Development of a camera trap for perching dragonflies: a new tool for freshwater environmental assessment

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Abstract

Although dragonflies are excellent environmental indicators for monitoring terrestrial water ecosystems, automatic monitoring techniques using digital tools are limited. We designed a novel camera trapping system with an original dragonfly detector based on the hypothesis that perching dragonflies can be automatically detected using inexpensive and energy-saving photosensors built in a perch-like structure. A trial version of the camera trap was developed and evaluated in a case study targeting red dragonflies (*Sympetrum* spp.) in Japan. During an approximately 2-month period, the detector successfully detected *Sympetrum* dragonflies while using extremely low power consumption (less than 5 mW). Furthermore, a short-term field experiment using time-lapse cameras for validation at three locations indicated that the detection accuracy was sufficient for practical applications. The frequency of false positive detection ranged from 17 to 51 over an approximately 2-day period. The detection sensitivities were 0.67 and 1.0 at two locations, where a time-lapse camera confirmed that *Sympetrum* dragonflies perched on the trap more than once. However, the correspondence between the detection frequency by the camera trap and the abundance of *Sympetrum* dragonflies determined by field observations conducted in parallel was low when the dragonfly density was relatively high. Despite the potential for improvements in our camera trap and its application to the quantitative monitoring of dragonflies, the low cost and low power consumption of the detector make it a promising tool.

Introduction

Recent advances in computing power, digital cameras, batteries, acoustic devices, and other digital tools have facilitated the development of novel techniques for long-term and broad-scale biodiversity observations, which are required for successful large-scale conservation and planning *(Bush et al., 2017)*. In particular, camera traps and unmanned aerial vehicles have made it possible to effectively investigate wildlife populations *(Rowcliffe et al., 2008; Hodgson et al., 2016; Nakashima, Fukasawa & Samejima, 2018)*. Methods for the acoustic monitoring of birds and frogs are also rapidly advancing *(Acevedo & Villanueva-Rivera, 2006)*.

Many environmental indicator organisms, however, have not been adequately monitored using digital tools. Dragonflies (Odonata) are a prominent example. They are often assumed to be important indicators for assessing freshwater ecosystems *(Clark & Samways, 1996; Kadoya, Suda & Washitani, 2009; Yoshioka et al., 2014)*. Furthermore, as multi-habitat dwellers, they can indicate the status of complex aquatic and terrestrial ecosystems, including traditional agricultural landscapes, which support considerable biodiversity *(Kadoya et al., 2008; Kadoya & Washitani, 2011; Yoshioka et al., 2017)*. However, existing survey methods for dragonflies are mainly based on field observations by experts or researchers *(e.g., Kadoya et al., 2008)*. This limits the area-wide monitoring of dragonflies because field observation methods are sensitive to the skill of investigators and to weather conditions.

77   One potential method for monitoring dragonflies is the camera trap technique, a common
78   approach for monitoring mammalian taxa. Commercial camera traps are relatively inexpensive
79   have a high resolution and are easy to maintain owing to their low power consumption; it is only
80   necessary to collect the digital records and change the batteries a few times a year *(Fukasawa et*
81   *al., 2016; Yoshioka et al., 2016)*. However, these camera traps usually target homeotherms and
82   are triggered by passive infrared sensors, such as a pyroelectric sensors, which are not usually
83   applicable to insect detection. Some active photoelectric sensors can sensitively detect insects
84   *(Kawada & Takagi, 2004; Silva et al., 2015)*. However, they require a considerable amount of
85   power and are relatively expensive owing to their light projection systems. Thus, the cost to
86   maintain these types of traps becomes prohibitive when used in the field for an adequate period
87   to survey insects.
88   The behavioral characteristics of dragonflies provide a basis for resolving this issue. In
89   particular, many species of dragonflies are referred to as "perchers" *(Corbet, 1999)*; they often
90   perch on the highest point of a structure to search for prey and competitors *(Gorb, 1994; Switzer*
91   *& Walters, 1999; Kadoya, Suda & Washitani, 2004; Iwasaki, Suda & Watanabe, 2009)*. We
92   hypothesized that perchers can be attracted to the top of an artificial perch and that the
93   consequent interception of direct solar light at the top of the perch can be detected using passive
94   light sensors, thereby triggering a camera trap. According to this hypothesis, passive light
95   sensors, which are inexpensive and consume minimal electric power, are expected to effectively
96   capture perching insects.
97   Our aim was to contribute to the general question: can camera traps be used to monitor dragonfly
98   assemblages? In particular, we developed camera traps using passive light sensors for the
99   detection of percher dragonflies. First, we designed camera traps consisting of a commercially
100   available camera and an original dragonfly detection device, based on the idea that perchers can
101   be detected using an artificial perch with passive light sensors. To enable its application to
102   various percher species, the detection algorithm included various tunable parameters. Then, as a
103   case study, we implemented the camera trap for the detection of *Sympetrum* dragonflies in a
104   short-term field experiment. The detection frequency and sensitivity were evaluated at three sites
105   to obtain basic information on the accuracy of the trap. In addition, data from the camera trap
106   were compared with data from independent observations by an investigator to preliminarily
107   explore whether the trap detection frequency is a good indicator of the population density.
108

Materials & Methods

109
Fundamental concept of percher dragonfly detection using passive light sensors
110

111   The basic structure of the camera trap for percher dragonfly detection is shown in Fig. 1 (please
112   note that the National Institute for Environmental Studies obtained a national patent for the basic
113   idea [*Japan Patent Office, 2019*]). In the cylindrical rod-like structure (i.e., the detector section),
114   the first light sensor (or photoresistor) is set at the top and the second light sensor is set under the
115   first sensor. These sensors should be separated by a distance that is longer than the body size of a

116 dragonfly. At the top of the cylindrical structure, there is a transparent window above the first
117 sensor. Around the second sensor, the wall of the cylindrical structure consists of a light
118 diffusion material. These sensors are connected to a microcomputer to process the signals. The
119 circuit of the dragonfly detection device is powered by a DC battery.
120 The processor section is connected to a digital camera oriented at the top of the cylindrical
121 structure. The camera is set to be triggered when the signal values from the two sensors meet a
122 threshold condition, and the microcomputer outputs an imaging command.
123 When a dragonfly perches on the top of the detector, the direct solar radiation being detected by
124 the first sensor is expected to be sufficiently blocked, while diffuse solar light being detected by
125 the second sensor should remain relatively unchanged. Therefore, the relationship between the
126 signals from the two sensors is expected to change, triggering the connected camera when the
127 dragonfly is perching.
128

129 **Design and materials for the camera trap**

130 Using inexpensive and common materials, we assembled trial camera traps (Fig. 2A;
131 Supplemental Fig. S1). In the detector section, two cadmium sulfide (CDS) cells with 1 MΩ dark
132 resistance (GL5528; Nanyang Senba Optical & Electronic Co., Ltd.) were used as light sensors.
133 This passive light sensor cost about USD 0.25. The upper cell was covered by an LED silicone
134 cap (OptoSupply Ltd.). The bottom of each cell was colored black using a permanent marker.
135 These cells were connected to a microprocessor via USB cables. To enclose the cells, an acrylic
136 pipe (10 mm outer diameter, 7 mm inner diameter, and 500 mm length) was used. The top of the
137 pipe was surrounded by 150-mm-wide masking tape (Sekisui Chemical Co., Ltd.) as a
138 transmission diffuser, as well as 20-mm-wide black vinyl tape, and capped with a 0.5-mm-thick
139 polyethylene terephthalate plate (Acrysunday Co., Ltd.) using Aron Alpha adhesive (Toagosei
140 Co., Ltd.).
141 In the processor section, a PIC microcomputer (PIC16F1827-I/P; Microchip Technology Inc.)
142 was used as the main processor. The microprocessor was connected to a >2.3 V DC battery
143 (three AA batteries were used in the experiment described below). Resistance values for each
144 CDS cell in the detector section, which decrease with illumination intensity, were converted to
145 signal values of 0–1023 and processed using the microcomputer. The processor section was
146 enclosed in a polyvinyl chloride (PVC) pipe. To prevent rainwater intrusion, two silicon caps
147 penetrated by the detector section were inserted on the top of the PVC pipe. This PVC pipe was
148 attached to a tripod to adjust the height of the camera trap. (In the following experiment, the
149 height was about 2 m.)
150 A commercial digital camera covered in a water-proof case (TLC 200; Brinno Inc.) was
151 connected to the microprocessor using video cables (VX-ML10G or VX-ML20G; JVC Kenwood
152 Co.). Note that the camera is usually used as a time-lapse camera and can function for dozens of
153 days with four AA batteries if controlled appropriately. The camera was attached to the top of
154 the PVC pipe to capture the top of the detector section.

155

Dragonfly detection algorithm

A simple detection algorithm for a field experiment was developed (Fig. 3). This algorithm was aimed at directing the connected camera to obtain a single image per perching dragonfly. That is, once an image of a dragonfly on the top of the sensor was obtained, the next photo should not be taken until after that dragonfly took off and another one perched on the sensor. In addition, to prevent the trap from detecting instantaneous light from organisms or materials other than dragonflies, a continuous perching signal for a given time period ("Z" in Fig. 3) was required. Issues related to individual differences in the sensitivity of CDS cells and detector sections were minimized by using the ratio of relative signal values (temporal change in the instantaneous ratio of two signal values to the average) as an indicator for dragonfly detection, rather than the ratio of absolute signal values.

167

Case study

Sympetrum dragonflies

In Japan, dominant *Sympetrum* species, such as *S. frequens,* are perchers and are considered environmental indicators for agricultural landscapes consisting of paddy fields *(Sprague, 2003; Inoue & Tani, 2010; Tanaka, 2016)*. Mature adult *Sympetrum* dragonflies have conspicuous red bodies in the autumn and are familiar to people in Japan *(Inoue & Tani, 2010)*. There are concerns about the rapid decrease of these species in some regions in Japan due to pesticide use *(Jinguji & Uéda, 2015)*. In addition, land abandonment can reduce aquatic ecosystems in Japan *(Ikegami, Nishihiro & Washitani, 2011)*, which can impact these dragonflies. Considering that the intensification and/or abandonment of paddy ecosystems are common in rice-producing regions, continuous broad-scale monitoring of these dragonflies is needed. However, monitoring methods for these species are fairly limited. Insects are usually observed by experts or trained citizens *(Inoue & Tani, 2010; Tanaka, 2016)*. Therefore, examining the applicability of our camera trap to *Sympetrum* species has implications for conservation ecology. Considering that the genus is distributed worldwide, except in Oceania and south-central Africa *(Sugimura et al., 1999)*, *Sympetrum* dragonflies were an ideal candidate for assessing our camera trap.

185

Detection parameters

In the field experiment, parameters for the detection algorithm were provisionally set based on empirical knowledge. The interval to reset the average ratio of signal values X was set to 300 s, and the threshold value Z for perching duration was set to 10 s. The threshold value for $Y,$ the ratio of the instantaneous relative signal value to the average relative signal value, was set 1.05.

191   The processor commanded the digital camera to reboot when the perching duration *Td* reached 7
192   s because the digital camera slept. Note that the microprocessor could not monitor the status of
193   the camera and the reboot signal was similar to that for taking a photo. In addition, the
194   microprocessor was set to periodically wake up after sleeping for 1 s to save power. Considering
195   that three 1.2 V, 1,900 mAh batteries were used per detector and lasted at least 66 days during
196   the preliminary study described below, power consumption was estimated to be less than 5 mW.
197   The algorithm (Supplemental Code S1) was described and compiled using MPLAB IDE v. 8.60
198   (Microchip Technology Inc.) and microprocessor programming was performed using the
199   MPLAB ICD3 In-Circuit Debugger (Microchip Technology Inc.).
200

201   *Field experiment*
202   Study sites and camera trap setting. In a preliminarily experiment, a camera trap was set in the
203   yard of the Fukushima branch, National Institute for Environmental Studies (NIES), Miharu
204   town, Fukushima prefecture, Japan (37.434ºN, 140.519ºE) from October 11 to December 16,
205   2016 (Fig. 2A). Note that dragonflies are very sparse in the region after November (Yoshioka,
206   personal observation).
207   A short-term field experiment was also conducted to examine the performance of the camera
208   trap. From 8:05 on October 21 to 17:30 on October 22, 2016, three camera traps were set in the
209   yard of the NIES, Tsukuba city, Ibaraki prefecture, Japan (36.049ºN, 140.117ºE; Fig. 4A–C).
210   The average temperatures on the two days were 14.5ºC and 14.9ºC, respectively, and
211   precipitation was not recorded (Japan Meteorological Agency
212   http://www.data.jma.go.jp/obd/stats/etrn/index.php?prec_no=44&block_no=&year=&month=&d
213   ay=&view, accessed February 7, 2018). This season corresponds to the late stage of adult
214   dragonflies *(Inoue & Tani, 2010)*. Two camera traps were set in areas where the density of the
215   dragonflies was relatively high, one in a field and one a pond. The field site consisted of small
216   experimental paddy fields neighboring a greenhouse. The paddy fields were apparently not
217   managed in the season and vegetation within the paddies was relatively short. *Sympetrum*
218   dragonflies rarely perched on the vegetation within paddies. Instead, they perched on artificial
219   poles and net-fences, or trees surrounding the site. The pond site consisted of a small pond and
220   wet vegetation, in addition to paved ground. The *Sympetrum* dragonflies were frequently
221   observed to perch on cattails (*Typha* spp.) and tall goldenrods (*Solidago canadensis*). The
222   remaining trap was set on the rooftop of the main building of the institute, where no vegetation
223   exists. There were some artificial poles, but dragonflies rarely perched at the site, which is
224   relatively distant from aquatic habitats (thus, dragonflies were expected to be rarely detected).
225   Each site was about 250 m^2 considering the homogeneity of land cover and accessibility for the
226   dragonfly census described below. In addition, these sites were more than 150 m apart and
227   intercepted by multiple buildings and trees.
228   Evaluation of auto-detected images. Images obtained from the three camera traps were used to
229   count true positives and false positives (i.e., photos with and without *Sympetrum* dragonflies).

230   The number of false positives indicated the extent of type I error. Each image was visually
231   evaluated. When there were multiple photos within a few seconds, the first photo was removed
232   from the analysis (see also the "not analyzed to avoid double count" column in Supplemental
233   Data S1). These images resulted from commands for rebooting the camera when it was already
234   active and led to overestimates of true positives.
235   Validation by time-lapse camera monitoring. To check perching dragonflies undetected by the
236   camera traps (i.e., false negative or type II errors) and to evaluate the detection sensitivity, an
237   additional digital camera was placed near each camera trap. At the field and pond sites, time-
238   lapse cameras (TLC 200) captured movies at 10-s intervals. At the rooftop site where dragonflies
239   were expected to be rare, a video camera captured movies at 30 fps, instead of a time-lapse
240   camera. After the experiment, the movies were thoroughly checked and the presence or absence
241   of *Sympetrum* dragonflies in each frame was recorded. Movies were initially used to screen for
242   files that include perching dragonflies. Then, movie files including perching dragonflies were
243   split to jpeg image frames using FFmpeg ver. 2015-04-02 (https://ffmpeg.org/) to evaluate frame
244   numbers. No dragonflies perched on the camera trap at the rooftop site during the experiment.
245   To calculate sensitivity, defining a false-negative case based on movie files obtained from the
246   cameras for validation was required. Because perching dragonflies often showed instantaneous
247   takeoff and landing, a "perching event" was defined as an array of movie frames including fewer
248   than two continuous frames without a dragonfly (Fig. 5A). That is, if a dragonfly left the camera
249   trap for more than two frames (20 s), the perching event was closed. Note that 20 s corresponds
250   to the bout criterion interval (Slater, 1974) and the number of "perching events" did not change
251   substantially by increasing the intervals to longer than 20 s. Based on the timestamps for the
252   image frames, the start and end times of each perching event were obtained. Then, the detection
253   of each perching event by camera traps was verified by matching timestamps of autodetected
254   images. If at least one image capturing a *Sympetrum* dragonfly was obtained by the camera trap
255   during a perching event period, the perching event was recorded as a true positive. If no image of
256   a dragonfly was detected during an event, this was recorded as a false negative. Then, sensitivity
257   was estimated for each site as (true positives ÷ (true positives + false negatives)). A caveat is that
258   an individual could contribute to multiple perching events, and the replacement of perching
259   individuals within 20 s is possible. Thus, sensitivity for a camera trap may reflect the activity of
260   dragonflies, but not necessarily the population density. In addition, Fisher's exact test was used
261   to compare the frequencies of true positives and false negatives among sites using the *fisher.test*
262   function implemented in R version 4.0.0 (R Core Team, 2020).
263   Comparison with the dragonfly census. To examine whether detection by the camera traps
264   reflects the dragonfly population density, a comparison among survey methods is important. In
265   parallel with the short-term experiment, census data for *Sympetrum* dragonflies were obtained at
266   each site. As a standardized census method, a timed survey (*Balzan, 2012; Harabis & Dolny,*
267   *2015*) was adopted because a transect survey was not suitable for the non-linear configurations of
268   sites. At each site, an investigator counted and recorded the number of *Sympetrum* dragonflies
269   for 10 min three times a day (six observations in total). Previous studies have reported that

270   marked individuals of some perching dragonfly species could maintain reproductive territories
271   for about 1.5‑2.5 hours (*Koenig & Albano, 1985; Moore & Martin, 2016*). Thus, three 3-hour
272   time periods were established (9:00–12:00, 12:00–15:00, and 15:00–18:00) and all of the sites
273   were visited for the census for each time period (note that dragonflies were rarely observed from
274   8:00 to 9:00). For each time period, the first site visited at first was randomly determined and the
275   remaining two sites were surveyed within 1 hour from the start of the first survey (see
276   Supplemental Data S3 for details). Therefore, the effect of sites was not confounded with
277   variation among time periods. During the timed survey, the investigator slowly and randomly
278   walked while searching for dragonflies within the site, because the dragonfly density was
279   relatively low and counting individuals at fixed points was not likely to be effective. To
280   minimize double counting, perching individuals at the same point were counted only once for
281   each 10-min survey, unless the investigator observed individuals leaving the point. For each site,
282   the numbers of *Sympetrum* dragonflies observed per 10 min period were summed to obtain the
283   "total frequency of dragonflies observed".
284   To obtain robust inferences on the relationship between camera detection and census
285   observations given the small sample size, two statistical analyses were used (see Supplemental
286   Code S2). Note that the number of images of *Sympetrum* dragonflies was used as an index for
287   camera detection rather than the perching events owing to the low values at the field and rooftop
288   sites (one and zero, respectively). First, differences in *Sympetrum* dragonfly detection by the
289   camera trap among sites and differences in the total frequency of dragonflies observed among
290   sites were evaluated. If camera detection indicates the dragonfly population density, similar to
291   census observation, statistical inferences should be similar for the two approaches. To test the
292   differences among the sites, a goodness-of-fit test was applied to each pair of sites under the null
293   hypothesis that the probability of dragonfly occurrence is equal between sites (i.e., 0.5). The
294   probabilities of obtaining data (or a more extreme difference than the observed value) under the
295   null hypothesis were computed by Monte Carlo simulations *(Hope, 1968)* with 1,000,000
296   replicates using the *chisq.test* function implemented in R version 4.0.0 *(R Core Team, 2020)*. The
297   random seed was set to 0. The significance probabilities were adjusted by Holm's method *(Holm,*
298   *1979)* to account for multiple comparisons. Next, a direct approach was used to examine
299   relationships between camera detection and census observation. Because the site number was
300   small, the sample unit was set to dragonfly detection over a 3-hour time period per day per site
301   and census observation corresponding to the time period (i.e., n = 18). This assumption was
302   based on the previous studies that perching individuals are usually replaced within 3 hours
303   (*Koenig & Albano, 1985; Moore & Martin, 2016*). Then, a generalized linear mixed model
304   (GLMM) with a quasi-Poisson error distribution was used to evaluate whether the number of
305   dragonflies detected per 3-hour period (the response variable) reflected the number of
306   dragonflies observed per 10 min (the explanatory variable). In the model, site, day, and time
307   period were included as random variables. The GLMM was implemented using the *glmmTMB*
308   function in the glmmTMB package for R version 4.0.0 (*Brooks et al., 2017; R Core Team,*
309   *2020*). Similarly, the GLMM was calculated using the number of dragonflies detected as the

310   explanatory variable and the number of dragonflies observed as the response variable. The caveat
311   is that the adherence of an individual *Sympetrum* dragonfly (mainly *S. frequens*) to a territory is
312   unclear. Nevertheless, the territorial behavior of *S. frequens* is not remarkable (*Sugimura et al.,*
313   *1999*) and their adherence to a specific perch may be relatively weak. In this study, the only
314   individual that perched on the camera trap in the field site held its territory for 25 min (from
315   13:30 to 13:55 on October 22) at most (see Supplemental Data S2). At the pond site, an
316   individual was considered to hold its territory for 2.4 hours (from 12:08 to 14:32 on 21th
317   October) at most, if we assumed that the replacement of individuals was indicated by leaving the
318   perch for more than 180 frames (30 min), which is an adequate period of time for copulation and
319   tandem oviposition (*Sugimura et al., 1999; Ishizawa, 2012*). Thus, a 3-hour time period should
320   be sufficient for the replacement of perching individuals.
321

322   ## Results

323   **Successful detection of *Sympetrum* species**

324   Through the preliminary experiment and the short-term experiment, we confirmed that the
325   developed camera traps were able to detect *Sympetrum* dragonflies in the outdoor environment.
326   As expected, our camera traps in the field experiments automatically obtained images of
327   *Sympetrum* dragonflies (Fig. 2B, Fig.4D).
328   During the preliminary experiment with a single camera trap, the batteries for the processor
329   section (three AA nickel-metal hydride batteries) were not exhausted during the study period.
330   However, the batteries for the connected camera (four AA alkaline batteries) were exhausted
331   after November 5th, exchanged on November 8th, and exhausted again after December 12th.
332   Among 1,609 images, seven captured *S. infuscatum* (Fig. 2B).
333   During the short-term experiment using three camera traps, we detected *S. frequens* and *S.*
334   *darwinianum.* Note that although we could identify *S. infuscatum* to the species level from the
335   images based on the conspicuous dark color of the tips of wings, we could not distinguish *S.*
336   *frequens* from *S. darwinianum* owing to the low resolution. Furthermore, during the case study,
337   no images detecting other flying organisms were obtained (i.e., the observed false positives could
338   be explained by external abiotic factors, such as the movement of the sun and clouds, or to
339   unexpected internal device errors).

340   **Frequency of successful detection and type I errors**

341   To quantify to what extent the automatic detection correctly captured *Sympetrum* dragonflies, the
342   images obtained from the camera traps in the short-term experiment were checked. The
343   frequency of true positives was highest at the pond site (50 pictures) and was lowest at the
344   rooftop site (zero pictures) (Fig. 6; Supplemental Data S1). The numbers of false positives were
345   49, 51, 17 at the field, pond, and rooftop sites, respectively.

346 **Frequency of type II errors and sensitivity**

347 Then, the extent to which the camera traps sensitively detected perching *Sympetrum* dragonflies
348 without overlooking was quantified using data from the camera traps and the time-laps cameras.
349 The numbers of true positives on perching events were 1, 8, and 0 at the field, pond, and rooftop,
350 respectively, while the numbers of false negatives were 0, 4, and 0, respectively. Most perching
351 events longer than 10 s could be detected (Fig. 5B; Supplemental Data S2). The sensitivity
352 values based on perching events were 1.0 and 0.67 for the field and the pond sites, respectively.
353 Although all false negatives were recorded at the pond site, a one-sided Fisher's exact test (p =
354 0.6923) did not indicate that the ratio of false negatives at the pond site was higher than that at
355 the field site owing to the small sample size. Note that the rooftop site was not analyzed owing to
356 the lack of perching events.

357 **Comparison with census data**

358 Simultaneously, the census of the dragonflies was conducted by an investigator to be compared
359 with the result of camera trapping. The total frequency of *Sympetrum* dragonflies observed was
360 highest at the pond site (35 individuals) and lowest at the rooftop site (8 individuals) (Fig. 7;
361 Supplemental Data S3).
362 The goodness-of-fit tests on the detection frequency by camera traps showed that there was a
363 statistically significant difference (significance level of adjusted p-value was 0.05) among the
364 three sites (Fig. 7). The adjusted p-values based on Holm's method for pairwise comparisons
365 were 0.000036 (field vs. pond), 0.000003 (pond vs. rooftop), and 0.000074 (field vs. rooftop).
366 For investigator observations, we did not obtain a significant difference between the field and
367 pond sites, with adjusted p-values based on Holm's method of 0.0814 (field vs. pond), 0.0486
368 (pond vs. rooftop), and 0.000129 (field vs. rooftop).
369 The GLMM showed that the effect of census observation per 10 min period on camera detection
370 for a 3-hour period was significantly positive (estimated regression coefficient ± S.E. = 0.4040 ±
371 0.2024, Z-value = 1.996, p-value based on the Z-value = 0.0459). However, in the model
372 examining the effect of camera detection on census observations (i.e., in which explanatory and
373 response variables were replaced with each other), the regression coefficient was not significant
374 (estimated regression coefficient ± S.E = 0.02764 ± 0.01726, Z-value = 1.602, p-value based on
375 the Z value = 0.109).
376

377 # Discussion

378 During the study, the newly developed camera trap was successfully used to detect and obtain
379 images of percher *Sympetrum* dragonflies in the field. The percher detector made of passive light
380 sensors was inexpensive and power-saving, as expected. These properties make the detector a
381 major advance for the automated ecological monitoring of perchers.
382 Of course, extensive analyses, beyond the confirmation of the automatic capture of perchers, are
383 required for the practical application of the camera trap, as is feasible for mammals *(e.g.,*

384 *Fukasawa et al., 2016; Nakashima, Fukasawa & Samejima, 2018)*. For ecological monitoring,
385 data for spatial and temporal dynamics of population density at multiple locations are usually
386 required for statistical analyses. Ideally, perchers should be captured with high accuracy when
387 they land on the detector. Then, the detection frequency can be used as an indicator of population
388 density. It is important to determine whether the detection frequency corresponds to density or is
389 just a rough indicator of presence/absence. Finally, additional traps set across broader areas for
390 longer durations should be demonstrated.
391 The results of our short-term experiment provide convincing evidence for the performance of the
392 detection device. As expected, the approach was efficient with respect to time. A few tens of
393 false positive detections per day were obtained (consistent with preliminary work in Fukushima
394 and in the field experiment in Tsukuba). This indicated that the type I error rate was acceptably
395 small, considering the time required to check all images obtained in 10-s intervals using a time-
396 lapse camera. Note that commercial camera traps for mammalian monitoring also show a
397 considerable frequency of false-positive detection *(Newey et al., 2015)*. In addition, no organisms
398 other than *Sympetrum* dragonflies were detected during the short-term field experiment. The
399 sensitivity values for the field experiment over 2 days showed that relatively long perching
400 events were correctly detected. This suggested that the type II error rate was also acceptable.
401 Furthermore, we observed that the relationship between the detection frequency and dragonfly
402 population density was positive, but not strong. Comparing the camera trap data with
403 investigator data by the goodness-of-fit tests, both methods distinguished whether the dragonfly
404 abundance was low or high (i.e., rooftop vs. other sites). However, different results were
405 obtained for comparisons between the field and the pond, two sites where the dragonfly
406 abundance was relatively high. The GLMM analysis showed that camera detection was predicted
407 from the census data; however, the opposite was not true. This may be explained by the
408 relatively low information obtained by camera detection (15 out of 18 replications were zero
409 values). These analyses suggested that camera detection results were non-linearly related to the
410 population density and that information about population density obtained from a single trap in a
411 short time period is relatively limited compared with census observation data. In our case study,
412 the camera detection results did not adequately reflect the density at the field site. The camera
413 trap at the field site may be less conspicuous for dragonflies due to the adjacent greenhouse. In
414 addition, differences in abundance may have been difficult to detect if a minority of individuals
415 repeatedly occupied the detector section of the camera trap in a location where the dragonfly
416 density was high. If so, the accurate detection of a perching dragonfly does not always indicate
417 population density. The application of the trap to other species with stronger adherence to a
418 territory should be performed with caution.
419 These results suggested that our simple camera trap may be suitable for distinguishing among
420 locations with high and extremely low dragonfly densities. Of course, there is still room for
421 improvement. In this study, the detection algorithm and parameters were not adequately
422 optimized for *Sympetrum* dragonflies, despite the relatively high sensitivity, at least in the short-
423 term experiment. An improvement on the rate of false positives owing to movement of the sun

424 and clouds will directly save time for checking captured images. Exploring more sophisticated
425 algorithms may reduce the error and make the tool more convenient. If an improvement in
426 detection accuracy does not correspond to more accurate estimates of population density, better
427 spatial allocation and arrangements should also be explored. Multiple camera traps at a location
428 or multiple detector sections may prevent a minority of individuals from disproportionately
429 occupying the camera trap. In addition, the surrounding environment may affect the behavior of
430 dragonflies. Use in adequately open habitats may be desirable because complex structures will
431 make the camera trap less conspicuous and appealing to the dragonflies. In addition, the
432 application of statistical techniques, such as site occupancy models with heterogeneous detection
433 probabilities *(Royle, 2006)*, will improve population size estimation.
434 Furthermore, the camera trap only targeted adult dragonflies. To infer the population dynamics
435 of *Sympetrum* dragonflies more precisely, comparisons with other sampling methods, such as
436 counting exuviae *(Tanaka, 2016)*, are required. Accordingly, data obtained from long-term field
437 experiments with dozens of camera traps are needed.
438 For the broader application of the trap to percher dragonflies, the ability to accurately identify
439 species is an important issue. There is room for improvement with respect to camera positioning.
440 In the current version of the camera trap, cameras were set about 40 cm below the tip of the
441 detector to prevent dragonflies from perching on the camera, considering the tendency for
442 *Sympetrum* dragonflies to perch at higher points. This camera positioning provided small images
443 of only the ventral side of individuals. Although the remarkable pattern on the wings can be used
444 to identify the dragonflies in the current positioning, species with key morphologies based on
445 other body parts, such as the thorax, cannot be distinguished. Further research may be required to
446 set the camera appropriately at a higher position and a shorter distance from the detector tip,
447 preventing the camera from interfering with perching behaviors. Connecting a camera with a
448 higher resolution will improve the accuracy of species identification. Considering the recent
449 development of small and power-saving digital cameras, improvements in species identification
450 may be not a major issue for long.
451 Improvements in hardware may be useful from the viewpoint of sustainability and durability. For
452 example, longer-lasting batteries for the camera will make it possible to use a trap for months.
453 Sealing the electronic circuit with gels, such as silicon, can minimize damage from condensation.
454 Nevertheless, our camera trap had remarkable advantages over existing sampling methods for
455 percher dragonflies, including its automatic action, low labor requirements, low power
456 consumption, low cost, and non-destructive nature, in addition to the potential improvements and
457 extensions mentioned above. These advantages will be particularly important in areas where
458 access by investigators is restricted (e.g., strict nature reserves and evacuation zones after nuclear
459 power accidents). Furthermore, the camera trap is appropriate for examining the impacts of the
460 abandonment of rice paddy fields on percher dragonflies. Unlike existing sampling methods,
461 such as counting exuviae, camera traps do not require aquatic habitats, which are often lost in
462 abandoned lands *(Ikegami, Nishihiro & Washitani, 2011)*. Of course, combinations with other
463 sampling methods are expected to be effective. For example, the combination with mark and

464 recapture methods (i.e., "recapturing" by camera traps instead of investigators) will save effort
465 for the estimation of population size and dispersal ability.
466

Conclusions

468 Our study demonstrated that the ecological monitoring of perching insects using simple and
469 inexpensive camera traps is realistic owing to rapid advancements in digital cameras, processors,
470 storage, and batteries, by implementing a simple strategy based on the behaviors of focal species.
471 Although the scope of our approach in this study is limited to perching insects and not applicable
472 to any others, looking again common behaviors like perching may find a way for automatic
473 monitoring of other type of insects. Our approach is expected to be a key step toward the
474 construction of automatic and well-standardized area-wide monitoring systems for insects and to
475 contribute to global observation networks of biodiversity and the environment.
476

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482

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586

Figure 1

Schematic diagram of the proposed camera trap for *Sympetrum* dragonfly detection.
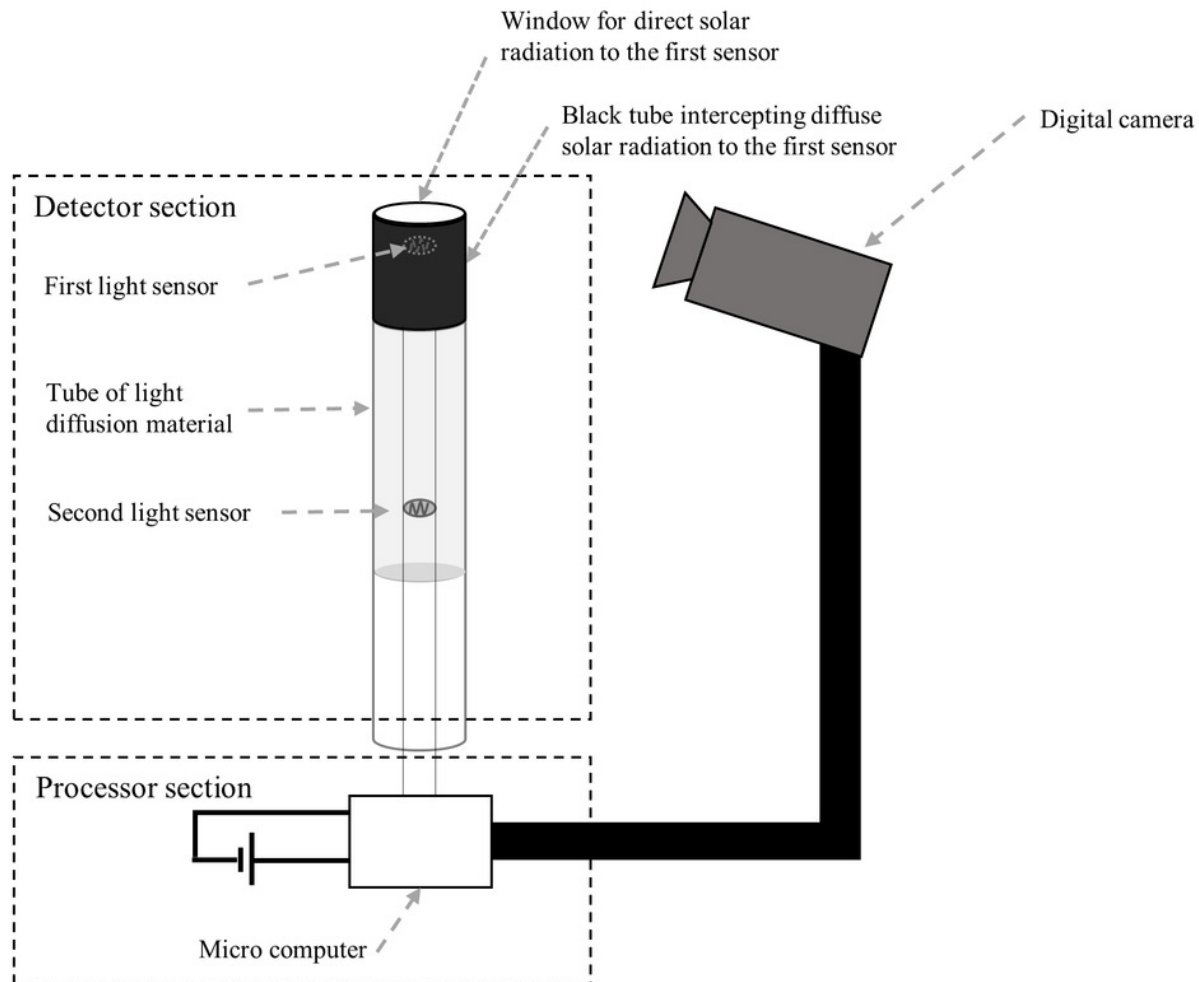
Figure 2

(A) A trial camera trap used for the field experiment and (B) an image of *Sympetrum infuscatum* obtained by the camera trap.
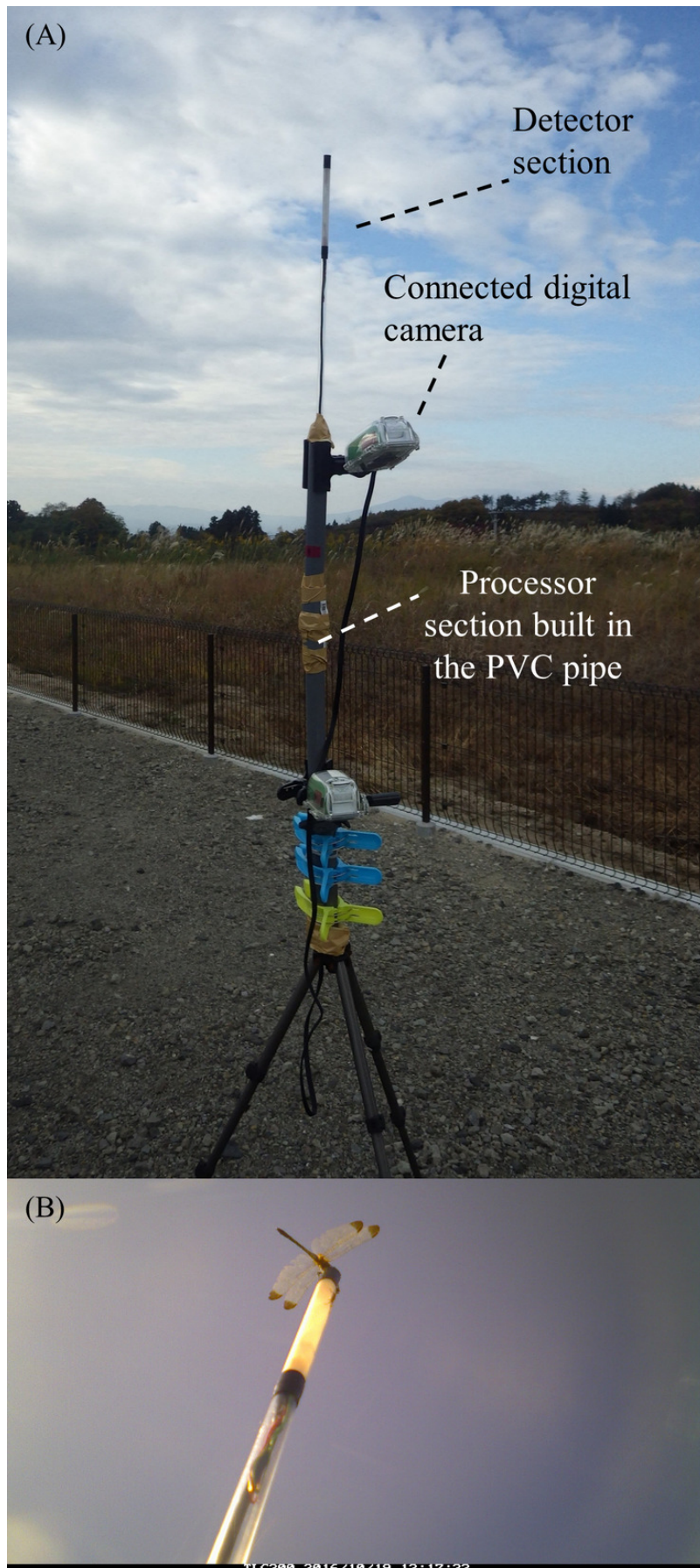
Figure 3

Schematic algorithm for dragonfly detection. Each cycle of the process is executed at 1-s intervals.

Each cycle of the process is executed at 1-s intervals.

```
                                    ┌──────────────────────────────────┐
  ╭──────────────────╮             │ #Set the initial timer values Te, Td and │
  │   #Start          │───────────▶│ accumulated signal values IVm, IVr.       │◀───
  │ the detection     │             │         Te = 0, Td =0                      │
  │   program         │             │         IVm = 0, IVr =0                    │
  ╰──────────────────╯             └──────────────────────────────────┘
```

#Start
the detection program

#Set the initial timer values *Te, Td and accumulated signal values IVm, IVr.*
$Te = 0, Td = 0$
$IVm = 0, IVr = 0$

#Get the instantaneous signal values from the first sensor (Vm) and the second sensor (Vr) every second.

#the value Rs has set already

No → #Set the initial value of Rs.
$Rs = Vm/Vr$

Yes

#Calculate the ratio of Vm to Vr
$Rm = Vm/Vr$

#Check if a dragonfly perches
$Rm > Y*Rs$

No → #Reset perching duration time Td
$Td = 0$

#Get time and update Te (sec.)
$Te = Te+1$

Yes

#Accumulate perching duration time and reset the accumulated signal values.
$Td = Td+1, Te = 0, IVm = 0, IVr = 0$

#Accumulate signal values
$IVm = IVm+Vm$
$IVr = IVr +Vr$

#Check the timer value Te
$Te = X$

No

Yes

#Calculate average ratio of signal values from the first and second photoresistors for the past Te seconds
$Rs = IVm/IVr$

#Check the perching duration time
$Td = Z$

No

Yes

#Command a camera to take a photo

Figure 4

Field experiment sites, including (A) field, (B) pond, and (C) rooftop sites, and (D) a photo of a *Sympetrum* dragonfly obtained by the camera trap at the pond site.
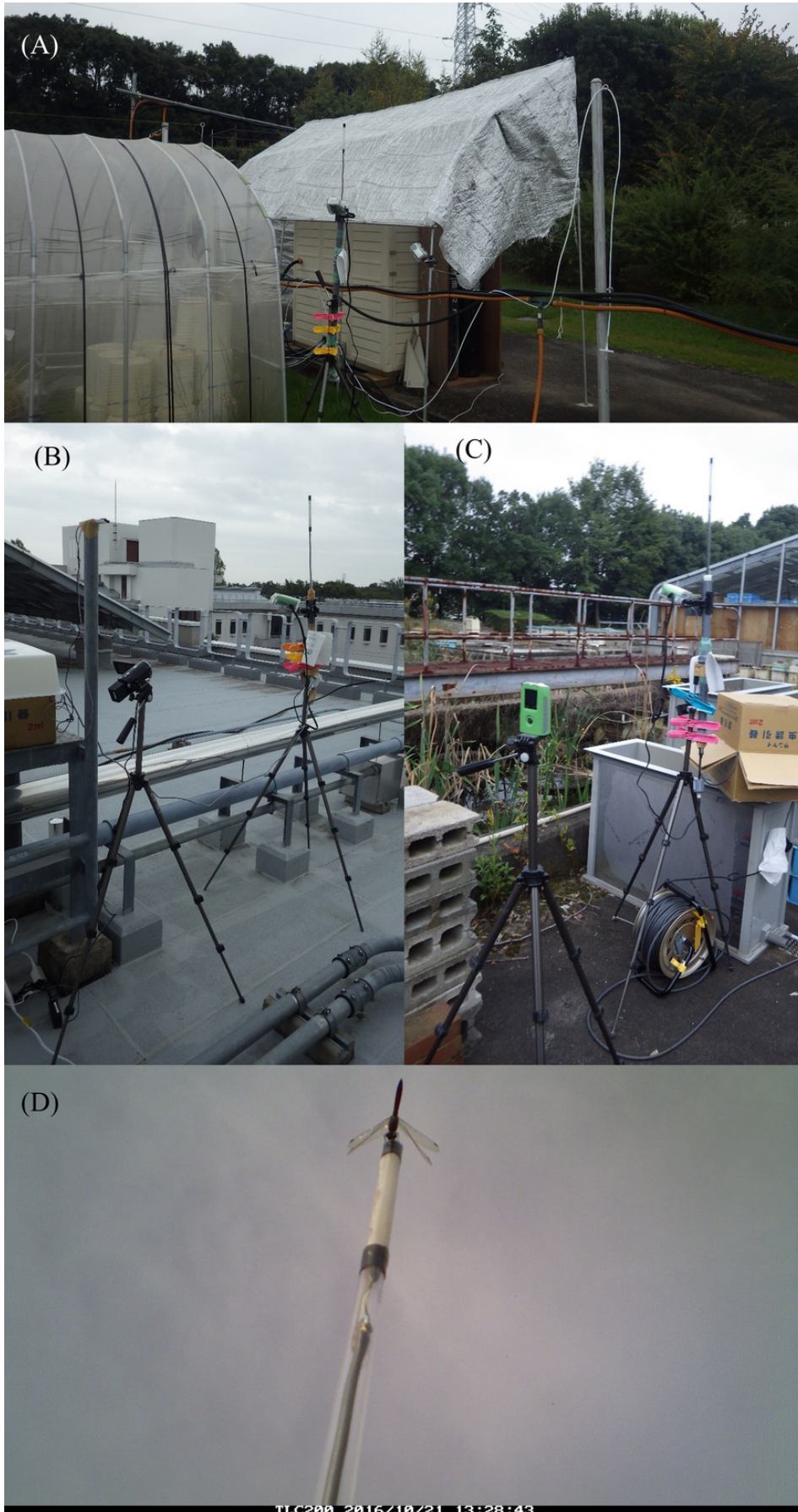
Figure 5

(A) Schema of a "perching event" extracted from a movie captured by the time-lapse camera for validation. (B) Number of perching events automatically detected by the camera trap at each site.

Black bar shows the number of detected perching events. White and grey bars show undetected perching events continuing for more than 20 s and less than 20 s (perhaps less than 10 s), respectively.

(A)

(B)
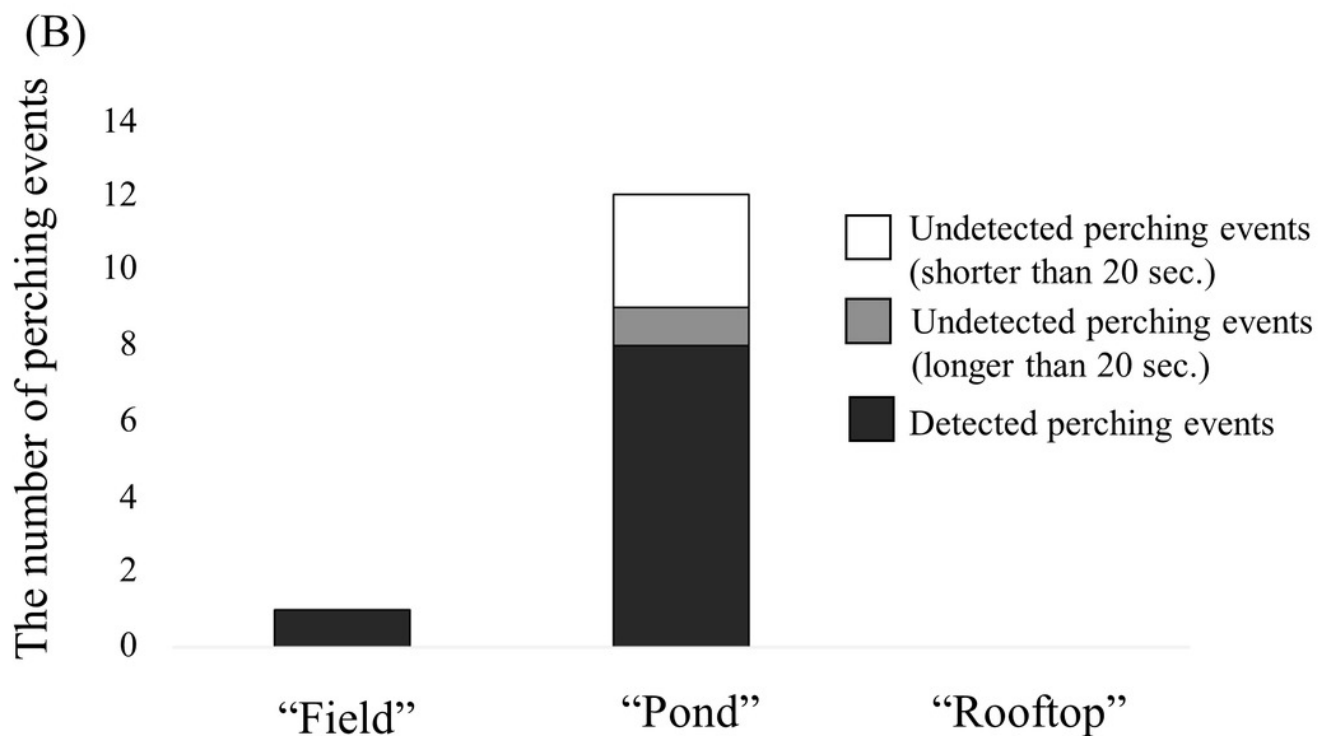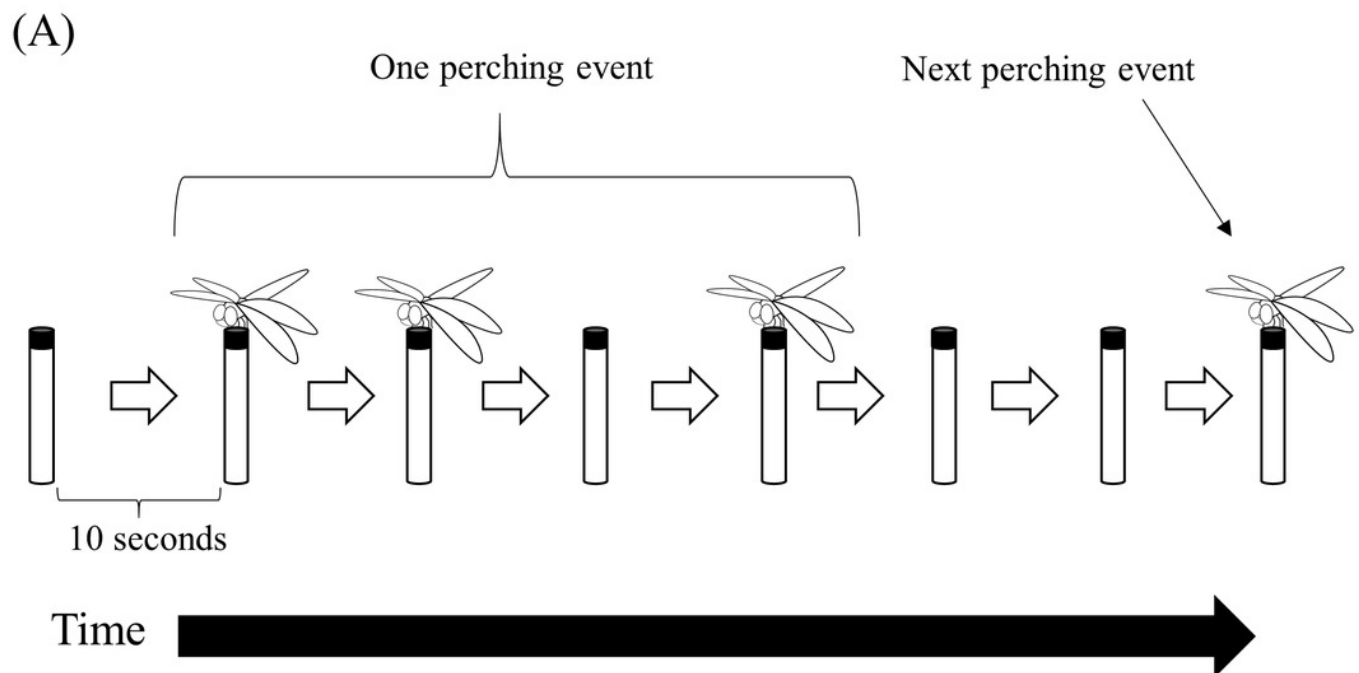
Figure 6

Number of images automatically obtained by the camera trap at each site.

Black bar and grey bars show true positives (photos with a perching dragonfly) and false positives (photos without dragonflies), respectively.

-1

-1
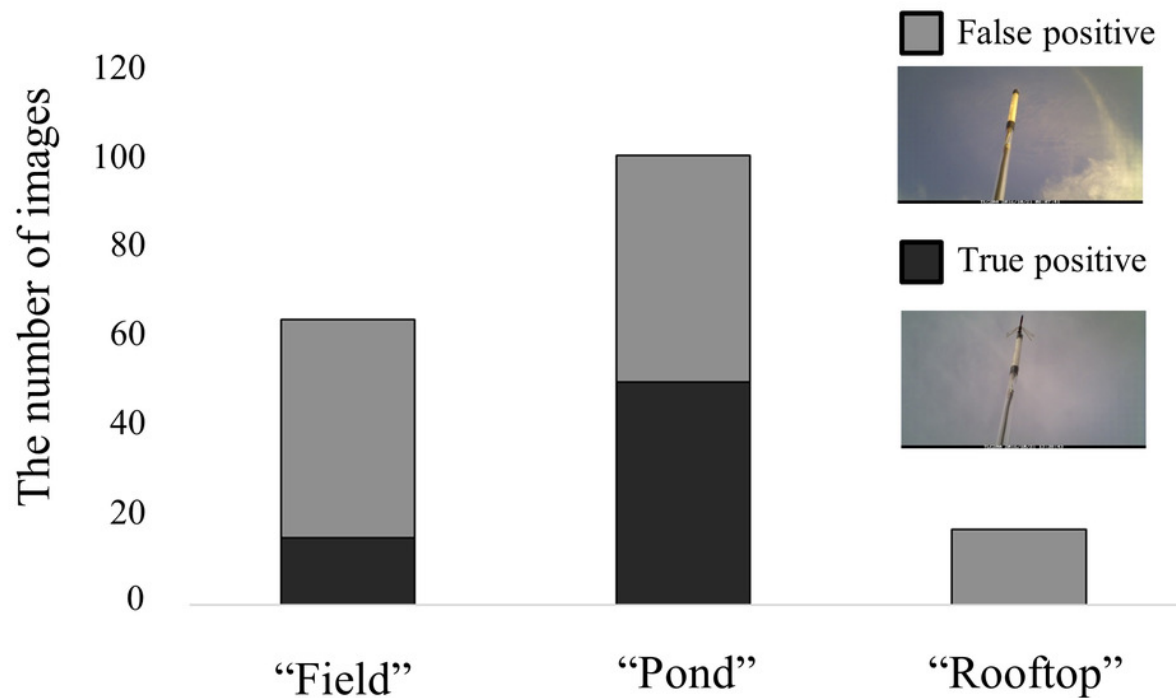
Figure 7

(A) Number of images of *Sympetrum* dragonflies detected by the camera trap at each site and (B) total frequency of *Sympetrum* dragonflies observed by the investigator at each site.

The "total frequency" corresponds to the total number of *Sympetrum* dragonflies observed during six times 10-min surveys. Bars with the same lowercase letters in each graph were not statistically different (A goodness-of-fit test was applied to each pair of sites). Note that the graph in (A) is same as the graph of true positives in Fig. 6.