/26		4/11 - 5/29	
Treatment	Sidewalk	Field	Sidewalk	Field	Sidewalk	Field
Site	1	1	2	1	2	1
Individual	18	17	12	15	28+30	33

Table 6 Experimental information of Exp. 4

Experimental information of Exp. 4 Laboratory cage experiment: larval performance under sidewalk temperature regimes.

	2018/5/5 - 6/13		
	Sidewalk-fluctuating	Field-fluctuating	Sidewalk-fixed
Site	1	1	1
Pot	10	10	10
Individual	30	29	29
Stage identified pot	5	5	5
Stage identified individual	14	14	15

Table 7 Low development threshold temperature of *P. rapae*

Low development threshold temperature of *P. rapae*. This data were collected by a previous study (鄭秋玲 and 許長漢 2003). We used these data to calculate the effective cumulative temperature of *Pieris canidia* larvae in Exp. 3 and Exp. 4.

		Larval stage					
	Egg	1	2	3	4	5	Pupal
Low deveplopment threshod (˚C)	7.38	9.41	10.96	8.06	5.36	-5.00	7.43

Table 8 Experimental information of Exp. 5

Experimental information of Exp. 5 Field manipulation experiment: survivorship on eggs and caterpillar decoys.

	2016		2018	
	Sidewalk	Field	Sidewalk	Field
Site	3	2	3	2
Eggs	60	27	153	122
Caterpillar decoys	90	46	50	58

Table 9 Microenvironment temperature of sidewalks and meteorological data

The temperature of sidewalks microenvironment and weather in *Pieris* season (April and May) in Taipei city.

The Meteorological data were collected by automatic weather stations of Taipei station in Taipei and saved in the Central Weather Bureau Observation Dara Inquire System. The sidewalk temperature was predicted from meteorological data. The unit was degree (˚C). (a) Whole day temperature. (b) Day temperature. (c) Night temperature

(a) Whole day temperature

	Sidewalk				Meteorological			
	2016	2017	2018	**Average**	2016	2017	2018	**Average**
Mean	26.54	24.98	26.90	**26.14**	25.57	24.05	25.90	**25.17**
SD	4.75	4.78	5.36	**4.96**	3.72	3.89	4.45	**4.02**
Minimum	17.13	11.61	13.55	**14.10**	17.20	11.80	13.70	**14.23**
1st quartile	23.06	22.14	23.26	**22.82**	22.65	21.70	23.00	**22.45**
Median	25.82	24.90	26.71	**25.81**	25.40	24.40	26.10	**25.30**
3rd quartile	29.07	27.65	30.10	**28.94**	27.80	26.40	28.90	**27.70**
Maximum	41.66	40.00	42.66	**41.44**	36.70	35.20	37.80	**36.57**
Range	24.53	28.40	29.11	**27.35**	19.50	23.40	24.10	**22.33**

(b) Day temperature

	Sidewalk				Meteorological			
	2016	2017	2018	**Average**	2016	2017	2018	**Average**
Mean	28.61	26.96	29.19	**28.26**	26.77	25.17	27.29	**26.41**
SD	5.28	5.08	5.73	**5.36**	4.07	4.05	4.73	**4.28**
Minimum	17.13	11.61	13.55	**14.10**	17.20	11.80	13.70	**14.23**
1st quartile	24.41	23.83	25.18	**24.47**	23.60	22.85	24.00	**23.48**
Median	28.35	27.07	29.49	**28.30**	26.70	25.55	27.80	**26.68**
3rd quartile	32.27	30.55	33.36	**32.06**	29.85	27.90	30.80	**29.52**
Maximum	41.66	40.00	42.66	**41.44**	36.70	35.20	37.80	**36.57**
Range	24.53	28.40	29.11	**27.35**	19.50	23.40	24.10	**22.33**

(c) Night temperature

	Sidewalk				Meteorological			
	2016	2017	2018	**Average**	2016	2017	2018	**Average**
Mean	24.48	22.99	24.61	**24.03**	24.38	22.92	24.51	**23.94**
SD	2.96	3.46	3.77	**3.40**	2.88	3.38	3.68	**3.31**
Minimum	17.74	11.61	13.75	**14.37**	17.80	11.80	13.90	**14.50**
1st quartile	22.14	20.86	22.55	**21.85**	22.10	20.80	22.50	**21.80**
Median	24.79	23.77	24.79	**24.45**	24.70	23.70	24.70	**24.37**
3rd quartile	26.43	25.41	27.55	**26.46**	26.30	25.30	27.40	**26.33**
Maximum	34.36	30.60	32.87	**32.61**	33.30	30.10	32.10	**31.83**
Range	16.62	18.99	19.11	**18.24**	15.50	18.30	18.20	**17.33**

Table 10 Amount of plants on sidewalk sites

Total length of plant abundance on cracks of 2m × 60 sites sidewalk. The unit of plant abundance was meter.

	All plants	Brassicaceae	*Rorippa* spp.	*Cardamine* spp.
		2015		
December	52.03	**1.48**	1.45	0.03
		2016		
January	49.16	**1.77**	1.73	0.04
February	54.37	**3.31**	2.29	1.02
March	54.81	**4.51**	3.43	1.08
April	72.88	**4.72**	4.18	0.54
May	72.44	**2.90**	2.44	0.46
June	65.81	**1.33**	1.21	0.12
July	40.70	**1.21**	1.21	0
August	49.74	**0.11**	0.11	0
September	54.31	**1.48**	1.39	0.09
October	55.25	**1.37**	1.25	0.12
November	48.17	**1.95**	1.59	0.36
December	55.29	**2.53**	2.05	0.48
		2017		
January	53.66	**2.76**	2.16	0.6

Table 11 *Pieris* egg and larval density analysis

The eggs and larvae density per plant in 2016, 2017 and 2018 *Pieris* breeding season between sidewalk and field habitats were analyzed by GLMM.

The P values were given, bold value represented a significant difference ($P < 0.05$) and underline value represented a marginal significant difference ($P < 0.1$).

	Egg	larva
2016	0.495	**0.00138**
2017	0.967	0.28416
2018	0.941	0.49746

Table 12 Survival test

Comparing the overall survival probability between sidewalk and field habitat (Exp. 3) or temperature regimes (Exp. 4) base on the Log rank test and Gehan-Breslow test. The P values were given, bold value represented a significant difference (*P* < 0.05) and underline value represented a marginal significant difference (*P* < 0.1)

	Log rank test			Gehan - Breslow test	
	Chisq	*Df*	*P*	*Z*	*P*
2016	4	1	**0.0463**	-2.2277	**0.0259**
2017	2.1	1	0.1430	1.4221	0.1550
2018	1	1	0.3090	-0.2747	0.7836
2018 Exp. 4	0.4	1	0.5430	-1.8243	0.0681
Exp. 3 2018 & Exp.4	1.6	3	0.6570	4.8454	0.1835

Table 13 Survival rate of regimes

Comparing the stage-specific survival rate of habitats or temperature regimes in each year/experiment. Bold value represented a significant difference ($P < 0.05$). (a) Exp. 3 and Exp. 4, analyzed by Fisher exact test of count data. The *P* values were given. (b) Exp. 3 2018 and Exp. 4, analyzed by row-wise Fisher's exact test of count data. The adjusted *P* values were given.

(a) Exp. 3 and Exp. 4, analyzed by Fisher exact test of count data

	2016	2017	2018	Exp. 4	Exp. 3 2018 & Exp.4
Egg	0.338	0.38	1	0.77	0.0593
Stage 1	1	0.204	0.662	0.342	0.580
Stage 2	0.196	0.565	1	0.185	0.169
Stage 3	1	1	1	1	0.935
Stage 4	0.414	0.497	0.556	0.544	0.55
Stage 5	1	0.107	0.708	1	0.885
Pupal	1	0.322	0.24	0.886	**0.0358**

(b) Exp. 3 2018 and Exp. 4, analyzed by row-wise Fisher's exact test of count data.

	Egg	Larval stage					Pupal
		1	2	3	4	5	
Sidewalk	0.304	0.558	1	1	1	1	**0.0353**
Field	0.606	0.710	1	1	1	1	1
Sidewalk-fluctuating	0.742	0.710	1	1	1	1	1
Field-fluctuating	0.628	0.275	0.454	1	1	1	1
Sidewalk-fixed	0.320	0.469	1	1	1	1	0.428

Table 14 Survival rate of life stages

Comparing the stage-specific survival rate of life stages in different habitats or temperature regimes. Bold value represented a significant difference (*P* < 0.05). (a) Exp. 3 and Exp. 4, analyzed by Fisher exact test of count data. The P values were given. (b) Exp. 3 and (c) Exp. 4, analyzed by row-wise Fisher's exact test of count data. The adjusted P values were given.

(a) Exp. 3 and Exp. 4, analyzed by Fisher exact test of count data

	Sidewalk	Field	Sidewalk fluctuation	Field fluctuation	Sidewalk fixed
2016	0.6310	0.2500			
2017	**0.00938**	0.0836			
2018	0.0559	0.0776			
Exp. 4			**0.0184**	**0.000367**	**<0.0001**

(b) Exp. 3, analyzed by row-wise Fisher's exact test of count data

	2016		2017		2018	
	Sidewalk	Field	Sidewalk	Field	Sidewalk	Field
Egg	1	0.311	**0.00102**	0.252	0.156	1
Stage 1	1	1	0.266	1	1	1
Stage 2	1	1	1	1	1	1
Stage 3	1	1	1	1	1	0.479
Stage 4	1	1	1	1	1	1
Stage 5	1	1	1	1	1	1
Pupal	1	1	1	0.284	1	0.269

(c) Exp. 4, analyzed by row-wise Fisher's exact test of count data

	Sidewalk fluctuation	Field fluctuation	Sidewalk fixed
Egg	1	0.52	0.238
Stage 1	1	1	0.96
Stage 2	1	1	0.238
Stage 3	1	0.471	0.96
Stage 4	1	0.471	0.96
Stage 5	1	0.52	0.211
Pupal	**0.00763**	**0.00784**	**< 0.0001**

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Table 15 Growth period analysis

Comparing the effects on stage-specific growth period at each habitat/experiment and year. The P values were given, bold value represented a significant difference ($P < 0.05$) and the underline value represented a marginal significant difference ($P < 0.1$).

(a) Exp. 3 and (b) Exp. 4, used GLMM analysis to examine effects on growth period.

(c, d) Exp. 3 and Exp. 4, used Kruskal-Wallis test with *post hoc* of effects on stage-specific growth period at each life stage. (e, f) Exp. 3 2018 and Exp. 4, Kruskal-Wallis test with *post hoc* of effects on overall and stage-specific growth period.

(a) Exp. 3, used GLMM analysis to examine effects on growth period

Effect	*Df*	*Chisq*	*P value*
Habitat	1	4.42	**0.04**
Stage	6	416.36	**<0.0001**
Year	2	20.88	**<0.0001**
Habitat × Stage	6	4.21	0.65
Habitat × Year	2	0.81	0.67
Stage × Year	12	35.36	**0.0004**

(b) Exp. 4, used GLMM analysis to examine effects on growth period

Effect	*Df*	*Chisq*	*P value*
Temperature	2	10.98	**0.005**
Stage	6	196.28	**<0.001**
Temperature × Stage	12	5.13	0.954

(c) Exp. 3 and Exp. 4, used Kruskal-Wallis test with *post hoc* of effects on stage-specific growth period at each life stage

Life stage	2016	2017	2018	Exp. 4
Egg	0.8329	**0.2638**	**0.4070**	**0.1582**
Stage 1	0.4850	0.0114	0.0265	0.0000
Stage 2	**0.0062**	0.9155	0.1042	0.1237
Stage 3	0.1967	0.4066	0.9254	0.1716
Stage 4	0.0909	0.1366	**0.0117**	**0.0001**
Stage 5	0.7760	0.3227	0.5081	**0.0239**
Pupa	**0.0013**	0.6515	0.6584	**0.0001**
Egg to pupation	**0.0024**	**0.0410**	**0.0032**	**<0.0001**
Pupa	**0.0013**	0.6515	0.6584	**0.0001**
Egg to eclosion	**0.0003**	**0.0323**	**0.0101**	**0.0001**

(d) Exp. 3 and Exp. 4, used Kruskal-Wallis test with *post hoc* of effects on stage-specific growth period at each life stage

	Egg	Larval stage					Pupal	Overall		
		1	2	3	4	5		Egg to pupation	Pupal stage	Egg to eclosion
2016										
Sidewalk	a	a	a	a	a	a	a	a	a	a
Field	a	a	b	a	a	a	b	b	b	b
2017										
Sidewalk	a	a	a	a	a	a	a	a	a	a
Field	a	b	a	a	a	a	a	b	a	b
2018										
Sidewalk	a	a	a	a	a	a	a	a	a	a
Field	a	b	a	a	b	a	a	b	a	b
Exp. 4										
Sidewalk-fluctuating	a	a	a	a	a	a	a	a	a	a
Field-fluctuating	a	b	a	a	b	b	b	b	b	b
Sidewalk-fixed	a	c	a	a	a	a	a	a	a	a

(e) Exp. 3 2018 and Exp. 4, used Kruskal-Wallis test with *post hoc* of effects on stage-specific growth period at each life stage

	Overall		
	Egg to pupation	Pupal stage	Egg to eclosion
P value	**<0.0001**	**0.0002**	**<0.0001**
Sidewalk	a	a	a
Field	a	b	a
Sidewalk-fluctuating	b	bc	b
Field-fluctuating	b	bc	c
Sidewalk-fixed	b	c	c

(f) Exp. 3 2018 and Exp. 4, used Kruskal-Wallis test with *post hoc* of effects on stage-specific growth period at each life stage

	Egg	Larval stage					Pupal
		1	2	3	4	5	
P value	0	**<0.0001**	0.1413	**<0.0001**	**<0.0001**	0.0921	**0.0002**
Sidewalk	a	a	a	a	a	a	a
Field	a	a	a	a	a	ab	b
Sidewalk-fluctuating	b	b	a	a	b	ab	bc
Field-fluctuating	b	b	a	b	b	b	bc
Sidewalk-fixed	b	c	a	b	b	b	c

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Table 16 Effective cumulative temperature

The effective cumulative temperatures of sidewalk larvae at each life stage in (a) Exp. 3 and (b) Exp. 4. The unit was degree-day.

(a) Exp. 3, effective cumulative temperatures of sidewalk larvae at each life stage

	2016		2017		2018	
	Mean	SE	Mean	SE	Mean	SE
Egg	33.51	3.84	74.18	3.38	84.33	1.89
Stage 1	31.58	7.29	30.29	4.36	38.35	2.68
Stage 2	17.91	0.00	40.48	7.68	38.35	2.41
Stage 3	25.09	2.39	30.34	4.08	33.34	1.94
Stage 4	43.14	3.42	47.36	3.62	57.41	3.11
Stage 5	138.02	5.65	120.31	4.25	132.85	7.80
Pupa	136.59	5.31	165.55	1.14	159.22	3.73
Sum	**425.84**		**508.51**		**543.85**	

(b) Exp. 4, effective cumulative temperatures of sidewalk larvae at each life stage

	Sidewalk fluctuation		Field fluctuation		Sidewalk fixed	
	Mean	SE	Mean	SE	Mean	SE
Egg	53.82	0.63	46.97	1.23	52.56	0.00
Stage 1	35.32	2.24	43.35	2.70	44.68	2.62
Stage 2	41.80	3.15	34.17	2.46	35.39	2.92
Stage 3	42.62	2.44	42.19	3.19	42.75	2.14
Stage 4	50.41	3.36	59.53	3.67	54.77	2.53
Stage 5	122.31	5.12	132.19	10.66	118.11	4.04
Pupa	130.17	3.59	140.24	3.30	133.94	3.28
Sum	**476.45**		**498.64**		**482.2**	

Table 17 Analysis of effective cumulative temperature

Analysis for effects on effective cumulative temperature. The P values were given, bold value represented a significant difference ($P < 0.05$) and underline value represented a marginal significant difference ($P < 0.1$).

(a) Exp. 3 (only in sidewalk habitat) and Exp. 4 used LMM analysis to examine effects on effective cumulative temperature. (b) Exp. 3, analyzed by Kruskal-Wallis test with *post hoc* on effective cumulative temperature. (c) Exp. 3 (only in sidewalk habitat) and Exp. 4, analyzed by Kruskal-Wallis test with *post hoc* on effective cumulative temperature.

(a) Exp. 3, LMM analysis for effective cumulative temperature in each stage

Exp. 3 (only in sidewalk habitat)				Exp. 4			
Effect	*Df*	*Chisq*	*P value*	Effect	*Df*	*Chisq*	*P value*
Stage	6	700.66	< **0.001**	Stage	6	794.01	**<0.001**
Year	2	15.33	< **0.001**	Temperature	2	2.27	0.322
Stage × Year	12	54.61	< **0.001**	Stage × Temperature	12	24.94	0.015

(b) Exp. 3, Kruskal-Wallis test with *post hoc*

	Egg	Larval stage					Pupal
		1	2	3	4	5	
P value	< **0.0001**	0.4206	**0.0039**	0.9369	**0.0366**	**0.0337**	< **0.0001**
2016	a	a	b	a	b	a	a
2017	b	a	a	a	ab	b	b
2018	c	a	a	a	a	b	c

(c) Exp. 3 and Exp. 4, Kruskal-Wallis test with *post hoc*

	Egg	Larval stage					Pupal
		1	2	3	4	5	
P value	**0**	0.0946	**0.0040**	**<0.0001**	**0.0133**	**0.0152**	**<0.0001**
2016	a	ab	b	b	b	a	b
2017	b	b	a	b	ab	b	a
2018	c	ab	a	b	a	ab	a
Exp. 4	d	a	a	a	a	b	b

Table 18 Performance of adult butterfly

Comparing the effects on body weight and forewing length at each habitats of temperature regimes. Exp. 3 used LMM to analyze (a) body weight and (b) forewing length, with (c) Kruskal-Wallis test with *post hoc*. The P values were given, bold value represented a significant difference ($P < 0.05$) and the underline value represented a marginal significant difference ($P < 0.1$).

(a) Exp. 3, used LMM to analyze body weight

Effect	*Df*	*Chisq*	*P value*
Habitat	1	16.76	< **0.001**
Sex	1	2.93	<u>0.087</u>
Year	2	3.18	0.203

(b) Exp. 3, used LMM to analyze forewing length

Effect	*Df*	*Chisq*	*P value*
Habitat	1	7.17	**0.007**
Sex	1	3.55	<u>0.059</u>
Year	2	4.88	<u>0.087</u>

(c) Exp. 3 and Exp. 4, used Kruskal-Wallis test with *post hoc* on body weight and forewing length

	Male		Female	
	Body weight	Forewing length	Body weight	Forewing length
2016	<u>0.0790</u>	0.1432	**0.0067**	0.1967
2017	**0.0073**	0.6847	**0.0339**	**0.0339**
2018	0.3991	0.7518	<u>0.0828</u>	<u>0.0986</u>
Exp.4	0.4398	0.2862	0.4673	0.6800

Table 19 Survivorship under biotic factors

Results of Exp. 5. (A) Number of eggs and caterpillar decoys. (B) Analyzed by Fisher's exact test for count data. The P values were given, bold value represented a significant difference ($P < 0.05$) and the underline value represented a marginal significant difference ($P < 0.1$).

(a) Exp. 5, number of eggs and caterpillar decoys

	Eggs		Caterpillar decoys	
	placed	intact	placed	intact
Sidewalk	213	160	140	100
Field	149	98	104	88

(b) Exp. 5, analyzed by Fisher's exact test for count data

	Eggs	Caterpillar decoys
p-value	0.05939	**0.02048**

Table 20 Conclusions of this study

The conclusions of this study.

	Sidewalk		**Field**
Microenvironment			
Average temperature	Higher	>	
Temperature fluctuation	Larger	>	
***Pieris* performance**			
Survivorship	Similar or Better	≥	
Development rate	Faster	>	
Adult size		<	Larger
Abiotic factor effects			
Average temperature	Development faster	>	
Temperature fluctuation	Similar	=	Similar
Other factor effects		<	Development faster
Biotic factor effects			
Egg survivorship	Less predator	>	
Larva survivorship		<	Less disturbance

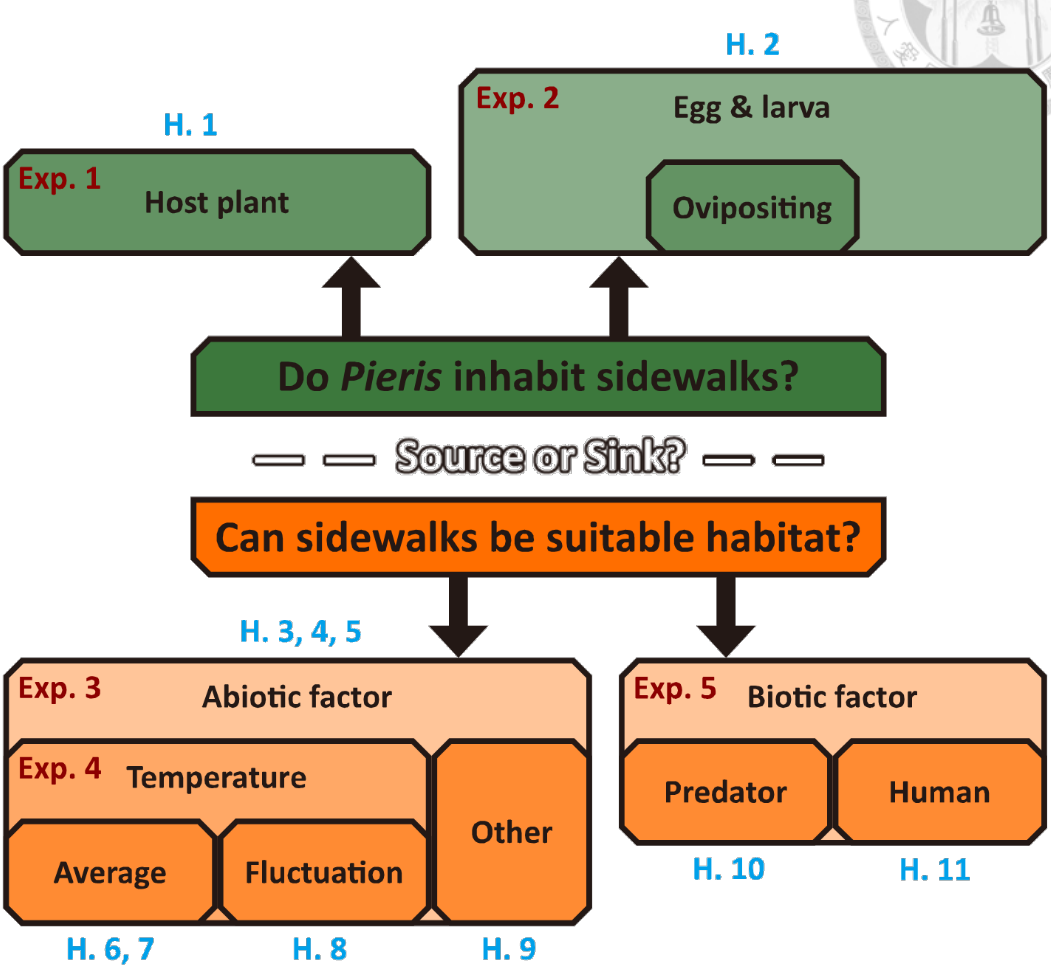

Figure 1 Concept map

This study includes the following aims and hypotheses to answer two questions: (a) Do *Pieris* inhabit sidewalks? (b) Can sidewalks be suitable habitat for *Pieris*?

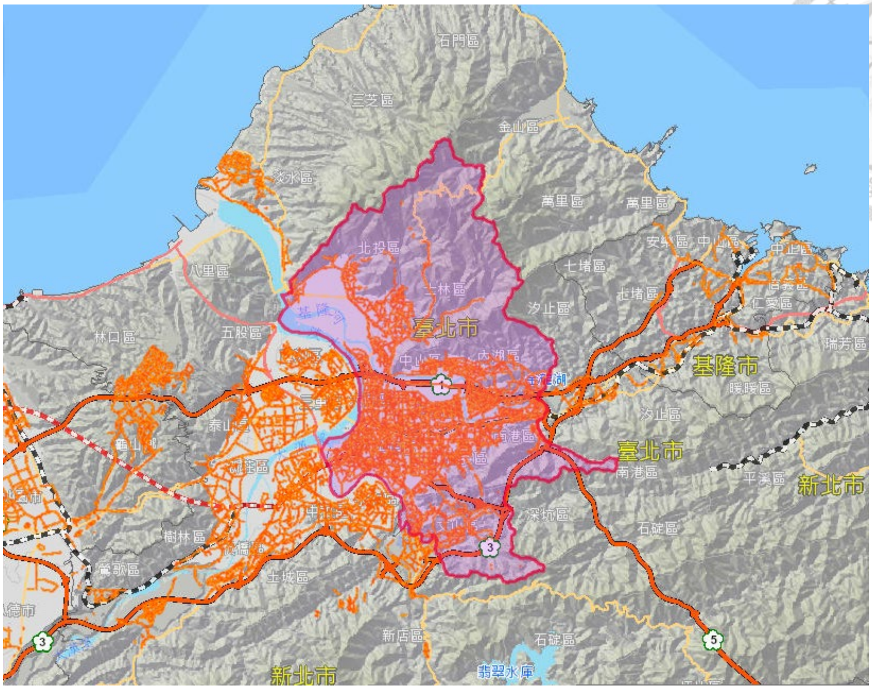

Figure 2 Sidewalk in Taipei city

Orange lines represent the sidewalks in Taipei. There were 939,745 meters of goverment-builed sidewalks (2,527,900 m^2, 0.93% area of Taipei) in 2015 in Taipei, Taiwan.

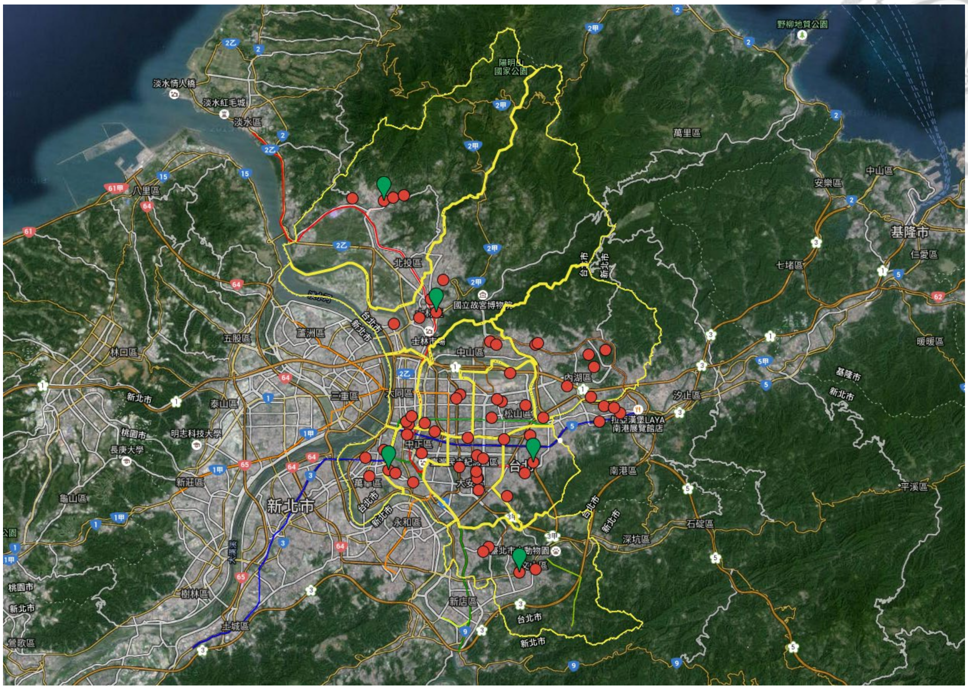

Figure 3 Study sites of Exp. 1 and sidewalk microenvironment monitoring

The location of 60 sidewalk sites in Exp. 1 Field survey: host plant density. Red points represent the field survey sites; green bubbles represent the iButton measurement sites; yellow lines represent the district borders of Taipei city.

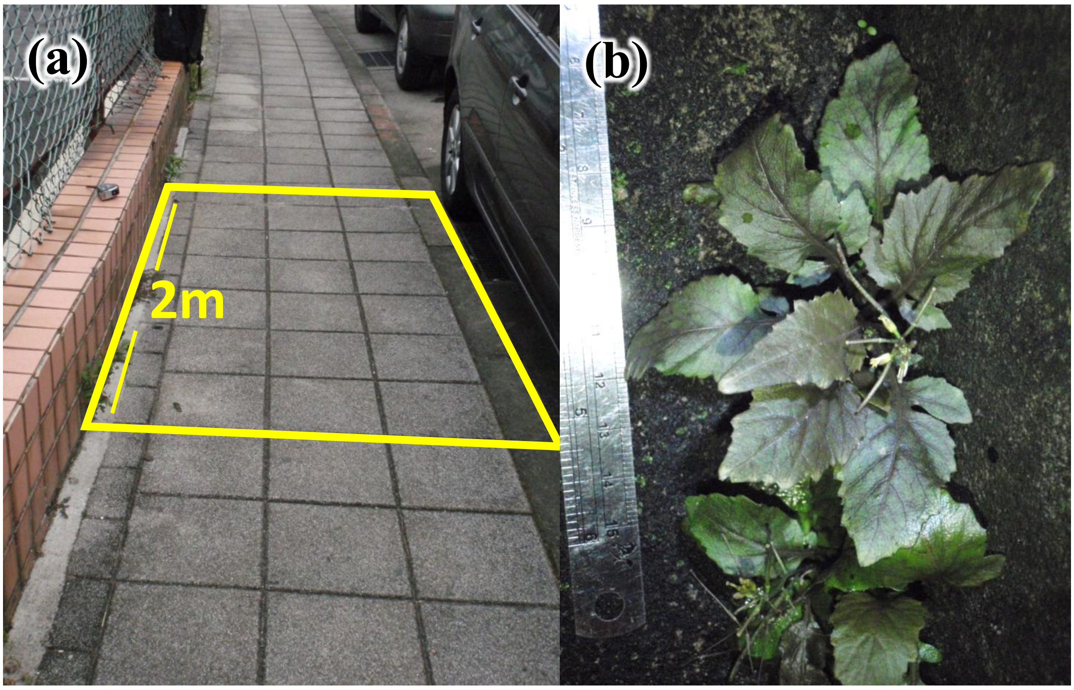

Figure 4 An example of sampling quadrat and plants on sidewalk site in Exp. 1

(a) One of our survey sidewalk site. Yellow lines represented the range of two-meters long sampling quadrat. (b) Plants on sidewalk.

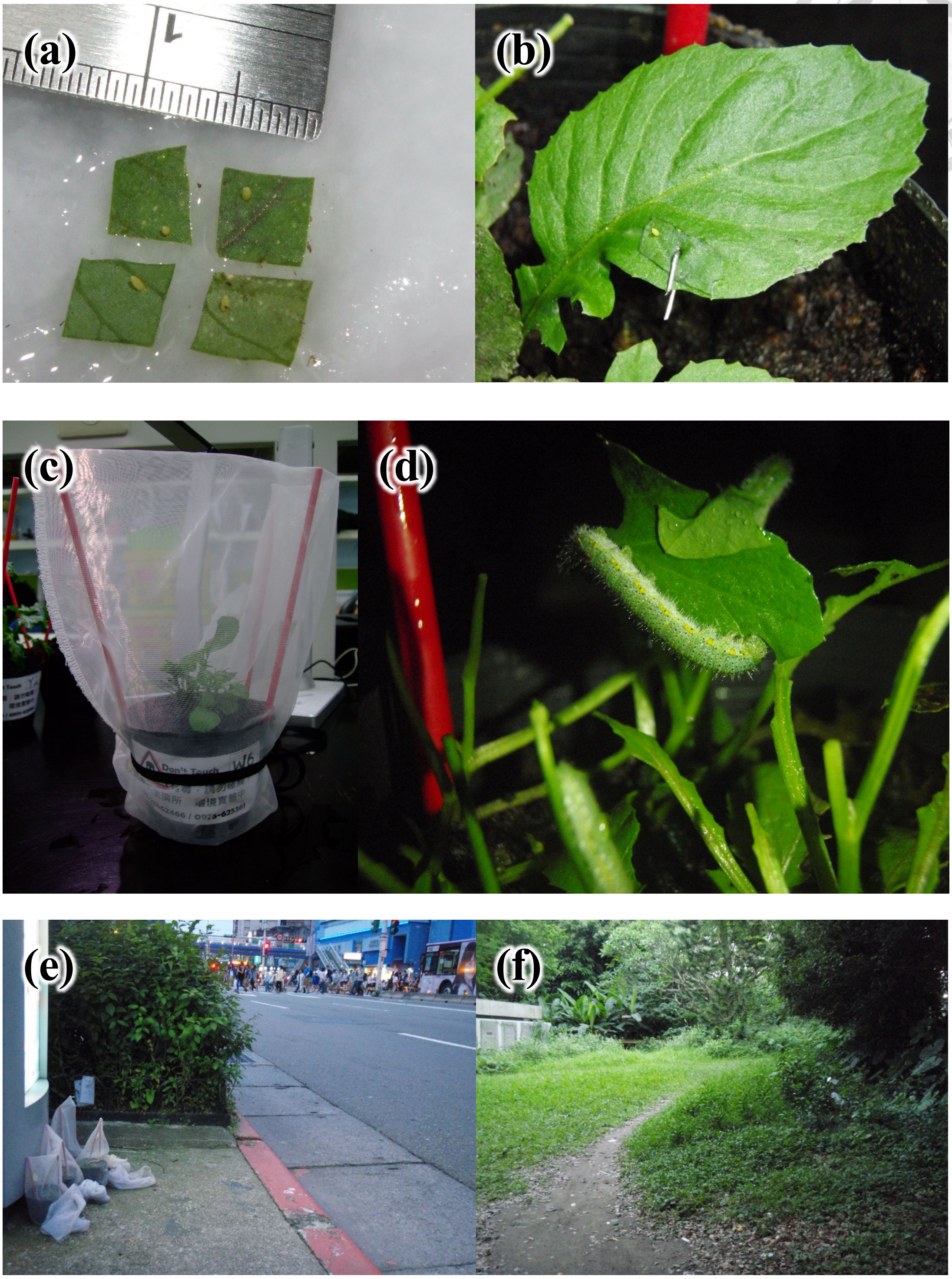

Figure 5 Procedure and sites of Exp. 3

Procedure and sites of Exp. 3 Sidewalk cage experiment: larval performance in sidewalk microenvironment. (a, b) Leaf pieces with eggs were attached to *R. indica* by starch and staples. (c) Pots were covered by mesh nest. (d) *Pieris* larvae on plants (e) Sidewalk sites example (f) Field site.

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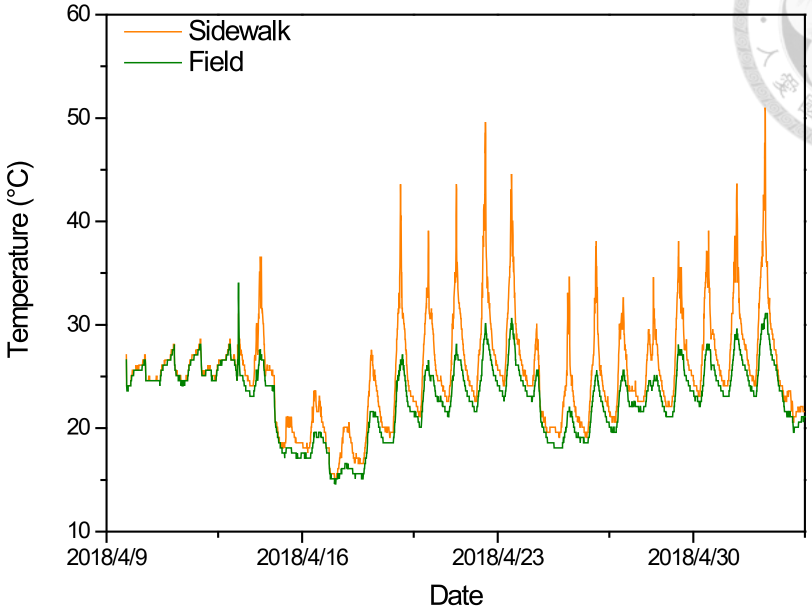
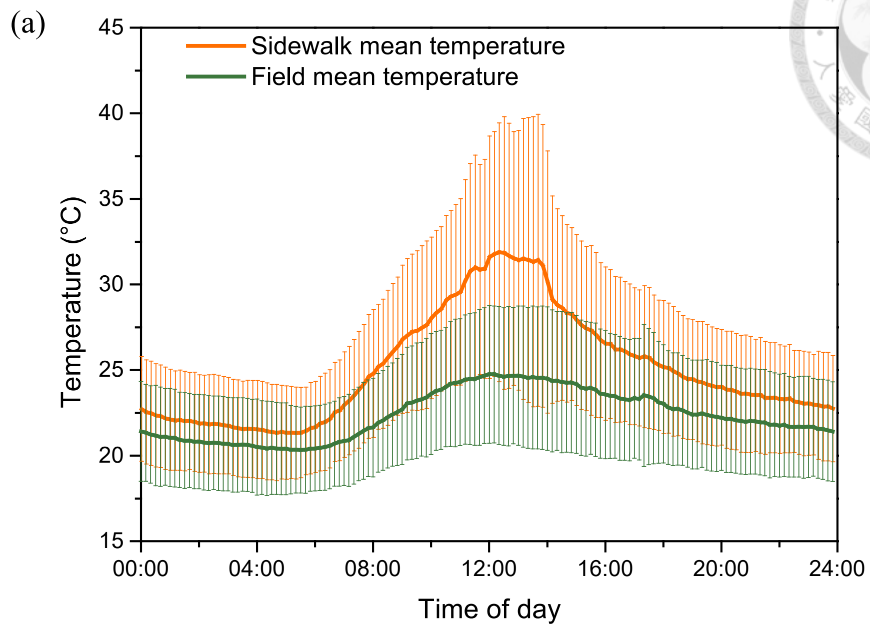


Figure 6 Temperature record in Exp. 3 2018 site

This data were collect by iButton on sidewalk and field sites of Exp. 3 2018 (2018/4/9 - 2018 5/3). The orange and green line represented daily temperature fluctuations in sidewalk and field sites.



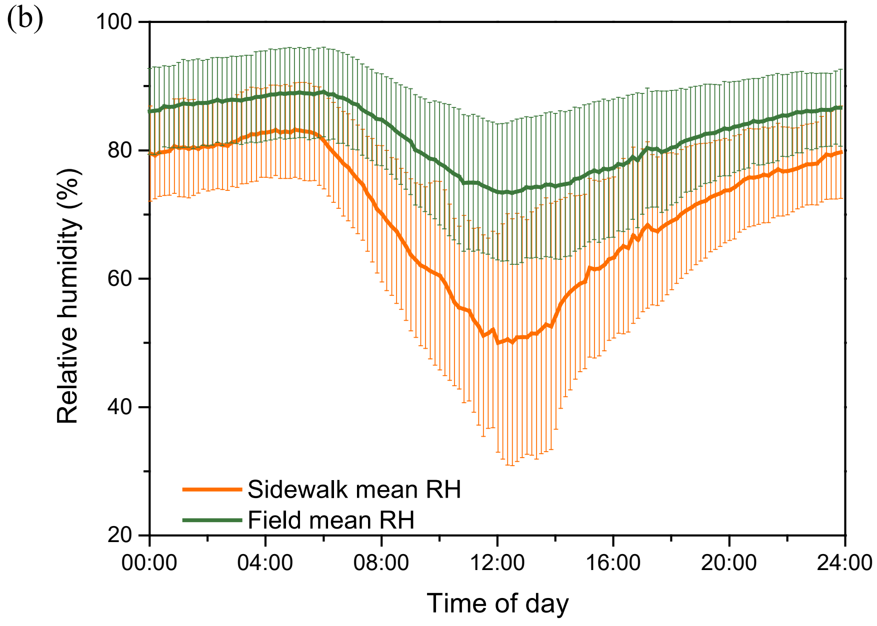


Figure 7 Temperature and relative humidity on Exp. 3 2018 site

The temperature and relative humidity on sidewalk and field sites of Exp. 3 (2018/4/13 - 2018 5/3). Data were averaged by day every 10 minute. (mean ± SD) (a) The daily temperature fluctuations. (b) The daily relative humidity fluctuations.

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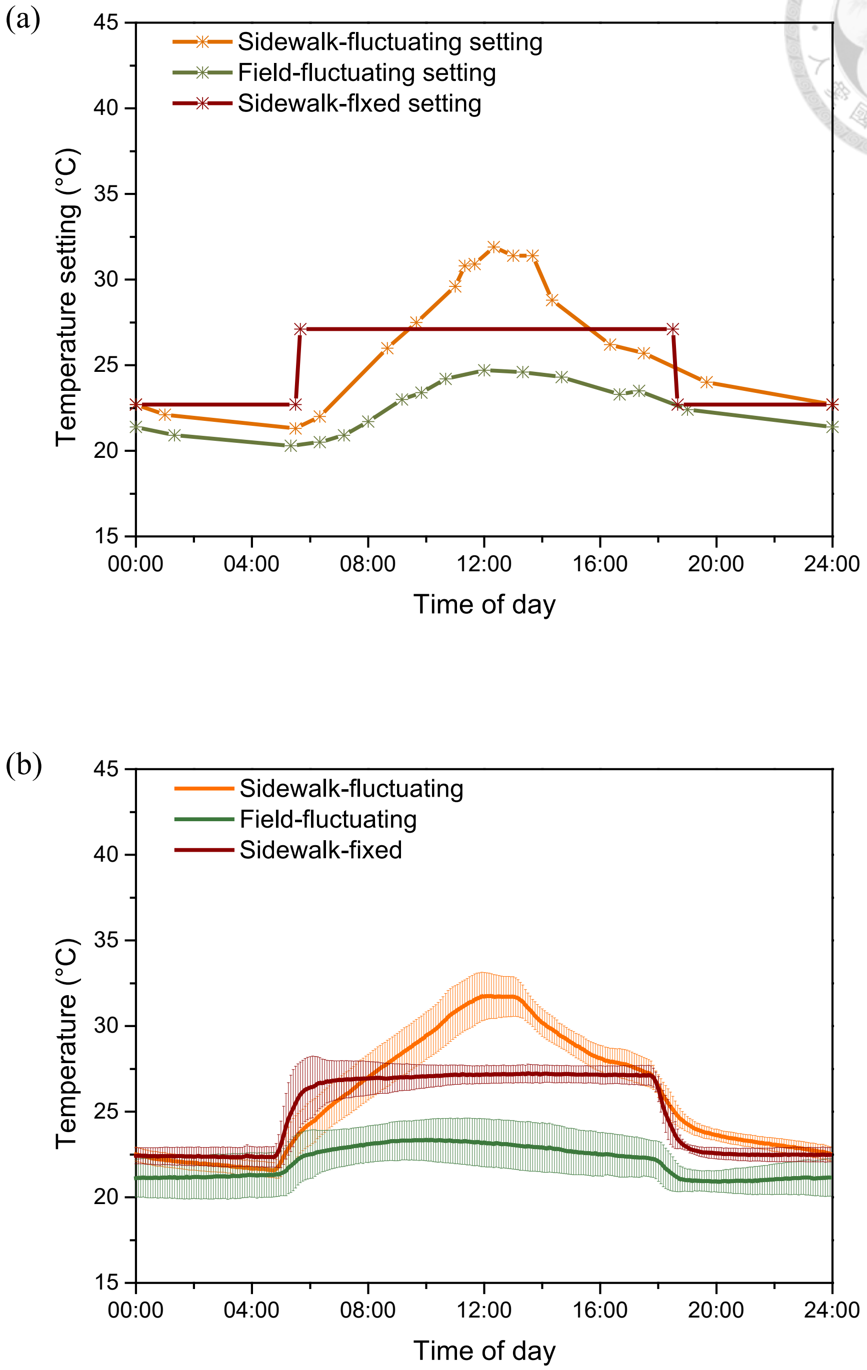

Figure 8 Temperature setting in Exp. 4

(a) The temperature setting for growth chambers in Exp. 4. The stars represent temperature setting of temperature turning points of growth chambers. (b) The real temperature in growth chambers during experiment (mean ± SD).

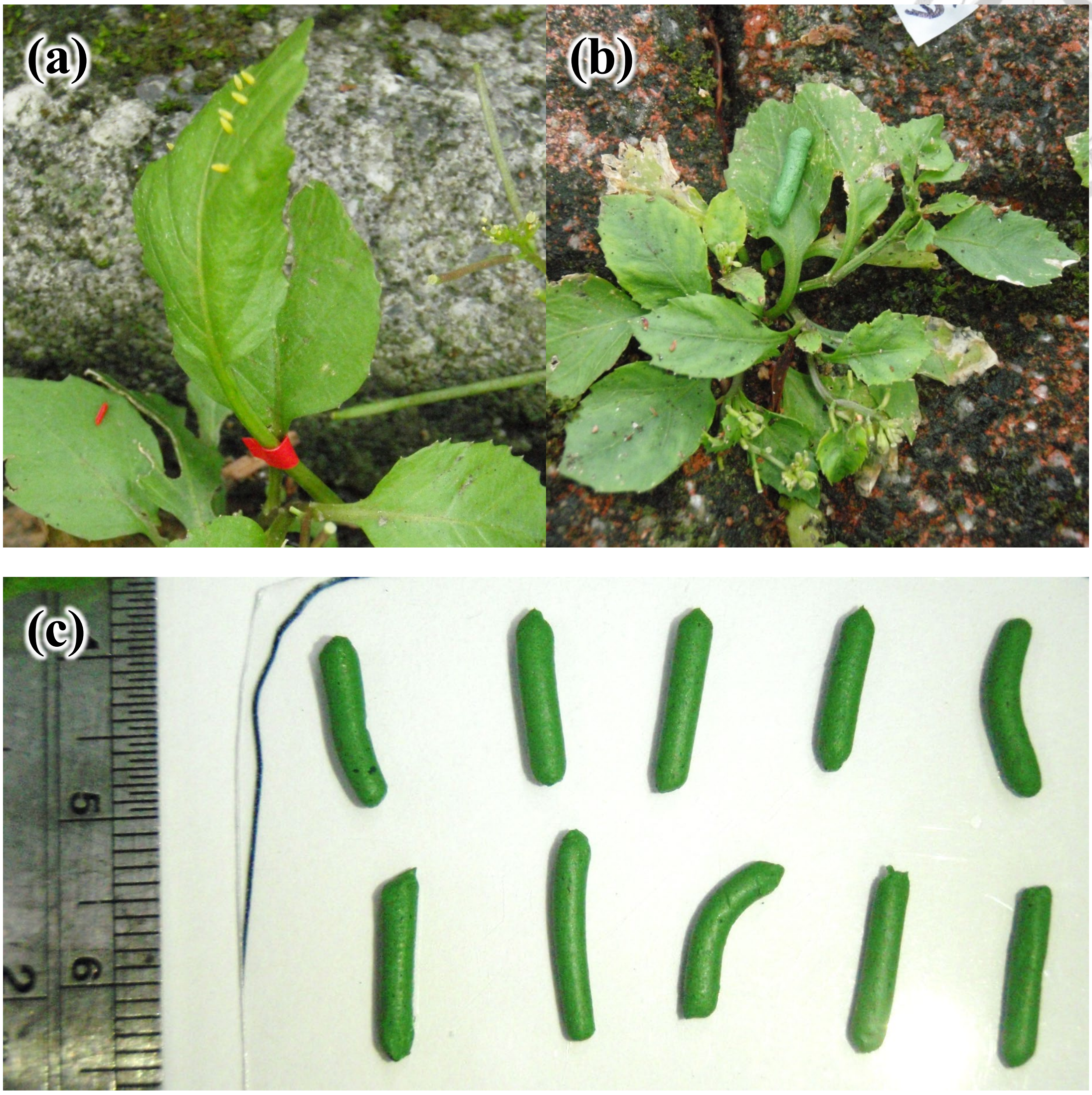

Figure 9 Procedure of Exp. 5

(A) A leaf with *Pieris* eggs was attached to a *R. indica* plant growing on the sidewalk or field sites. (B) Caterpillar decoys were put on plants. (C) Caterpillar decoys before the experiment.

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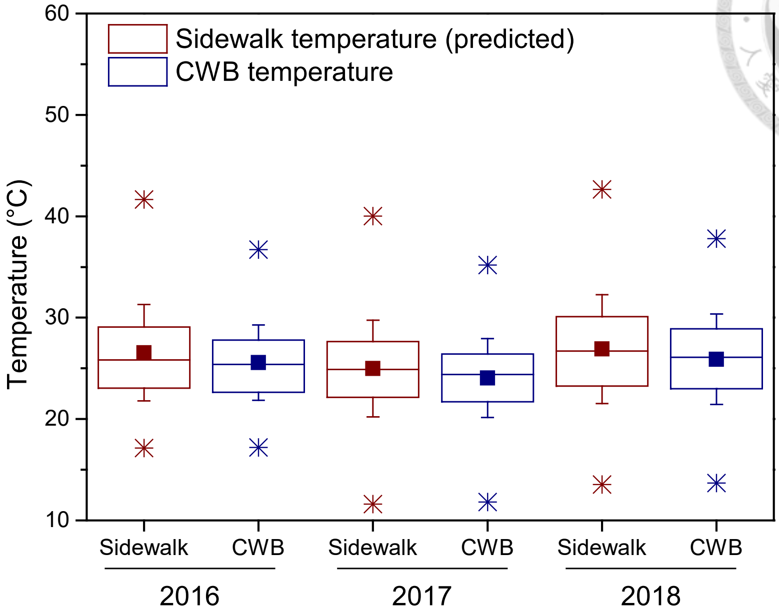
(a)



(b)

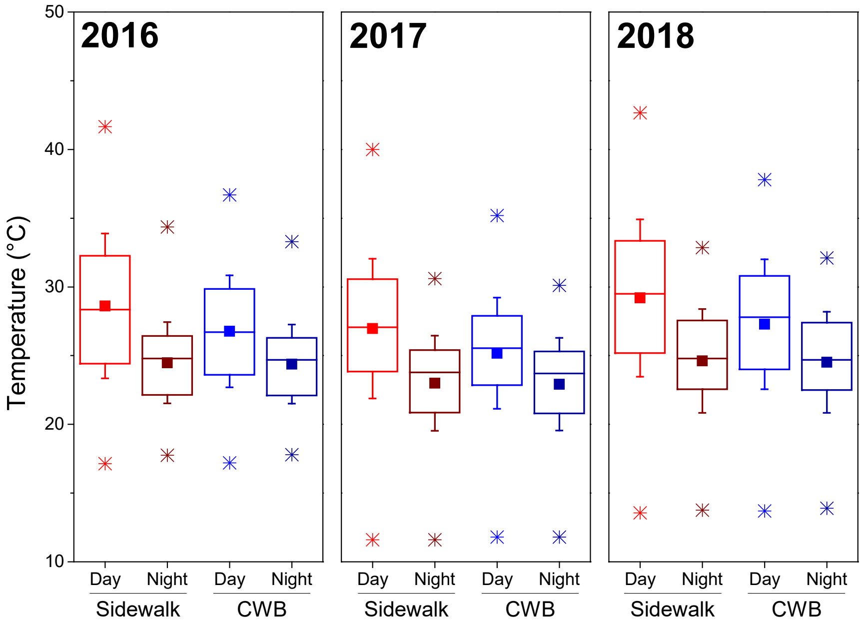


Figure 10 Temperature in *Pieris* breeding season

Sidewalks and meteorological temperature in April and May. The sidewalk temperatures were predicted from the Central Weather Bureau data. The CWB represented the meteorological weather data. (Solid squares represented the average; the boxes represented the 75, 50 and 25 percent values; Whiskers represented SD; Asterisk (*) represented the Maximum and minimum values.) (a) All. (b) Day and night temperature.

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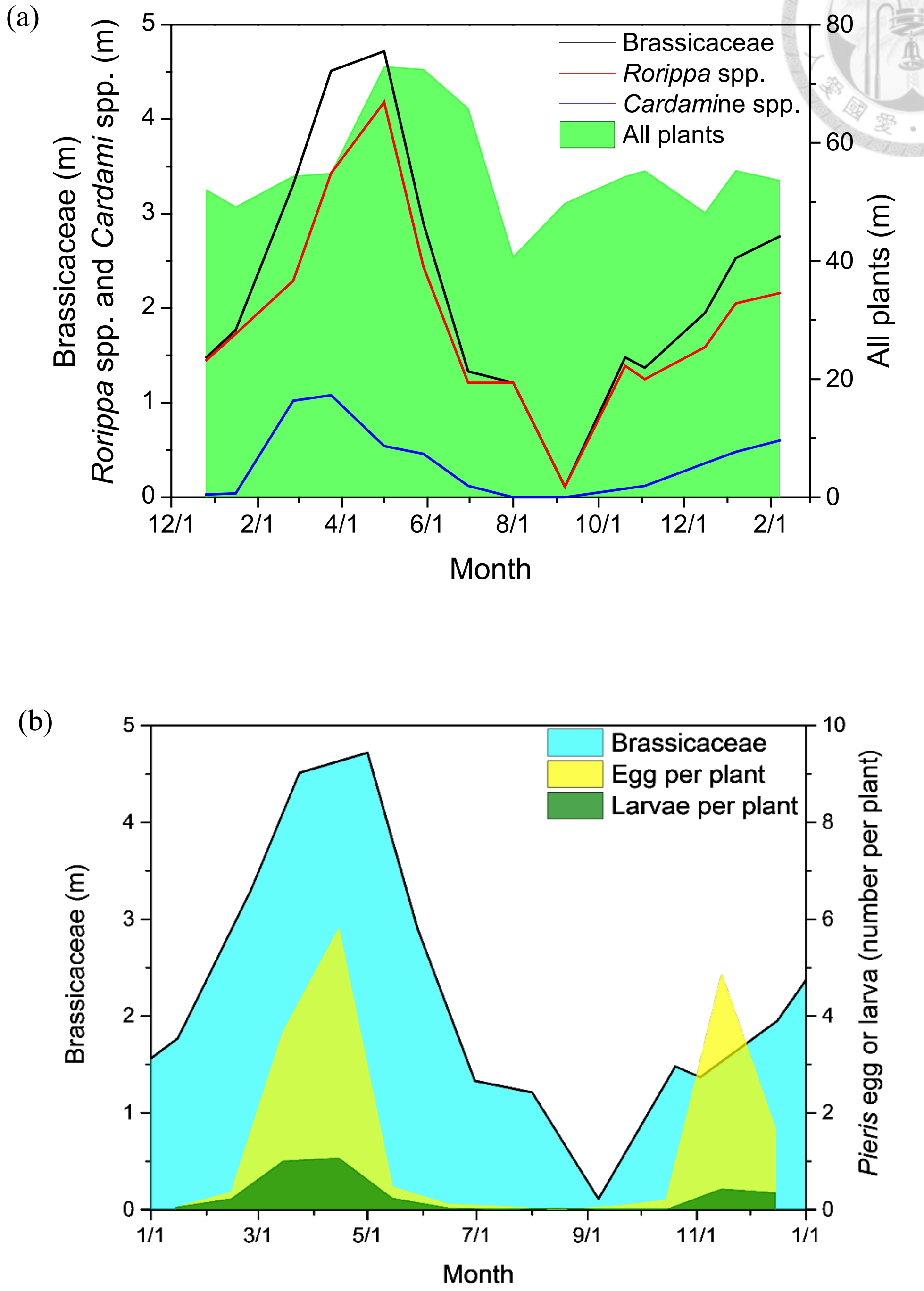

Figure 11 Host plant density

(a) Total abundance of *Pieris* larvae host plant on quadrats in 60 sidewalk sites. Green filling represented abundance of all plant species on sidewalks. (b) Comparing the host plant density to egg and larvae density on sidewalks. Blue filling represented abundance of Brassicaceae plants. Yellow and green filling represented *Pieris* egg and larvae number per plant, respectively, from the survey in a previous study in Taipei City (林正鴻 2015).

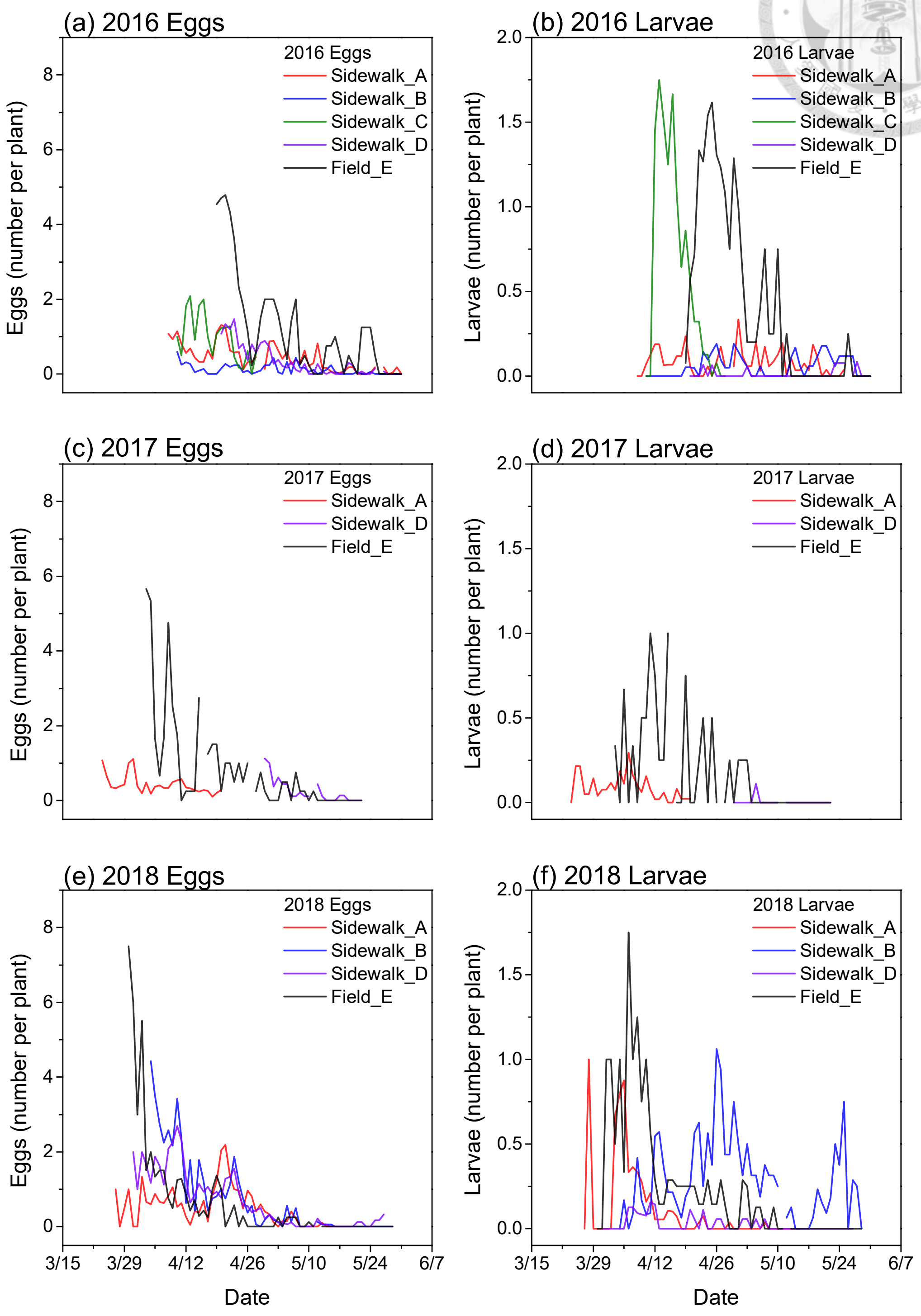

Figure 12 *Pieris* Eggs and larvae density survey: sites

The eggs and larvae density per plant in 2016, 2017 and 2018 *Pieris* breeding season. Results were presented separately according to egg and larvae, years and sites.

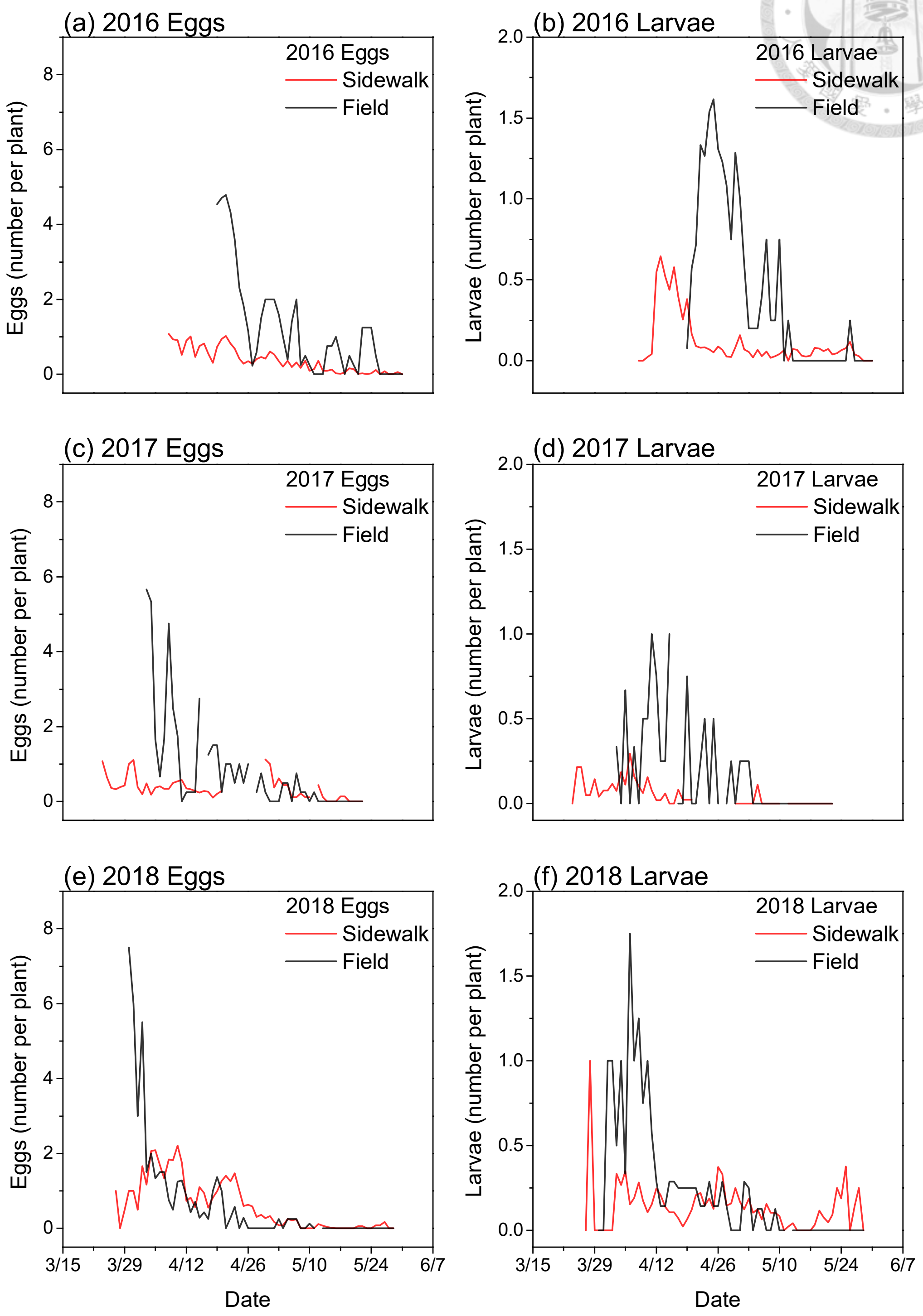

Figure 13 *Pieris* Eggs and larvae density: habitats

The eggs and larvae density per plant in 2016, 2017 and 2018 *Pieris* breeding season. The data in different sidewalk sites were averaged.

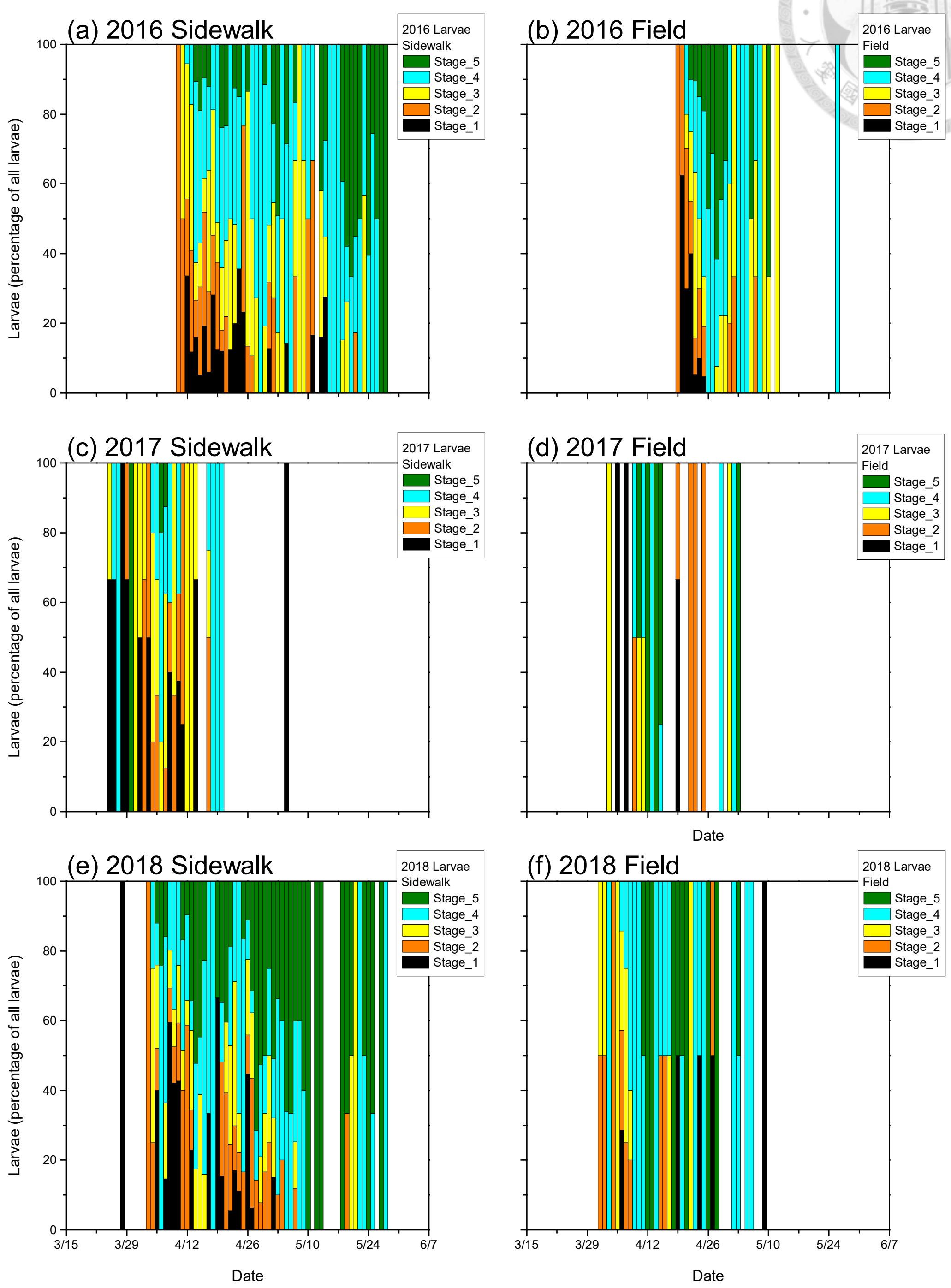

Figure 14 Eggs and larvae survey: larval stage composition

The daily percentage of larvae at each stage. Results were presented separately according to years and habitat types.

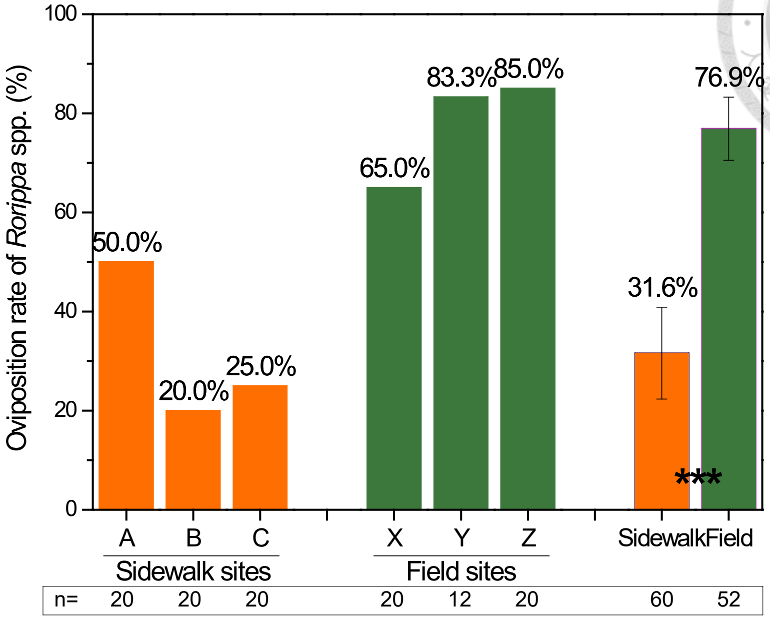

Figure 15 Ovipositing rate of *Pieris* on *R. indica*

The percentage of *R. indica* that was oviposited by *Pieris*. Asterisk (*) represented a significant difference between treatments

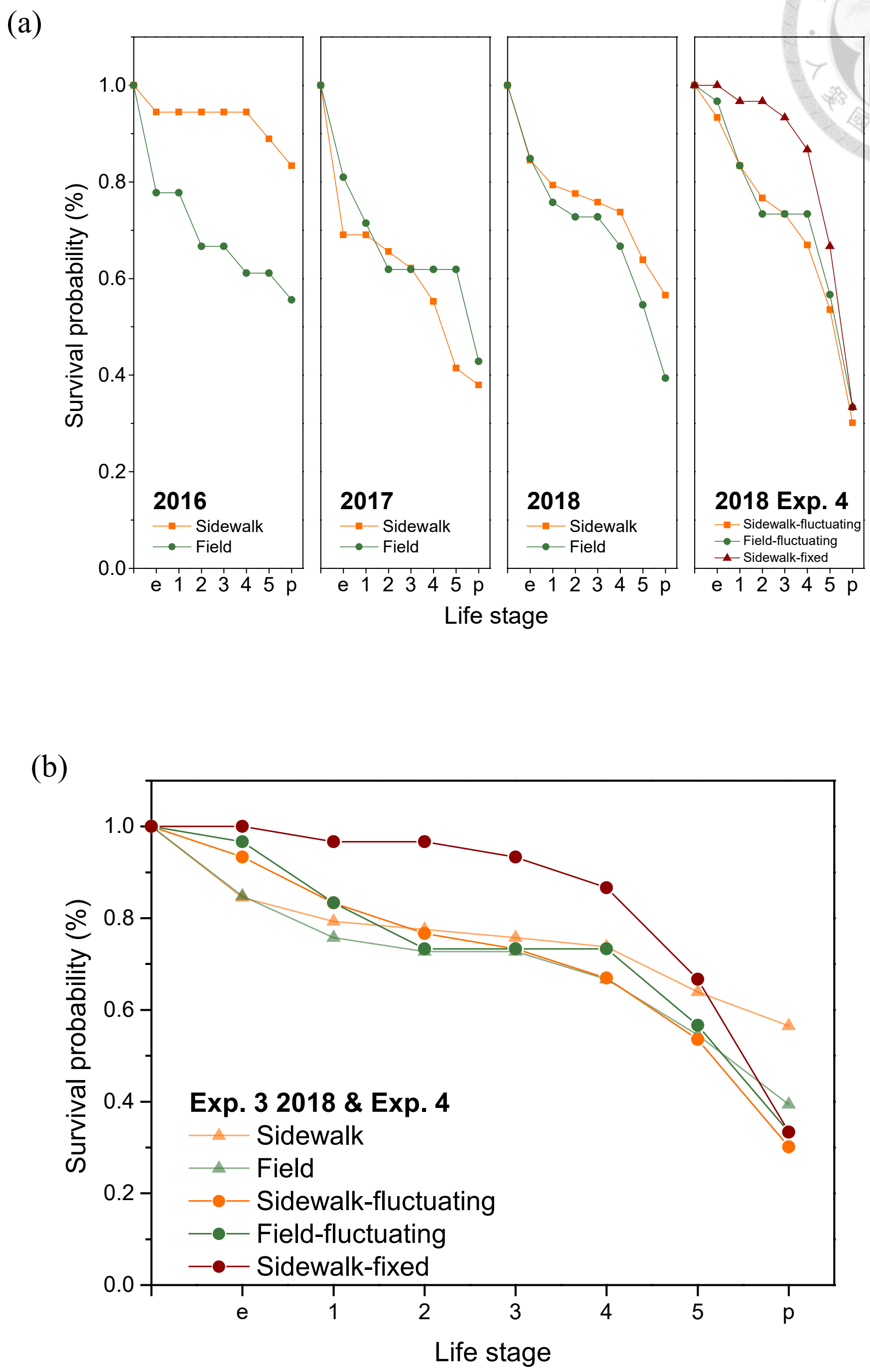

Figure 16 Survival curve of *Pieris* larva in Exp. 3 and Exp.4

The survival curve (Kaplan-Meier curve) of larvae stage from egg to eclosion. (a) Results were presented separately by year and experiments (b) Comparing Exp.3 2018 and Exp. 4 results.

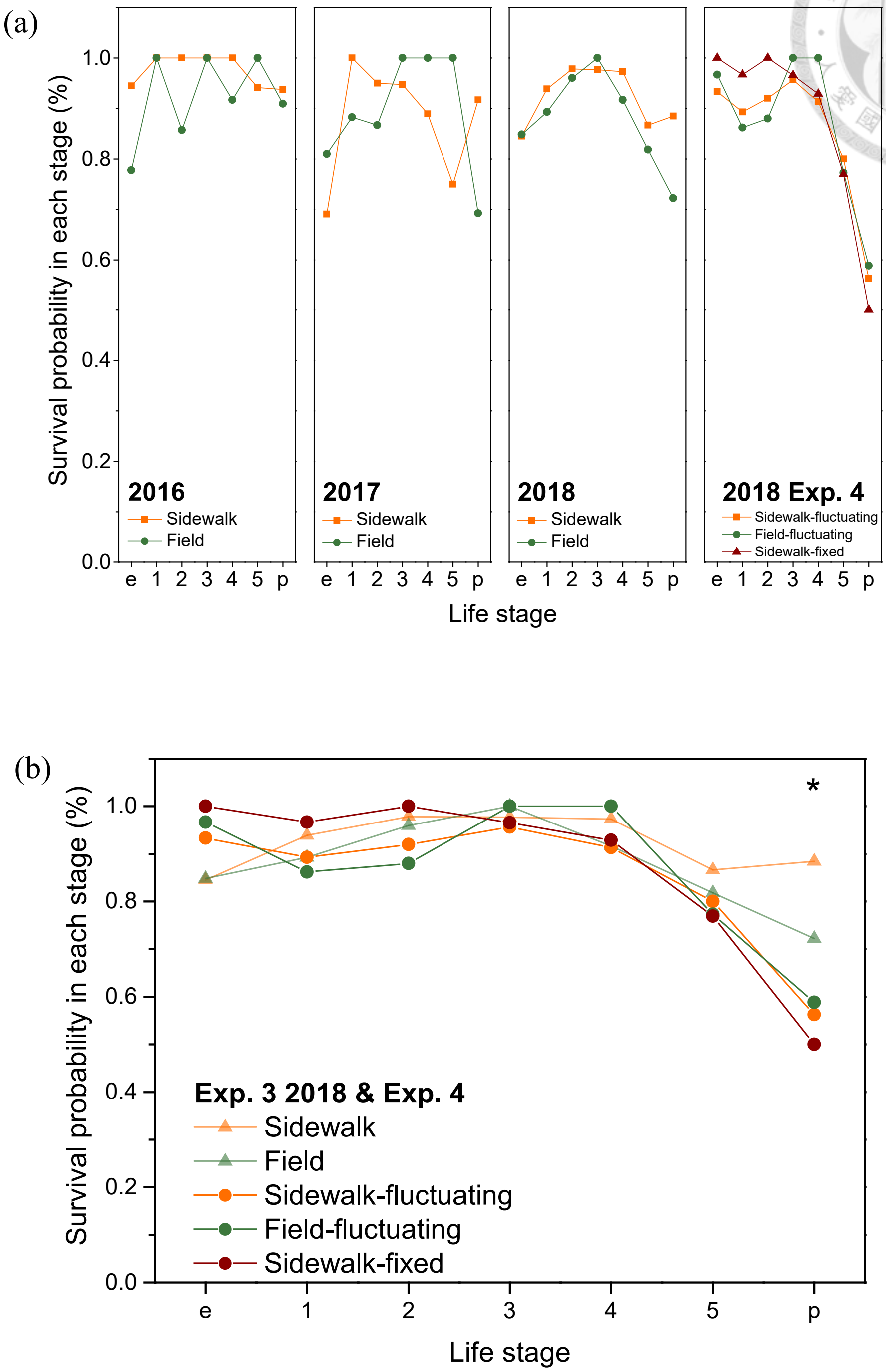

Figure 17 Survival rate in each life stage of *Pieris* larvae in Exp. 3 and Exp.4

The survival rate in each larval development stage. Asterisk (*) represented a significant difference between treatments. (a) Results were presented separately by year and experiments (b) Comparing Exp.3 2018 and Exp. 4 results.

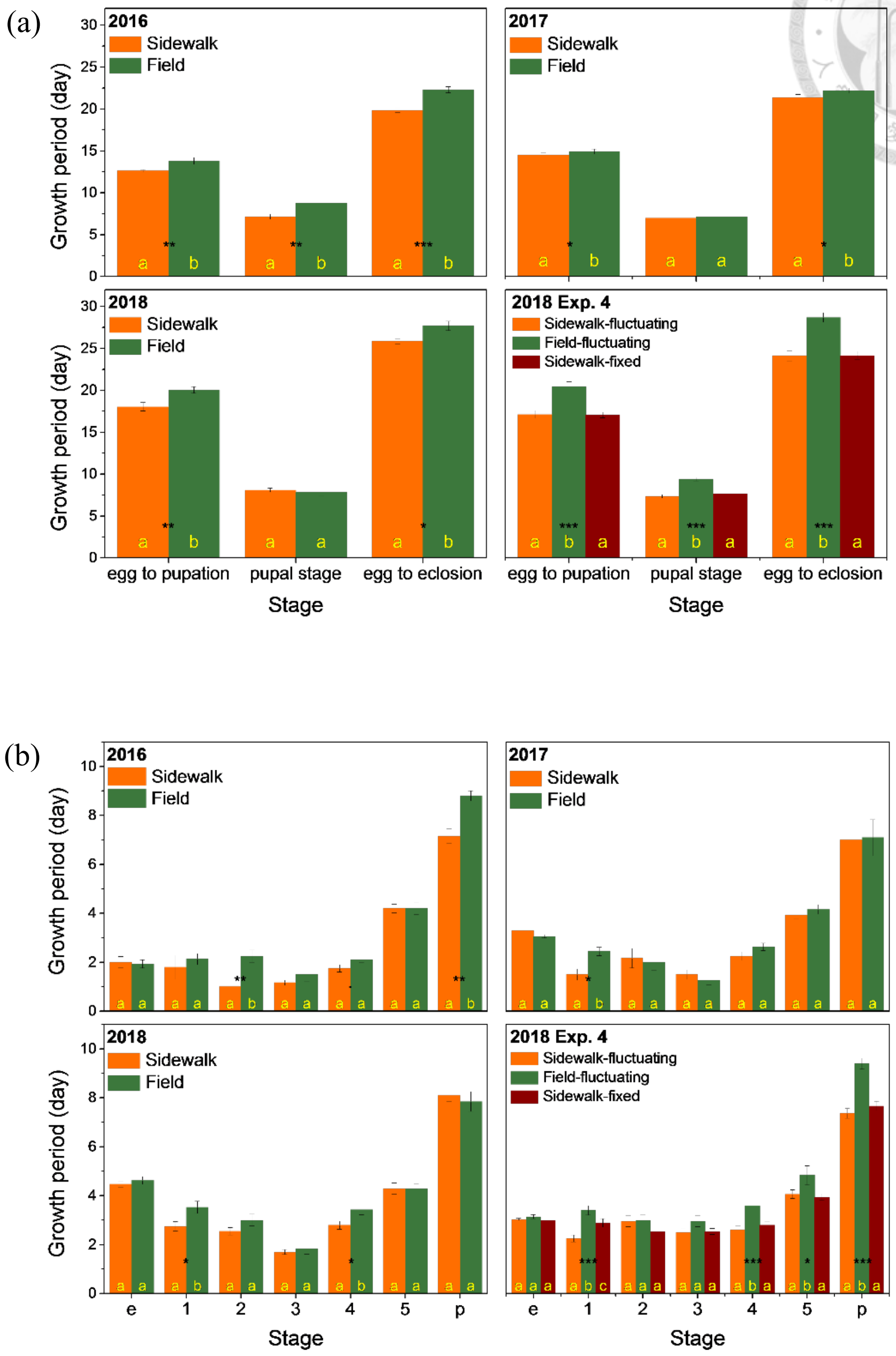

Figure 18 Growth period of *Pieris* larvae in Exp. 3 and Exp. 4

Growth period of *Pieris* larvae in Exp. 3 and Exp. 4 (mean ± SE). Asterisk (*) represented a significant difference between treatments. The same alphabets mean no significant difference in the same stage. (a) The growth period from egg to eclosion. (b) The growth period at each larval stage.

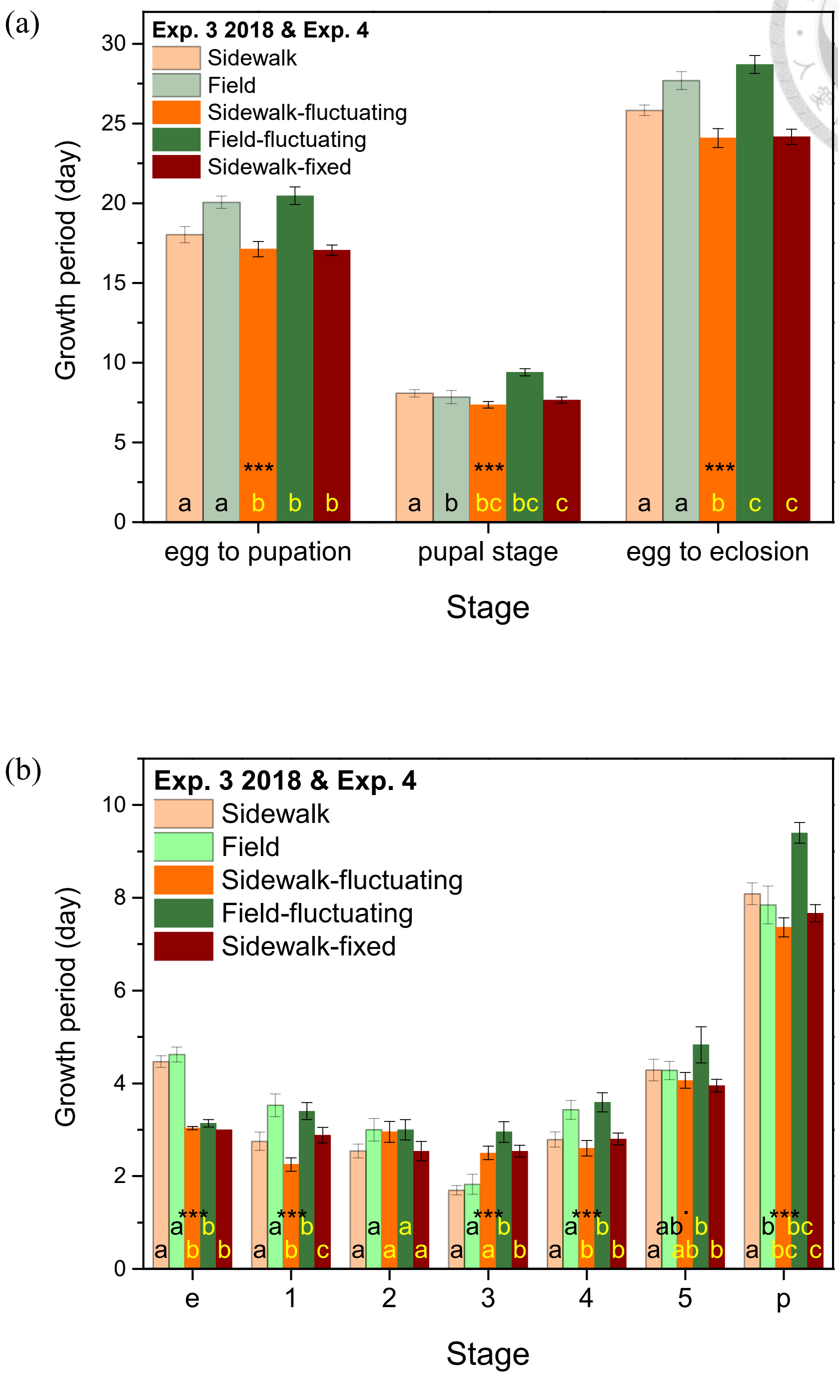

Figure 19 Growth period of *Pieris* larvae in Exp. 3 2018 and Exp. 4

Growth period of *Pieris* larvae in Exp. 3 2018 and Exp. 4 (mean ± SE). Asterisk (*) represented a significant difference between treatments. The same alphabets mean no significant difference between treatments. (a) The growth period from egg to eclosion. (b) The growth period at each larval stage.

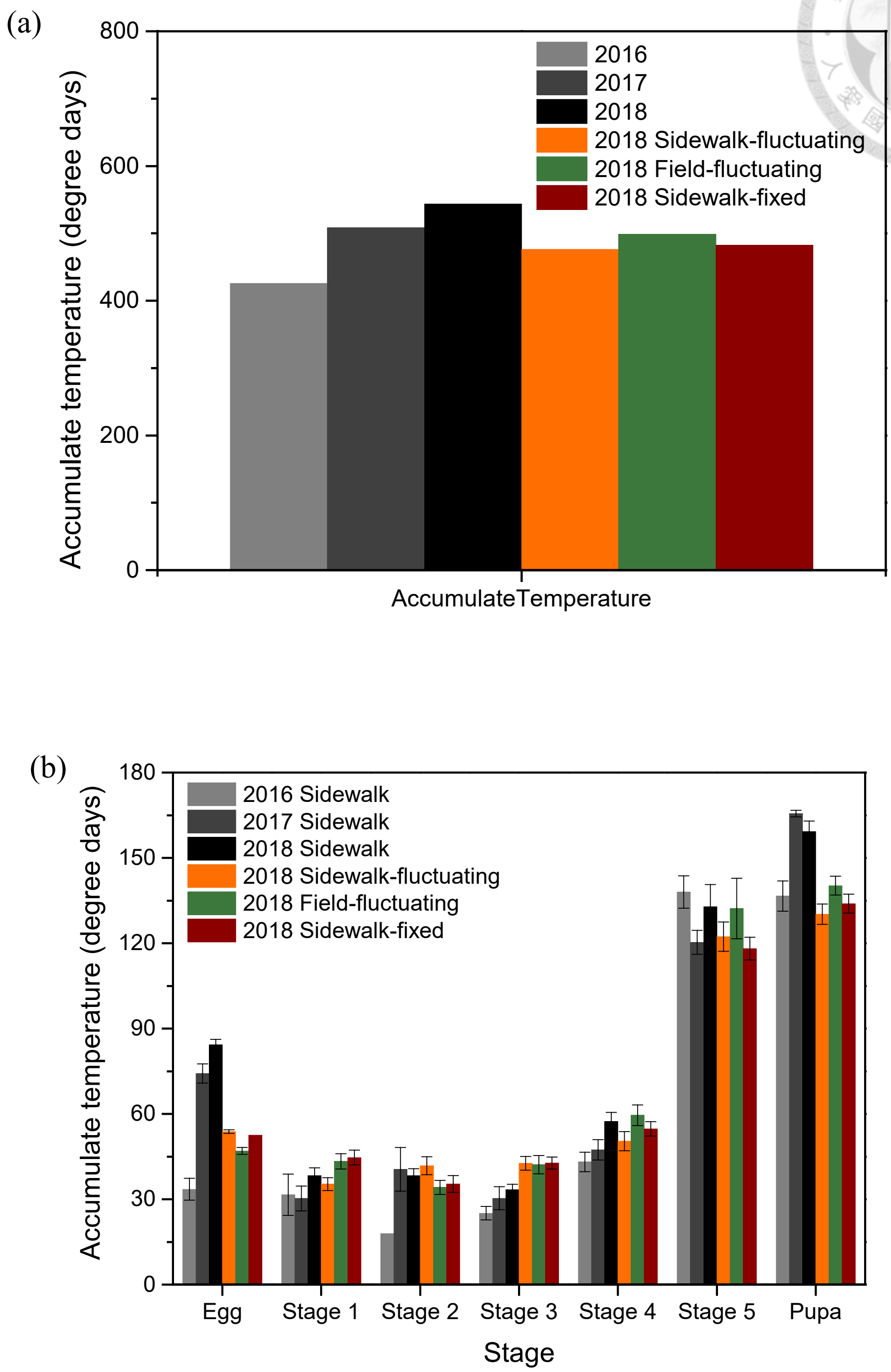

Figure 20 Effective cumulative temperature of *Pieris* larvae

Effective cumulative temperature of *Pieris* larvae in Exp. 3 sidewalk habitat and Exp. 4. (a) The effective cumulative temperatures of *Pieris* from egg to eclosion. (b) The effective cumulative temperatures of *Pieris* at each life stage (mean ± SE).

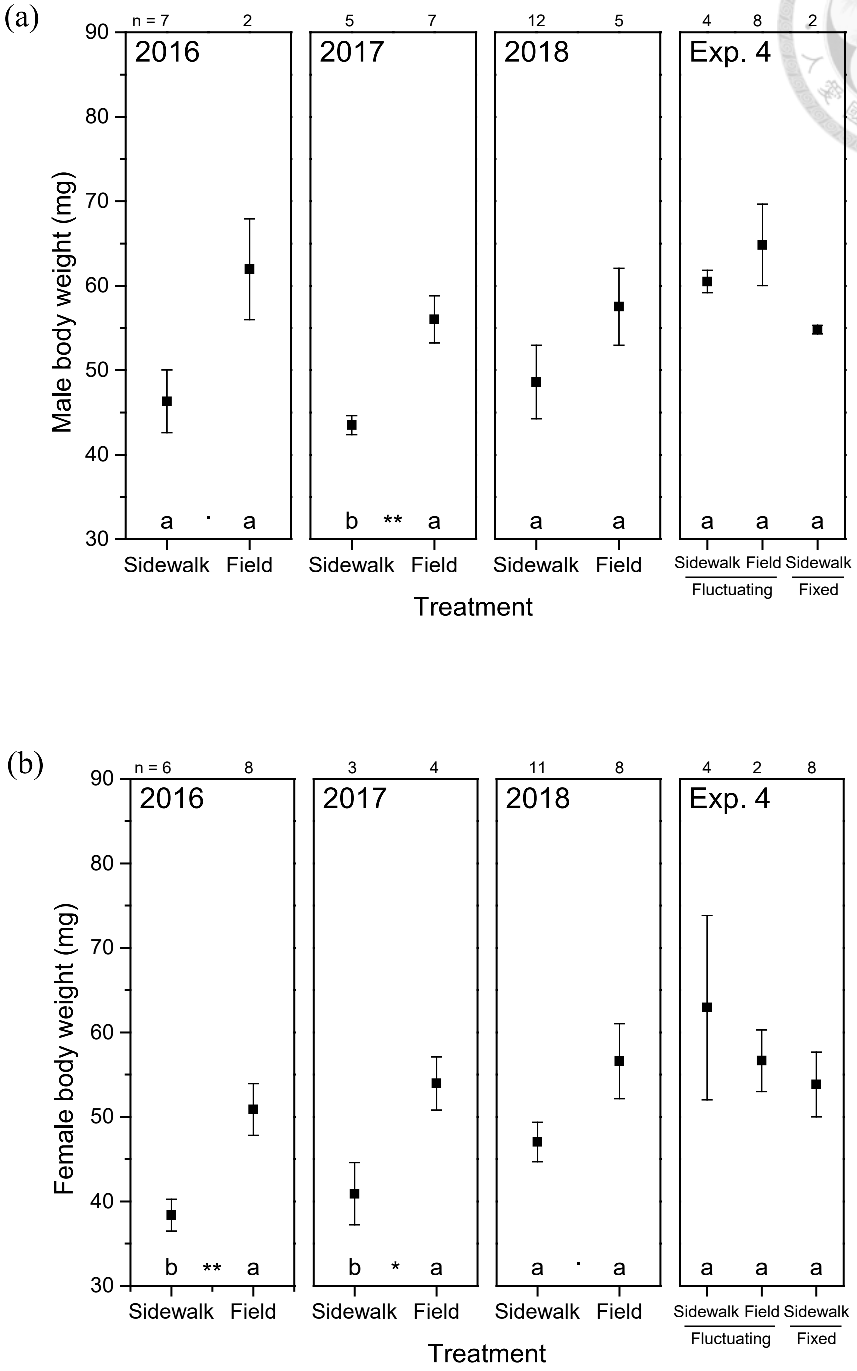

Figure 21 Body weight of adult butterflies in Exp. 3 and Exp. 4

Body weight of adult butterflies in Exp. 3 and Exp. 4 (mean ± SE). Asterisk (*) represented a significant difference between treatments. Dot (.) represented a marginal significant difference between treatments. (A) Male. (B) Female

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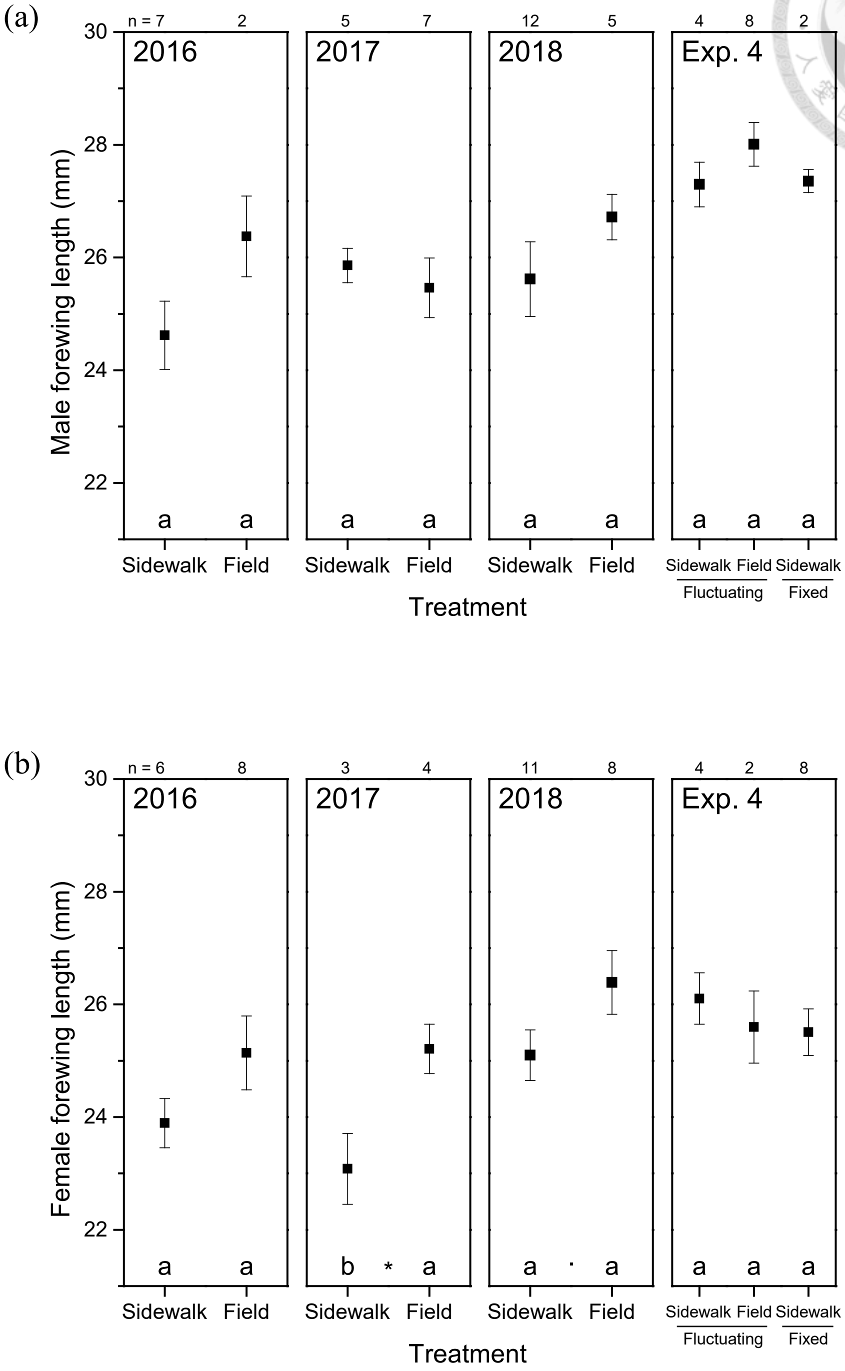

Figure 22 Forewing length of adult butterflies in Exp. 3 and Exp. 4

Forewing length of adult butterflies in Exp. 3 and Exp. 4. Kruskal-Wallis test was used to test the difference between habitats (mean ± SE). Asterisk (*) represented a significant difference between treatments. Dot (.) represented a marginal significant difference between treatments.) (A) Male. (B) Female

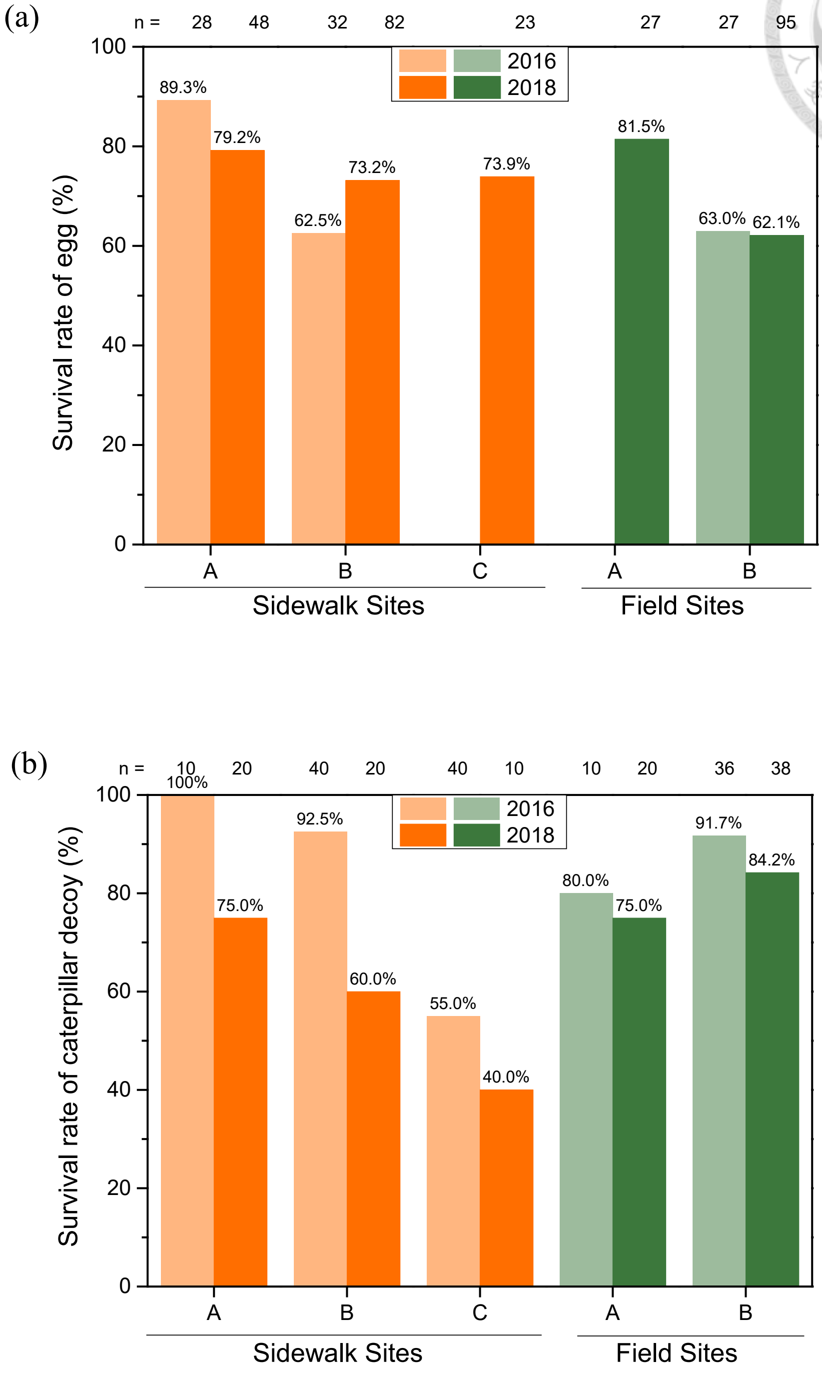

Figure 23 Survivorship of eggs and caterpillar decoys in Exp. 5

The percentage of *Pieris* eggs or larvae that remained intact after 24 hours. (a) Eggs. (b) Caterpillar decoys.

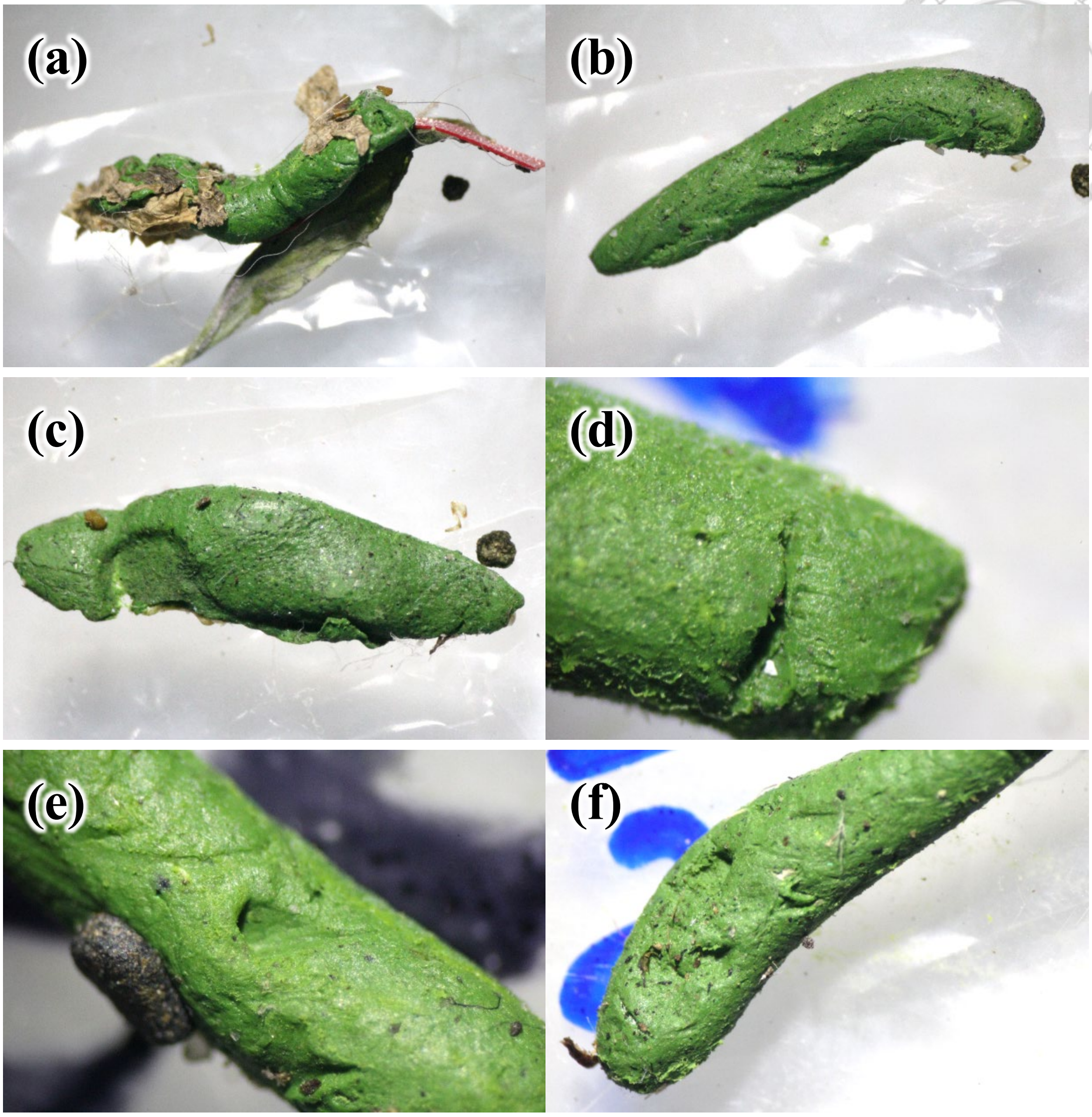

Figure 24 Caterpillar decoys after biotic interference

The damage of caterpillar decoys that were retrieved after 24 hours on sidewalks. Damages were likely cause by (a, b) sweeping ,(c) human tramping, (d) ant biting (furry surface) and (e, f) other animals.

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Appendix

Appendix A: Larval stage identification

Data exploration

The individuals whose body length and head width were measured from each treatment group were treated as the ***base set*** (Table 6 Stage identified individual). The other half of individuals that were measured in body length only were treated as the ***test set***.

We then determined whether the daily body length, the first-day body length, or the last-day body length better reflected each larval stage. The relationship between the stage and daily body length in the base set was shown in Figure A1. The first-day body length (Figure A2) indicated the first measurement of an individual during a specific stage. The last-day body length (Figure A3) indicated the last measurement of an individual during a specific stage. The last-day data only included the cases where *P. canidia* successfully molted into the next stage.

We assumed that the body length of caterpillars from stage 1 to stage 4 instar continuously increased during each stage. Since our results showed that the last-day body length separated different stages better than the daily body length and the first-day body length (Figure A1 vs. Figure A2 vs. Figure A3), we used the last-day body length for larval stage identification.

Except for the first stage, there was no significant difference in the last-day length amoung the three treatment groups (Table A1). Therefore, we pooled the data from the three treatment groups for stage 2-5 in the following analysis.

Criterion selection

According to Chebyshev's theorem, at least 75% values locate within the range of two standard deviations of the mean, and at least 88.89% within the range of three standard deviations for any probability distribution distributions (Kvanli et al. 2005, Chernick 2011). Therefore, we examined the potential to use the value of mean + 2 × SD (as Rule A) and mean + 3 × SD (as Rule B) of the last-day body length as the upper limit for each stage (Figure A4).

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For base set, Rule A and B produced an accurate estimation by 85.52% and 76.8%, respectively. Most of the mismatches between the estimation and real larval life stage (defined by head width change) occurred for larvae smaller than 10 micrometer (underestimate, Figure A5 and Figure A6). Since the Rule A performed better, it was chosen as our conversion criterion.

Validation

To validate this conversion criterion and test the generality, we compared the data distribution in ground truth stage record of the base set and the predicted stage value of the base set and test set. There should be similar data distribution since the growth environment was the same.

The results showed no difference in predicted stage between the base set and the test set, suggesting the generalization of our approach to predict the larval stage based on larval body length (Table A2). However, some differences existed between the ground truth stage record of the base set and the predicted stage value of the base set and test set, possibly due to the estimation errors mentioned above (see “Criterion selection”).

The conversion criterion was shown in Table 4. Note that any individual with the body length that was equal to or shorter than the upper limit value of a specific stage would be assigned into that stage or an earlier stage. Any individual with body length longer than the upper limit value of stage 5 would be assigned into stage 5.

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Appendix B: Sidewalk temperature prediction

Data collection

The ground truth sidewalk temperature data were collected from our environmental monitoring using iButton data loggers on typical Taipei sidewalks. Loggers were set on five sidewalk sites (Figure 3 and Figure A7c-g) and 10 - 15 centimeters above ground (Figure A7b). Temperature and relative humidity were recorded every 10 minutes in 2016 to 2018 (Figure A7a). Temperature records from five sites showed different fluctuation but similar pattern. Therefore, data from all sites were averaged for analysis (Figure A8).

The Meteorological data (CWB data) in 2016/1/1 - 2018/12/31 were collected by automatic weather stations of Taipei station in Taipei and saved in the Central Weather Bureau Observation Dara Inquire System.

Procedure

Temperature records from sidewalks were interpolated and averaged to generate the hourly data, which were compared to the CWB weather station data. The relationship between sidewalk and weather station temperature was shown in Figure A8b and Figure

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A9.

We first examined the correlation between the sidewalk temperature and the weather station data, including CWB temperature, the hour of the day (hour), relative humidity (RH), precipitation (Precp), precipitation duration (PrecpHour), sunshine duration (SunShine) and global radiation (GlobRad) (Table A3a). According to regression model selection and model comparing (Figure A10 and Table A3b), we selected CWB temperature and global radiation to build a linear multiple regression model to predict sidewalk temperature.

Formula

The formula of linear multiple regression was:

$$\begin{aligned}&\mathbf{Predicted\ sidewalk\ temperature}\\&\quad= -\mathbf{0.454036} + \mathbf{1.022215} \times \mathbf{CWB\ temperature} + \mathbf{1.492239} \times \mathbf{Global\ radiation}\end{aligned}$$

As shown in Table A3b, these two independent variable explained 96.39% of the variance

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in sidewalk temperature (multiple R-squared = 0.9639). The average error of prediction was 1.329˚C (residual standard error = 1.329). Graphic model test was shown in Figure A11. The predictive effectiveness was shown in Figure A12.

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References of appendix

Kvanli, A., R. Pavur, and K. Keeling. 2005. Concise managerial statistics. Cengage Learning.

Chernick, M. R. 2011. The essentials of biostatistics for physicians, nurses, and clinicians. John Wiley & Sons.

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Figures and tables of appendix

Table A1 Statistics of the last-day larval body length at each stage from the base set
The larval stage and last-day body length of the three temperature treatment groups from the base set were analyzed with ANOVA. The length data was converted by box-cox method to conform to homogeneity and normal distribution. The P values were given, bold value represented a significant difference (*P* < 0.05).
(a) The ANOVA results of body length across different stages. (b) The ANOVA results of body length across different stages with pot as a fix effect. (c) *Post hoc* results (with Scheffe Test).

(a) The ANOVA results of body length across different stages

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Overall
F	5.723	0.3387	0.1944	1.8269	0.5297	0.2517
Df	2	2	2	2	2	2
Pr	**0.008037**	0.715144	0.824352	0.178358	0.596461	0.785569

(b) The ANOVA results of body length across different stages with pot as a fix effect

	Factors								
	Treatment			Plot			Treatment*Plot		
	F	*Df*	*Pr*	*F*	*Df*	*Pr*	*F*	*Df*	*Pr*
Stage 1	5.7293	2	**0.008679**	0.1009	1	0.753230	1.4657	2	0.249384
Stage 2	0.3321	2	0.720018	0.0678	1	0.796344	1.1446	2	0.331851
Stage 3	0.1865	2	0.830897	0.9675	1	0.333731	0.3874	2	0.682385
Stage 4	2.6040	2	0.092452	1.5681	1	0.221229	7.0957	2	**0.003338**
Stage 5	0.5756	2	0.572373	0.0096	1	0.922971	2.4062	2	0.118554
Overall	0.2386	2	0.788046	0.0242	1	0.876595	0.4714	2	0.625022

(c) *Post hoc* results (with Scheffe Test)

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Overall
Sidewalk fluctuation	a	a	a	a	a	a
Field fluctuation	b	a	a	a	a	a
Sidewalk fixed	ab	a	a	a	a	a

Table A2 Verification of criterion

The difference of stage distribution among the ground truth value of the base set, the predicted value of the base set and the predicted value of the test set were analyzed with Kruskal-Wallis test. The P values were given, bold value represented a significant difference ($P < 0.05$) and the underline value represented a marginal significant difference ($P < 0.1$).

(a) The ground truth value of the base set, the predicted value of the base set and the predicted value of the test set

	Kruskal-Wallis chi-squared	*df*	*p*-value
stage 1	2.0186	2	0.3645
stage 2	13.0678	2	**0.0015**
stage 3	16.4943	2	**0.0003**
stage 4	8.1378	2	**0.0171**
stage 5	5.2881	2	0.0711
stage all	4.0619	2	0.1312

(b) The ground truth value of the base set and the predicted value of the base set

	Kruskal-Wallis chi-squared	*df*	*p*-value
stage 1	1.5881	1	0.2076
stage 2	9.0647	1	**0.0026**
stage 3	11.2564	1	**0.0008**
stage 4	5.1932	1	**0.0227**
stage 5	1.7580	1	0.1849
stage all	1.5141	1	0.2185

(c) The predicted value of the base set and the predicted value of the test set

	Kruskal-Wallis chi-squared	*df*	*p*-value
stage 1	0.0023	1	0.9615
stage 2	0.2170	1	0.6413
stage 3	0.1607	1	0.6885
stage 4	0.1300	1	0.7185
stage 5	1.0844	1	0.2977
stage all	0.6656	1	0.4146

(d) The ground truth value of the base set and the predicted value of the test set

	Kruskal-Wallis chi-squared	*df*	*p*-value
stage 1	1.5436	1	0.2141
stage 2	10.6838	1	**0.0011**
stage 3	12.6072	1	**0.0004**
stage 4	6.9533	1	**0.0084**
stage 5	5.0477	1	**0.0247**
stage all	3.9346	1	**0.0473**

Table A3 Model selection for weather data

(a) Correlation matrix. GloblRad and SunShine had a high correlation, and therefore only GloblRad was selected in our model. (b) Factor selection by model comparing. *Df* = 15156.

All independent variables have significant coefficients and goodness of fit (*Pr* < 0.001) in ANOVA model comparison (not shown).

(a) Correlation matrix

	AvgSidewalkTemp.	CWBTemp.	Hour	RH	Precp	PrecpHour	Sunshine	GloblRad
AvgSidewalkTemp.	1.0000	0.9690	0.0570	-0.4700	-0.0390	-0.2901	0.5300	0.5800
CWBTemp.	**0.9690**	1.0000	0.0696	-0.4700	-0.0410	-0.3006	0.4500	0.4690
Hour	0.0570	0.0700	1.0000	-0.1200	0.0250	0.0082	-0.1100	-0.0270
RH	**-0.4710**	-0.4670	-0.1152	1.0000	0.2100	0.5019	-0.5800	-0.5580
Precp	-0.0390	-0.0410	0.0245	0.2100	1.0000	0.4089	-0.1100	-0.0790
PrecpHour	-0.2900	-0.3010	0.0082	0.5000	0.4090	1.0000	-0.3100	-0.2030
SunShine	**0.5330**	0.4460	-0.1071	-0.5800	-0.1090	-0.3132	1.0000	**0.7990**
GloblRad	**0.5800**	0.4690	-0.0270	-0.5600	-0.0790	-0.2030	0.8000	1.0000

(b) Factor selection by model comparing

	Temp. GloblRad RH	**Temp. GloblRad**	Temp. RH	Temp.
Residual standard error	1.329	**1.329**	1.65	1.726
Multiple R-squared	0.9639	**0.9639**	0.9443	0.9391
Adjusted R-squared	0.9639	**0.9638**	0.9443	0.9391

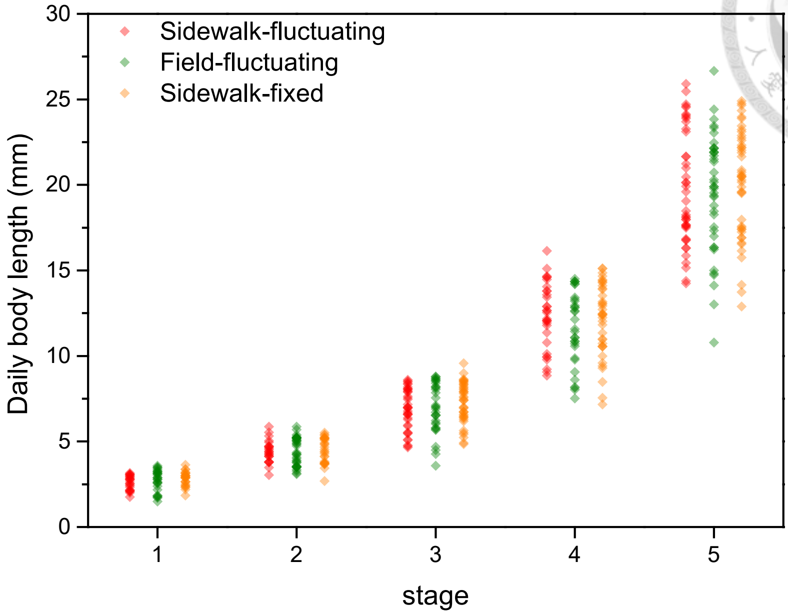

Figure A1The larval stage and daily body length data in Exp. 4 base set

Daily measurements of *P. canidia* larval body length.

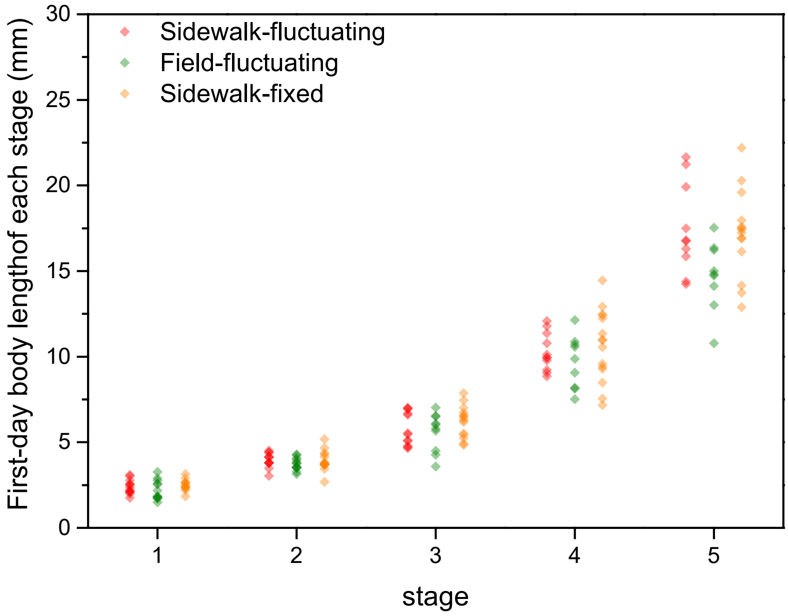

Figure A2 The larval stage and first-day body length data in Exp. 4 base set

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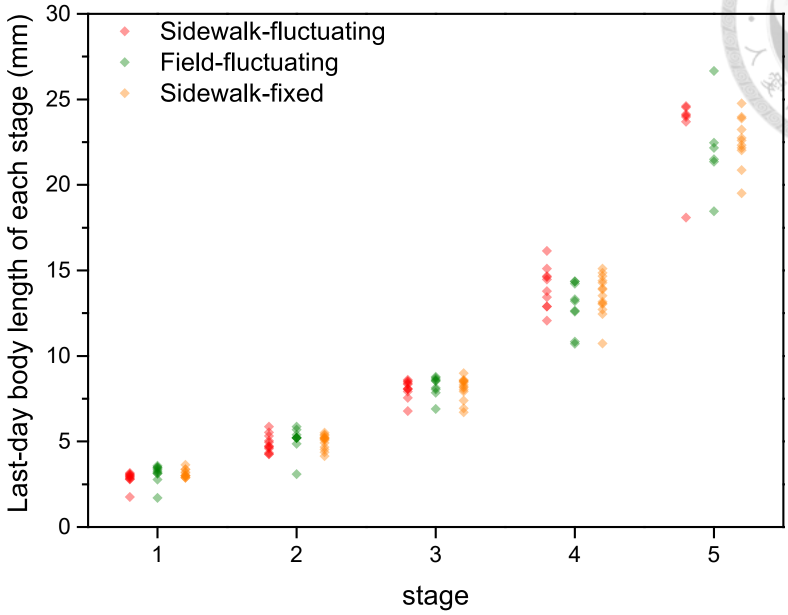


Figure A3 The larval stage and last-day body length data in Exp. 4 base set

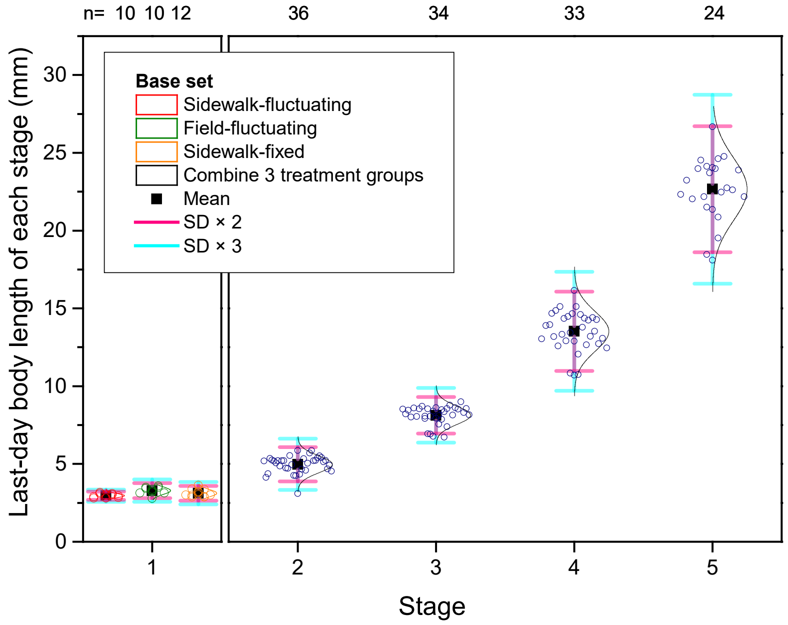


Figure A4 Standard deviations with last-day body length of each larval stage.

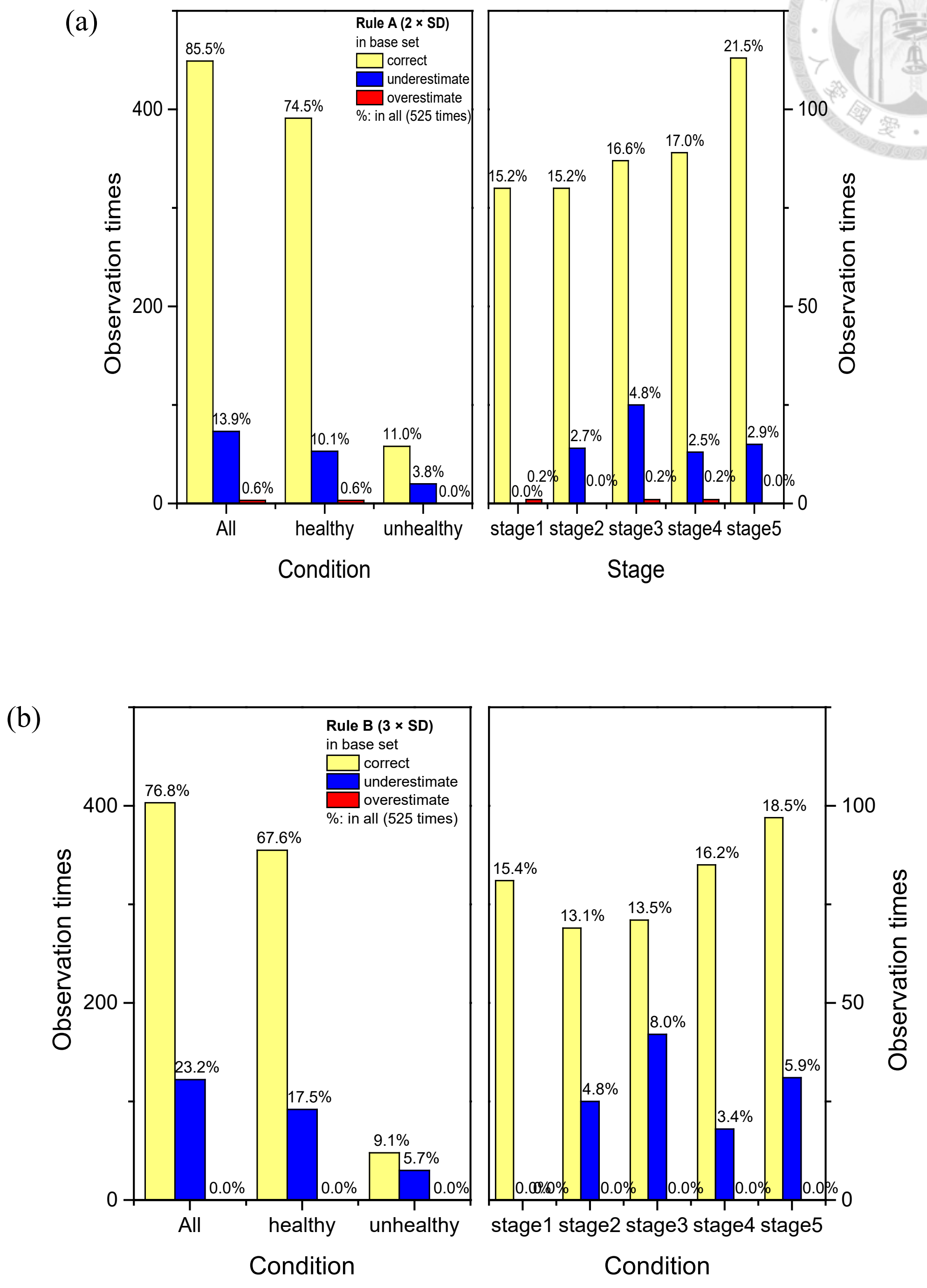


Figure A5 Accuracy of Rule A and B in each larvae condition

(a) Rule A. (b) Rule B. Data were from the base set. “Unhealthy” represented the larvae that failed to enter next stage.

doi:10.6342/NTU202003180

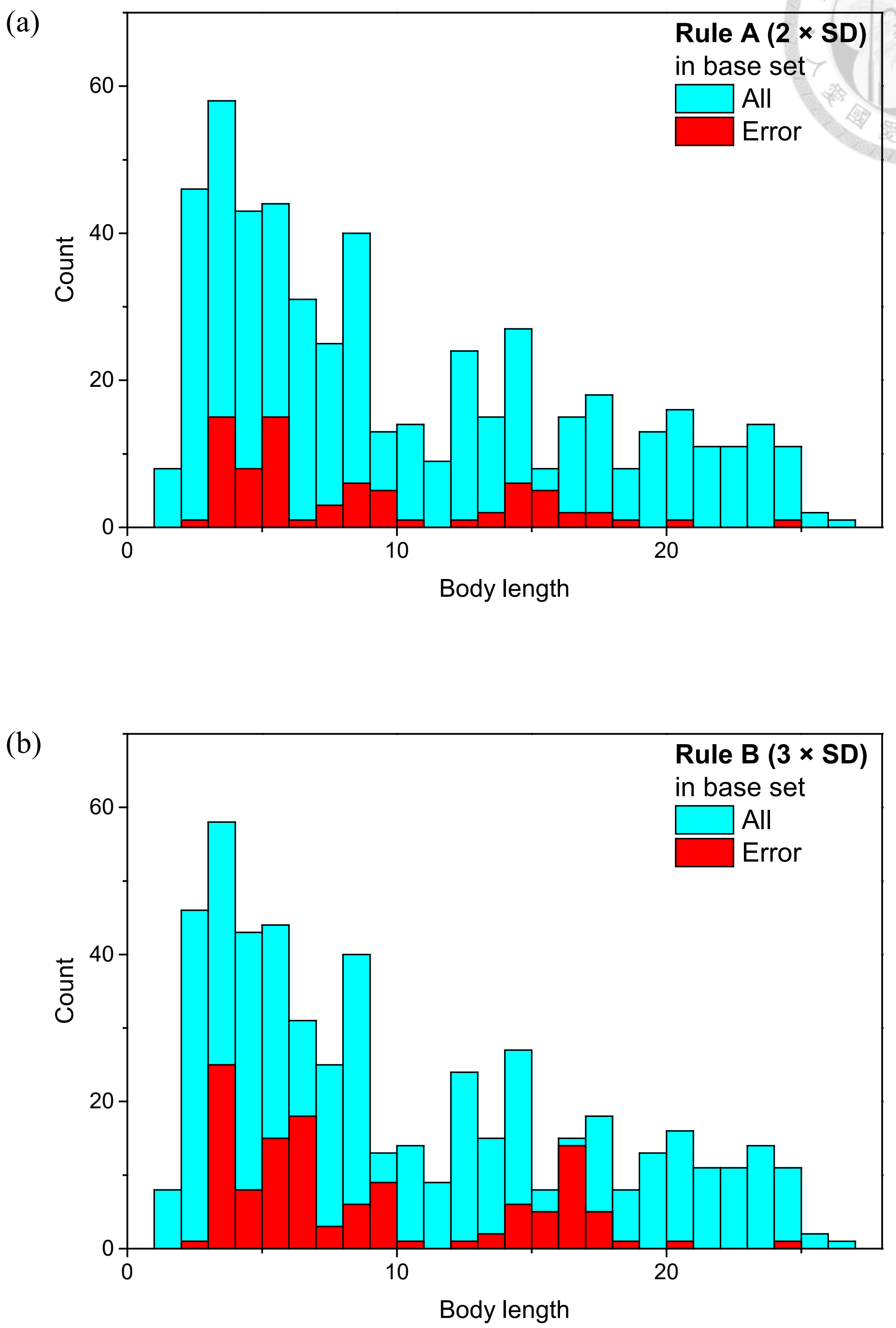


Figure A6 Accuracy of Rule A and B in each larvae condition in each body length

(a) Rule A. (b) Rule B.

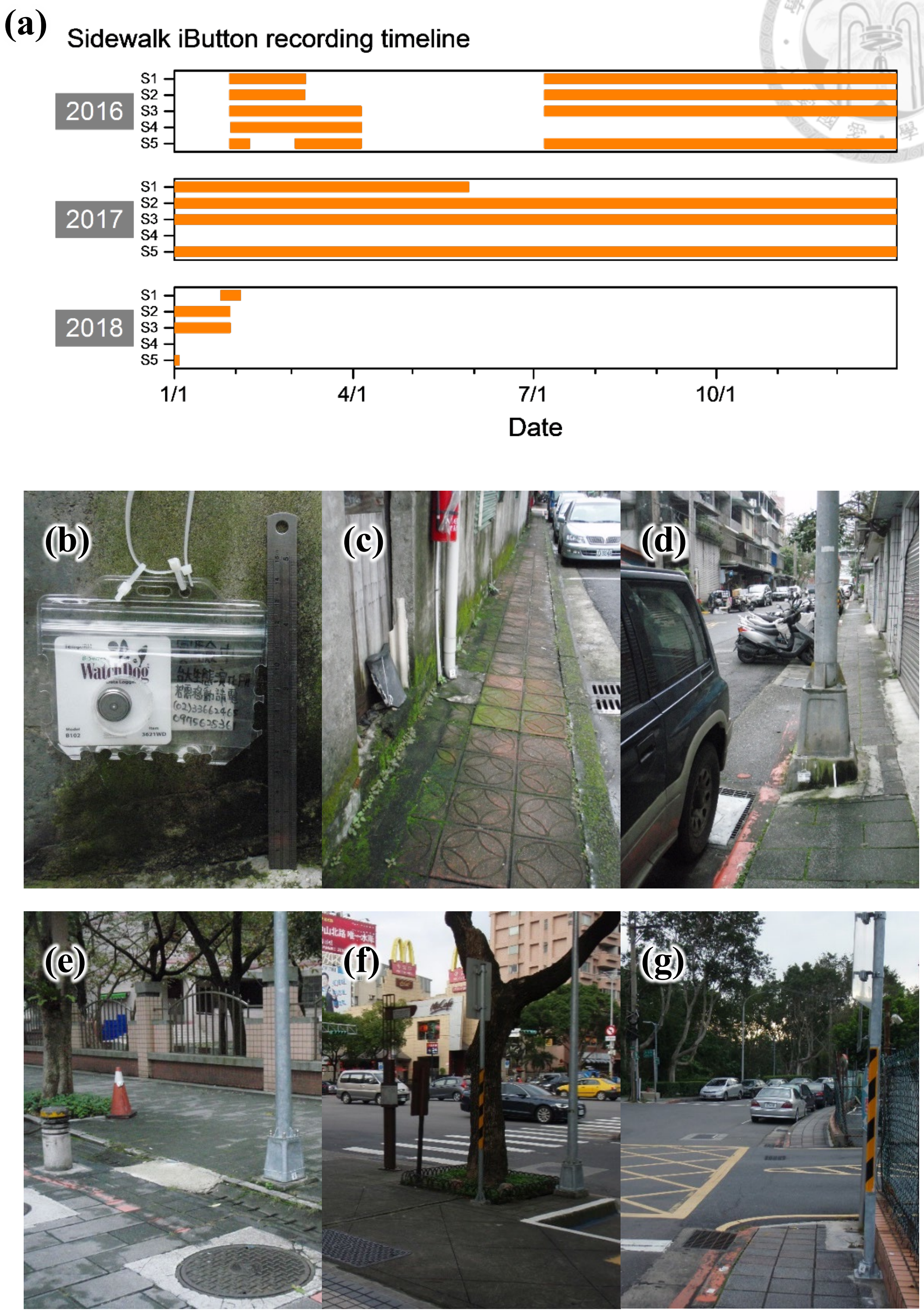
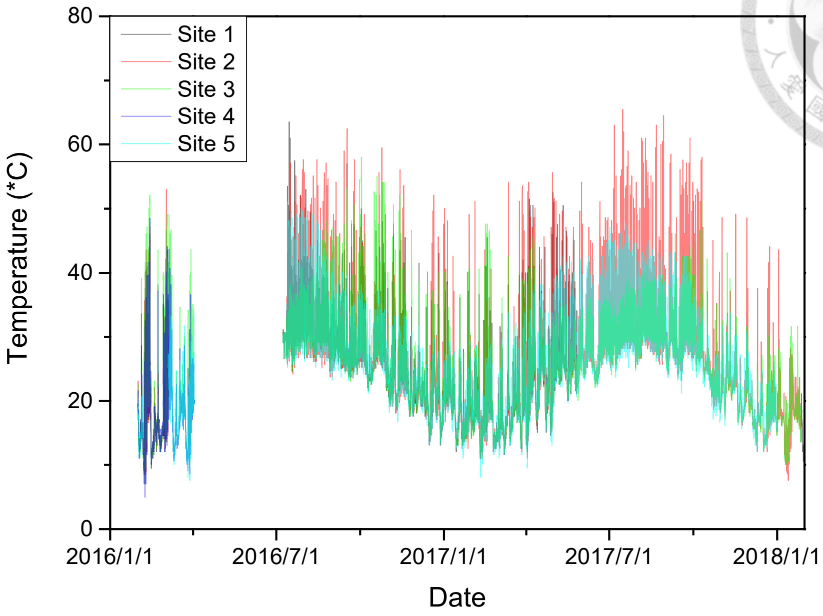


Figure A7 Temperature measurement of microenvironment on sidewalk

(a) The time period of survey. (b) iButton logger. (c-g) surveyed sidewalk sites.

(a)



(b)

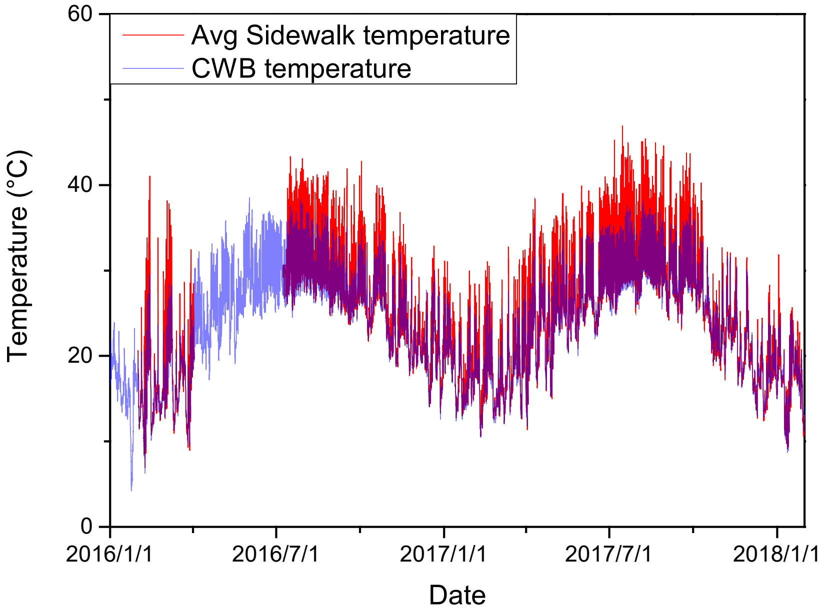


Figure A8 Temperature records from sidewalks

(a) Temperature records of iButton in five sites. (b) Temperature records on sidewalk versus CWB records.

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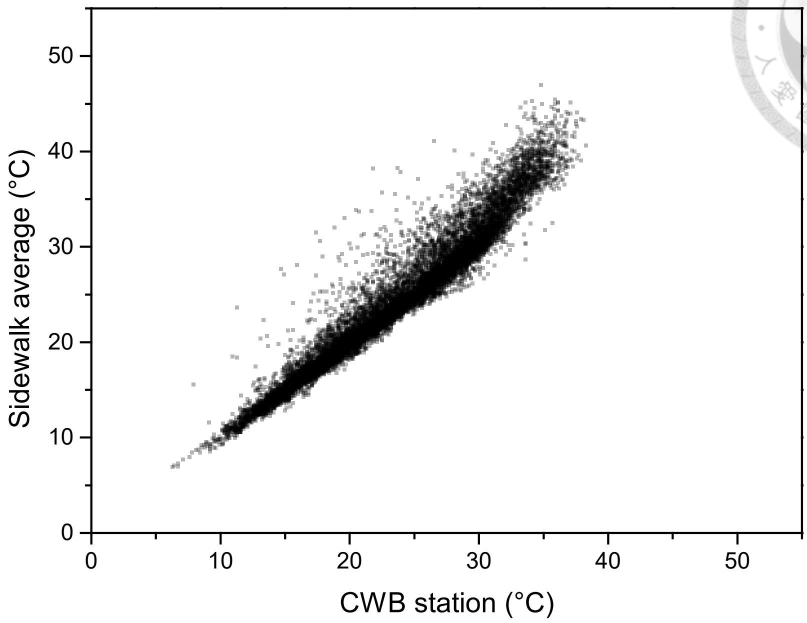

Figure A9 The relationship between CWB and sidewalk temperature

The relationship between CWB temperature data and sidewalk temperature record.

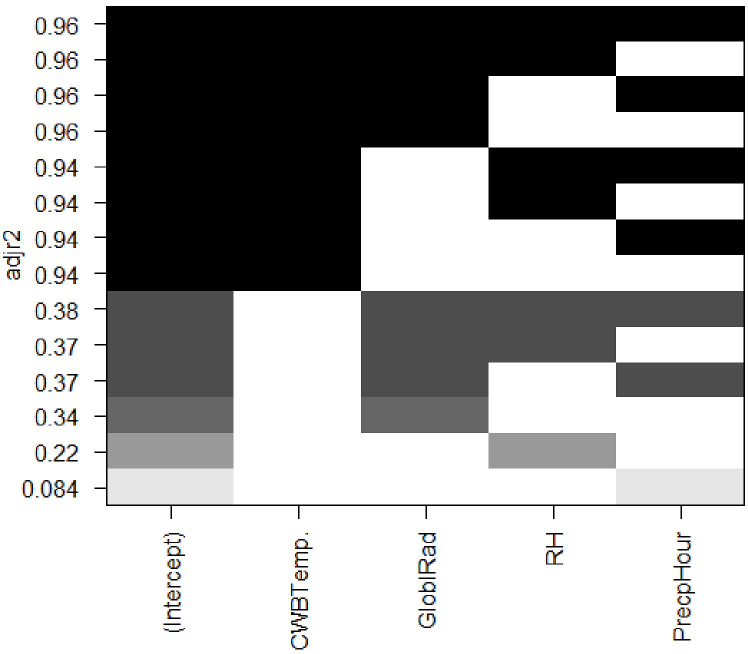

Figure A10 Regression subset selection

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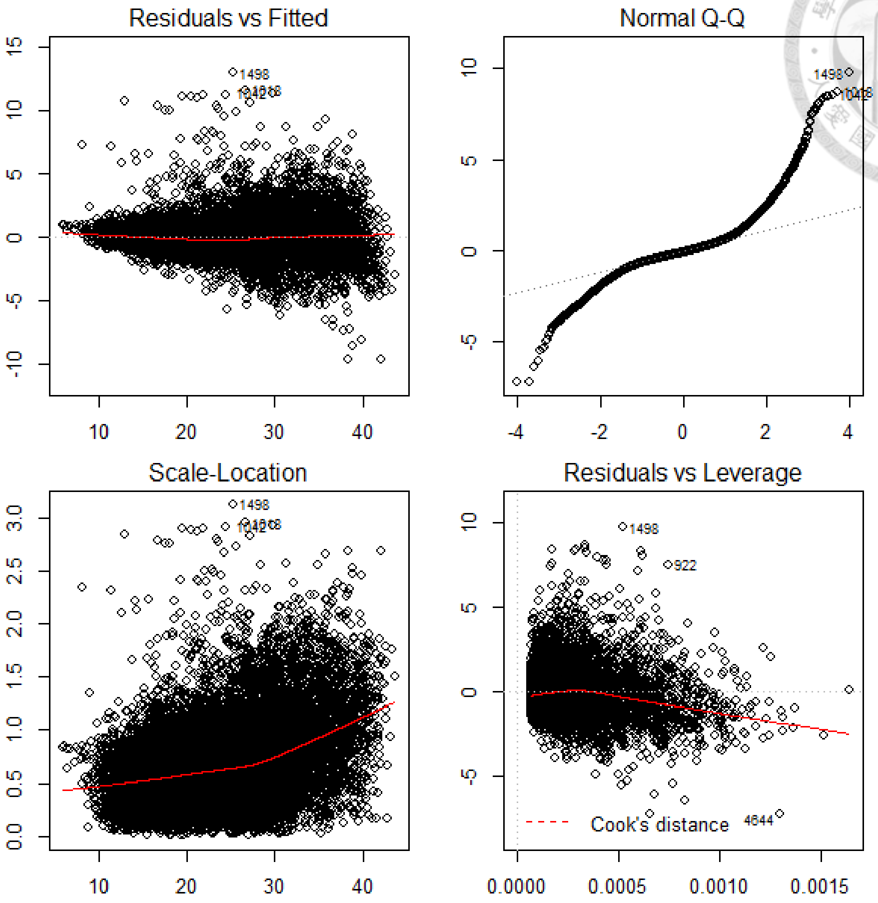

Figure A11 Graphic model test

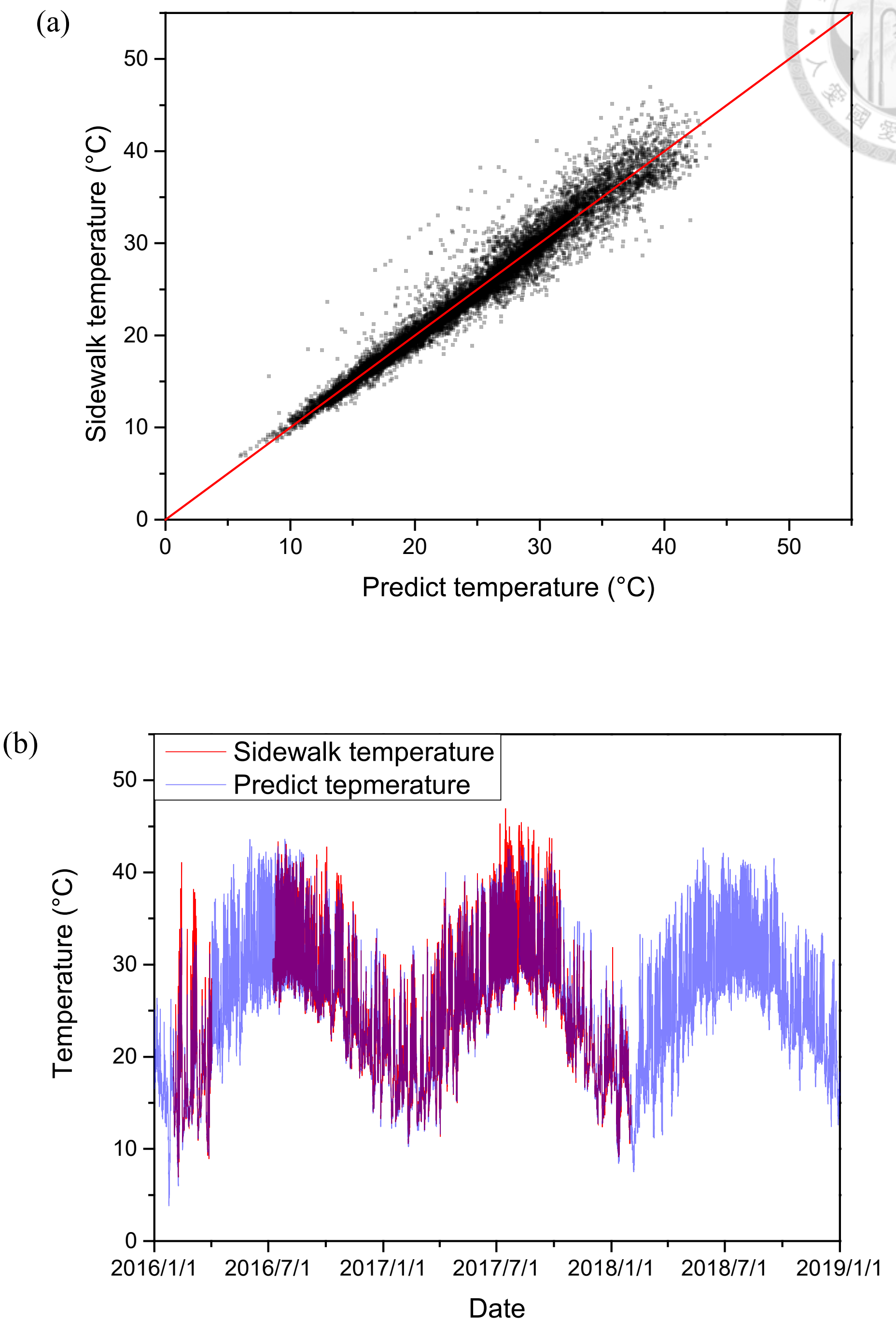

Figure A12 The relation between predicted and real sidewalk temperature

(a) Scatter plot, red line represented the 1: 1 ratio (X = Y). (b) The relationship between predicted and real temperature during the time period.