

## ORIGINAL CONTRIBUTION

**Citizen monitoring of invasive species: wing morphometry as a tool for detection of alien *Tetropium* species**J. Goczał<sup>1</sup>, R. Rossa<sup>1</sup>, J. Sweeney<sup>2</sup> & A. Tofilski<sup>3</sup><sup>1</sup> Institute of Forest Ecosystem Protection, University of Agriculture in Krakow, Krakow, Poland<sup>2</sup> Natural Resources Canada, Canadian Forest Service, Fredericton, NB, Canada<sup>3</sup> Department of Pomology and Apiculture, University of Agriculture in Krakow, Krakow, Poland**Keywords**automated species identification, citizen science, invasive species, monitoring, operator effect, *Tetropium***Correspondence**

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**Abstract**

The increasing threat of alien wood-boring insect has resulted in the initiation of large-scale monitoring programmes. These programmes are most often based on pheromone-baited traps, which allow the early detection and monitoring of invasive species. This approach is expensive because it entails the processing and accurate identification of large numbers of specimens. One of the most often suggested solutions to this problem is citizen participation in the monitoring of invasive species. Such an approach has the potential for reducing costs as well as providing data from a larger number of sites. However, citizens vary in taxonomic expertise and experience which can result in identification errors. This may be particularly important in the case of wood borers which include many morphologically similar species. In this study, we develop and discuss a semi-automated method of identifying four morphologically similar and invasive *Tetropium* spp. wood borers as a potential tool for citizen-based monitoring programmes. Identification is based on wing measurements and requires neither specialist knowledge nor expensive equipment. The method correctly identified the species of *Tetropium* with an error ranging from 1.3% for *T. fuscum* to 7.5% for *T. cinnamopterum*. We found that experience level of the individual user was not essential for correct identification; on average, inexperienced volunteers correctly identified the *Tetropium* species in 93% of cases. Further development of this method may be a significant step to overcoming the taxonomical impediment to citizen monitoring of taxonomically challenging groups of insects.

**Introduction**

It is well known that the early and accurate detection of new infestations is a keystone of invasive species management (Darling and Blum 2007; Crawl et al. 2008; Vander Zanden et al. 2010). Early detection of an invasive species provides more opportunity to eradicate, contain or manage them before populations establish and reach high populations (Myers et al. 2000; Byers et al. 2002). However, infestations are often difficult to detect until populations have grown and started to cause noticeable damage (Mehta et al. 2007; Haight and Polasky 2010). Moreover, invaders

can arrive by various pathways and established populations may be dispersed over a large area. The number and accessibility of specialists that are able to monitor and reliably identify newly arrived alien species is limited. Consequently, intensive, long-term monitoring conducted by qualified specialists over a large area is a very expensive approach, which results in a shortage of comprehensive and up-to-date databases containing information about invasive species (Delaney et al. 2008).

A potential solution to this problem is citizen participation in the monitoring of invasive species (Fore et al. 2001; Delaney et al. 2008; Crall et al. 2010;

Dickinson et al. 2010; Newman et al. 2010; Starr et al. 2014). Such an approach provides an opportunity to collect large amounts of data from large areas and also allows the dispersal of organisms to be tracked. There are, however, researchers who emphasize the weaknesses of this solution (Crall et al. 2010). Citizen scientists vary in ability, experience and type of training, which may lead to errors or bias (Dickinson et al. 2010; Gardiner et al. 2012). This can be particularly important in taxa for which there are a limited number of specialists able to correctly identify the species. Overworked specialists often lack the time required to verify identifications made by less experienced colleagues. This problem is often called taxonomic impediment (Do et al. 1999; de Carvalho et al. 2007). There are several different approaches to overcome this problem. The solution proposed most often requires involvement and oversight by scientists or qualified phytosanitary technicians, although their numbers and available time are also limited. Therefore, special emphasis should be paid to methods of identifying invasive species that minimizes the need for taxonomic expertise and involvement of specialists and, at the same time, minimize the risk of error.

Wood-boring beetles (Coleoptera: Cerambycidae, Buprestidae) are a good example of a taxonomically challenging group with a high economic and ecological impact. In recent decades, the globalization of world trade has increased the threat of invasive wood-boring pests (Liebhold et al. 1995; Haack 2001; Hoebeke and Page 2002; Loope and Howarth 2002; Vanhanen 2008). Wood-boring beetles spend most of their lives inside wood or under the bark and thus are difficult to detect and control. Moreover, they are extremely resistant to adverse factors associated with intercontinental shipments. The scale of the problem is alarming. About 20% of all exotic beetles found in the United States are herbivores on trees or shrubs (Mattson et al. 1994), and 109 exotic phytophagous species are known to have successfully invaded and established on Europe's woody plants (Vanhanen 2008). Over 100 non-indigenous Scolytinae species originating from 59 countries were intercepted in various shipments between 1950 and 2000 in New Zealand (Brockerhoff et al. 2006a). Over 2500 adult insects, representing more than 40 species of bark beetles, woodborers, and their associated parasitoids, predators and scavengers, blue-stain fungi and nematodes, were recovered in 1998 by the Canadian Forest Service from log bolts that had been used to brace goods inside ships (Allen and Humble 2002).

Species with the highest invasive potential seem to be cambio- and xylophagous beetles that pupate in

the xylem. During their immature stages, these organisms can survive not only in unmanufactured wood but also in solid wood-packing materials, such as dunnage, pallets or crates. Several species from this group in the *Tetropium* genus are considered highly invasive. *Tetropium castaneum* (L., 1758) is present on the list of quarantine pests in the United States (USDA-APHIS 2008) and Canada (CFIA 2002). It has been intercepted several times in North America (CFIA 2002; Johnson et al. 2002) but is not known to be established. Another European species, *Tetropium fuscum* (FABR., 1787), has successfully established in Canada (Smith and Hurley 2000), where it infests *Picea rubens* Sarg., *P. glauca* (Moench) Voss and *P. mariana* (Mill.) B.S.P., and is considered a risk to mature spruce forests undergoing periods of stress or reduced growth rates due to drought, defoliator outbreaks or other factors (O'Leary et al. 2003). It should be noted that this pest was established in Canada at least 9 years before it was discovered because specimens of *T. fuscum* collected in Halifax, Nova Scotia, in 1990 were misidentified as the morphologically very similar native species *Tetropium cinnamopterum* Kirby, 1837; these specimens, housed in the Nova Scotia Museum of Natural History, were correctly identified in 1999 after *T. fuscum* had been discovered in Halifax (Smith and Hurley 2000). The third European species, *Tetropium gabrieli* WEISE, 1905, is also considered a pest that has successfully established populations and reproduced outside its native range (Lindelöw et al. 2015).

The main aim of this study was to develop a semi-automated method to identify four invasive *Tetropium* species. The identification was based on wing measurements and required neither specialist knowledge nor expensive equipment. We evaluate the effectiveness of this method, estimate an operator effect and discuss the method's application for the monitoring of invasive species.

## Materials and Methods

Three European species (*T. castaneum* [36♀, 39♂], *T. fuscum* [39♀, 36♂] and *T. gabrieli* [23♀, 25♂]) and one North-American species (*T. cinnamopterum* [32♀, 21♂]) were chosen because they meet the following criteria: they are highly invasive organisms (for more details see section 'Introduction', paragraph 4); they have been repeatedly intercepted outside their native range (CFIA 2002; Johnson et al. 2002); two of them have successfully established invasive populations outside their native range (Smith and Hurley 2000; Lindelöw et al. 2015); they are very similar morphologically, and their proper identification is possible

only by experienced taxonomists; they are classified as economically important pests in forestry (Kolk and Starzyk 1996; Evans et al. 2004); and they are vectors of some Ophiostomatoid fungi (Jacobs et al. 2003; Jankowiak and Kolařík 2010).

Specimens of *T. fuscum*, *T. castaneum* and *T. gabrieli* were randomly selected from the collection of forest pests at the Institute of Forest Ecosystem Protection, Faculty of Forestry, University of Agriculture in Krakow, Poland; they were collected in various years and locations in Poland and the Czech Republic. The specimens of *T. cinnamopterum* were collected in Nova Scotia (Canada) between 2006 and 2013.

### Measurements

Hind wings were detached from the body and mounted between two transparent microscopic slides (Video S1). During mounting, the wings were straightened using a drop of water and a preparation needle. All slides were scanned with a resolution of 4800 dpi using an Epson V330 Photo scanner. On all wing images, 17 landmarks (fig. 1) were determined manually using DrawWing software (Tofilski 2004).

### Statistical analyses

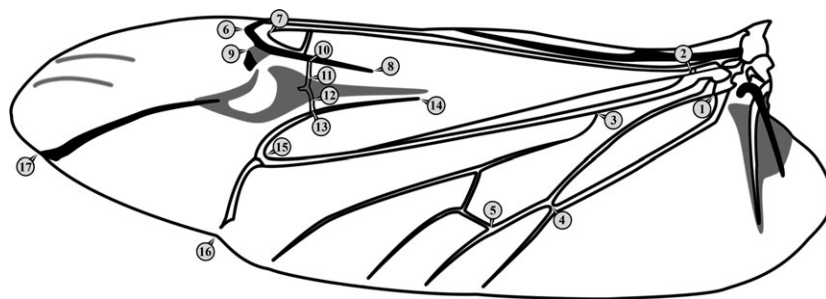
The coordinates of the landmarks were aligned using generalized orthogonal least-squares procedures (Rohlf and Slice 1990). Wing shape was described with 30 principal component scores obtained using MorphJ (v. 1.06a) (Klingenberg 2011). Wing size was expressed as a natural logarithm of centroid size. To analyse the differences in wing size between species and sexes of *Tetropium* beetles, we used two-factor analysis of variance (ANOVA), and to investigate the differences in wing shape, we used multivariate analysis of variance (MANOVA). Possible contrasts were tested for significance and confidence intervals by Scheffé's method. The Mahalanobis distance (MD) was used to

describe differences in wing shape. To detect any possible directional asymmetry, both left and right wings were measured in 189 individuals. In those cases, the average of the two sides was used in statistical analysis. The models of species identification were based on the canonical variate analysis (CVA) of wing shape using Statistica (10 v.) software (StatSoft 2011). The model was validated using the leave-one-out method (Jackknife method) in PAST 3.11 software (Hammer et al. 2001). The identification algorithm was exported to Identifly software (Przybyłowicz et al. 2015) which is freely available at [www.drawwing.org/identifly](http://www.drawwing.org/identifly).

### Estimation of equipment and operator effect

To determine the effects of different imaging devices on the identification of *Tetropium* spp., we obtained images of mounted wings from a verification sample of 38 individuals (*T. castaneum* 5♀, 5♂; *T. fuscum* 5♀, 5♂; *T. cinnamopterum* 6♀, 2♂; *T. gabrieli* 5♀, 5♂) using three devices: the aforementioned Epson scanner, a desktop scanner HP Scanjet 5590 (at resolution 4800 dpi) and stereomicroscope Delta Optical SZ-450T equipped with a Delta Optical DLT-Cam Pro 5MP camera. The camera was calibrated using scale graticule, and the resolution of the images was 3833 dpi. All other identification steps were performed by one of the authors (JG).

To estimate the variability among individual operators (or users), we invited volunteers who were interested in nature but had no previous training in entomology. Two stages of the identification procedure were tested: wing mounting and determination of landmarks. To estimate variation in wing shape caused by mounting, 38 specimens (one wing per specimen) were mounted by four different operators (JG and three volunteers). Each of the volunteers was trained on two *Tetropium* specimens before they mounted the wings from the test sample. Wings were unmounted immediately after each mounting and stored in water to allow remounting by subsequent



**Fig. 1** Schematic of landmarks positions on the hind wing of *Tetropium* (Coleoptera: Cerambycidae).

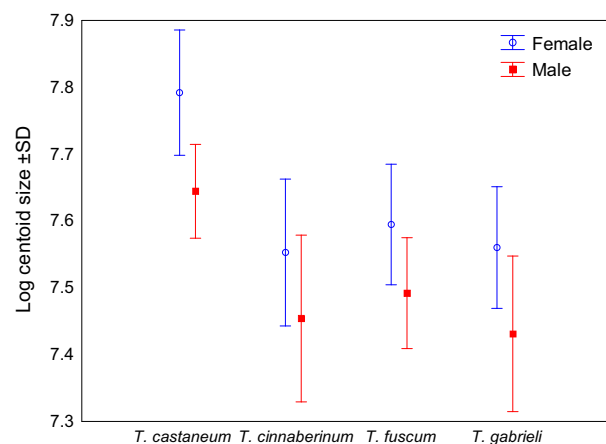
operators. All other identification steps, apart from mounting, were performed by one of the authors (JG) using Epson scanner.

To estimate variation in wing shape caused by variation among operators in landmark determination, each of the wings from the same 38 *Tetropium* specimens was measured by seven operators: two authors (JG and RR) and five volunteers. Prior to testing, volunteers watched a tutorial video describing the location of landmarks (Video S2) and were provided the scheme of wing landmarks (fig. 1) for reference. All other identification steps, apart from determination of landmarks, were performed by one of the authors (JG). Preparations were scanned using the Epson scanner. Additionally, to estimate variation within operators, one of the authors (JG) determined the landmarks three times on each of the images from the verification sample.

Errors made at different stages of identification could accumulate, therefore, in the last experiment; all steps of identification were made by four operators: one of the authors (JG) and three volunteers. Each of the specimens in the verification sample was analysed in this way. Each operator measured the sample, which had been previously mounted by himself.

## Results

The four species of *Tetropium* differed in wing size (ANOVA:  $F_{3, 243} = 78.49$ ,  $P < 0.0001$ ). *Tetropium castaneum* was markedly larger than the three other species (Scheffé's test:  $P < 0.0001$ , fig. 2), and *T. gabrieli* was significantly larger than *T. fuscum* (Scheffé's test:  $P < 0.0361$ , fig. 2). All other pairs of species did not



**Fig. 2** Logarithm of centroid size  $\pm$  SD of hind wings of four *Tetropium* (Coleoptera: Cerambycidae) species. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

differ in wing size (Scheffé's test:  $P > 0.3558$ ). In all species, females had larger wings than males (ANOVA:  $F_{1, 243} = 92.28$ ,  $P < 0.0001$ ) and the interaction between the factors species and sex was not significant (ANOVA:  $F_{3, 243} = 0.96$ ,  $P > 0.4117$ ).

There were significant differences in wing shape between the four *Tetropium* species (MANOVA: Wilks' lambda = 0.11,  $F_{90, 641} = 24.67$ ,  $P < 0.0001$ , fig. 3). Four separated clusters of points corresponding to the four study species can be observed in the plot based on canonical variate analysis (fig. 4). The first canonical variate allowed *T. castaneum* to be separated. The second canonical variate allowed *T. gabrieli* to be separated and the third *T. cinnamopterum* and *T. fuscum*. The largest MD was between *T. cinnamopterum* and *T. castaneum* and the smallest between *T. fuscum* and *T. cinnamopterum* (table 1).

The wing shape also differed between males and females (MANOVA: Wilks' lambda = 0.54,  $F_{30, 214} = 5.99$ ,  $P < 0.0001$ ). The identification of sex based on wing shape was less accurate than the identification of species. The percentage of correctly determined sexes (with cross-validation) was low and varied among species between 52.7% in *T. cinnamopterum* to 75.7% in *T. fuscum*; the average for all species was 69.0%.

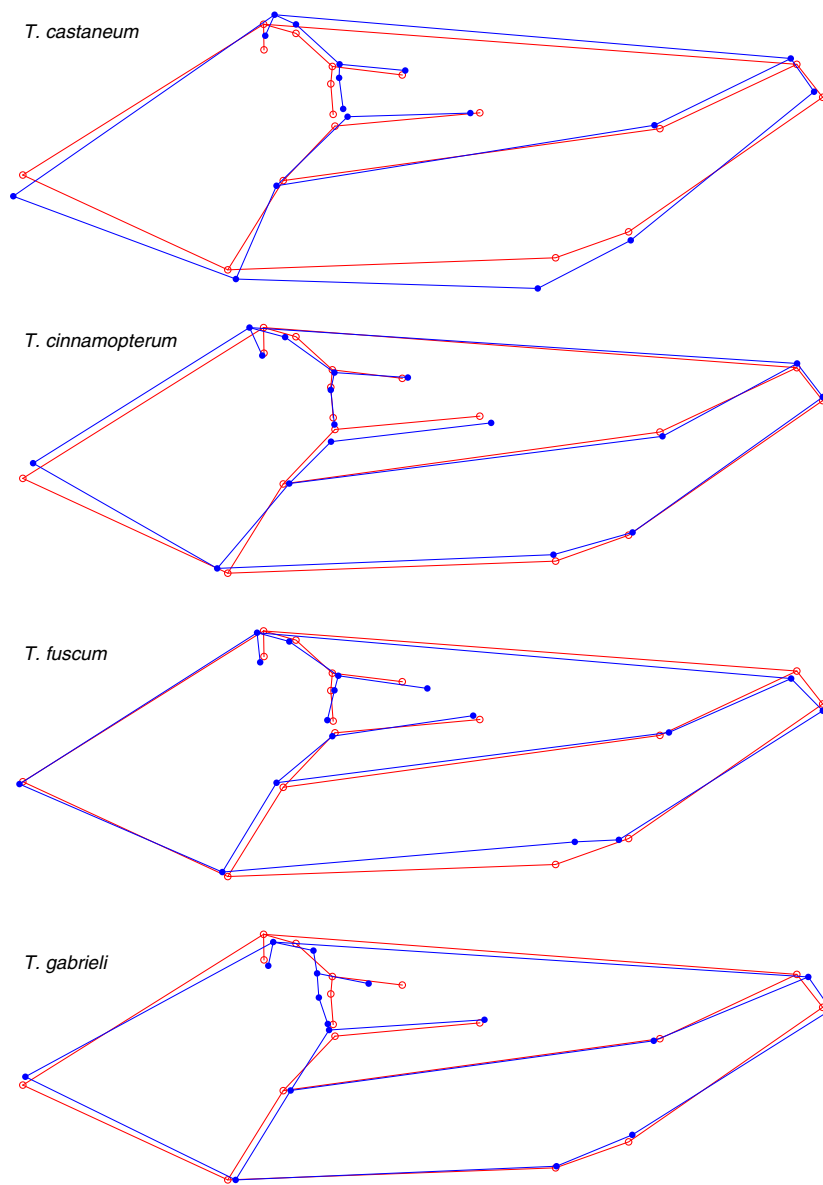
Wing shape did not differ significantly between left and right wings in any species (MANOVA: Wilks' lambda = 0.91,  $F_{30, 347} = 1.18$ ,  $P > 0.240$ ). MD between the two wing sides ranged from 0.91 in *T. fuscum* to 1.87 in *T. gabrieli*.

Accuracy of identification was the highest for *T. fuscum* at 98.7% and lowest for *T. cinnamopterum* at 92.5% (table 2). An average 95.6% of *Tetropium* specimens were correctly identified to species.

## Equipment and operator effect

### Image acquisition

There were significant differences in wing shape among images obtained from the three different devices (MANOVA: Wilks' lambda = 0.489,  $F_{60, 410} = 3.04$ ,  $P < 0.0001$ ). The largest MD (1.60) was between the stereomicroscope camera and the Epson scanner. The smallest MD (1.49) was between the two scanners. The differences were statistically significant between both scanners and camera (Scheffé's test:  $P < 0.0053$ ) but not between scanners (Scheffé's test:  $P > 0.6194$ ). However, in spite of the differences in wing shape obtained by the different devices, the success rate of species identification was similar for all three devices (table 3).



**Fig. 3** Differences in hind wing shape between four species of *Tetropium* (Coleoptera: Cerambycidae) (blue lines and filled circles) and average configuration (red lines and open circles). The differences in shape were exaggerated three times to make them more visible. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

### Preparation

There were also significant differences in shape among wings mounted by different operators (MANOVA: Wilks' lambda = 0.88,  $F_{90, 354} = 1.56$ ,  $P < 0.009$ ) with MD between operators ranging from 1.34 to 2.18. However, the correctness of the species identification was not significantly affected by the variation among operators in wing mounting (table 3).

### Landmark determination

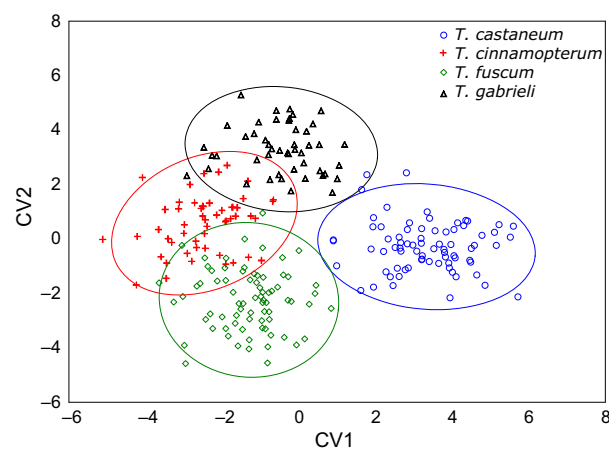
Wing shape did not differ significantly when the same operator (JG) determined the landmarks three times (MANOVA: Wilks' lambda = 0.74,  $F_{60, 176} = 0.48$ ,

$P < 0.899$ ) and MD between the replications ranged from 0.71 to 1.15. However, there were significant differences in wing shape between different operators who determined position of the landmarks (MANOVA: Wilks' lambda = 0.19,  $F_{180, 1447} = 2.62$ ,  $P < 0.0001$ ) and MD between the operators ranged from 1.41 to 3.10. Again, in spite of differences among operators in wing shape, the identification of species was not affected significantly (table 3).

### All identification steps

There were significant differences in wing shape when all measurement steps were performed by different operators (MANOVA: Wilks' lambda = 0.16,  $F_{90,$





**Fig. 4** Discrimination of four *Tetropium* (Coleoptera: Cerambycidae) species based on canonical variate analysis. Ellipses indicate 95% confidence intervals. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

$_{357} = 3.32$ ,  $P < 0.0001$ , fig. 5) and MD between operators ranged from 1.95 to 3.12. However, identification of species was not affected significantly by the operators who performed all measurement steps (table 3) and the identification accuracy rate was 99.1%, 97.4%, 99.1% and 96.1% for *T. castaneum*, *T. cinnamopterum*, *T. fuscum* and *T. gabrieli*, respectively.

## Discussion

Our results show that wing measurements allow reliable identification of four morphologically similar *Tetropium* species. The identification errors, which are

already relatively low, can probably be further reduced by increasing the sample size and number of landmarks. Most importantly, this method of species identification was implemented using free software (IdentiFly) and can be used by non-specialists, that is 'citizen scientists'.

Most national programmes for survey and detection of invasive bark and wood borers use traps baited with pheromones, for example New Zealand (Brockerhoff et al. 2006b), the United States (Rabaglia et al. 2008; USDA-APHIS 2011) and Canada (CFIA 2013). The Canadian Food Inspection Agency also incubates and rears insects from sections of trunks cut from trees that show signs of stress or insect infestation at sites at high risk of exotic wood borers, for example near ports or industrial parks in larger cities (Bullas-Appleton et al. 2014). These trapping surveys generate large numbers of captured specimens that need to be sorted and identified by taxonomists. It has already been demonstrated that traps baited with fuscumol, ethanol and a blend of spruce monoterpenes can be successfully used to monitor the invasive *T. fuscum* outside its native range (Sweeney et al. 2004, 2010); however, that lure combination also attracts the native *T. cinnamopterum* species (Silk et al. 2007; Sweeney et al. 2010). The method presented here could be used with citizen volunteers equipped with scanners (or digital cameras) and IdentiFly software to increase the number of sample points and total area sampled, at relatively low cost and reasonable accuracy.

Many recent studies have shown that cooperation with citizens increases the effectiveness of monitoring

**Table 1** Mahalanobis distances between four species of *Tetropium* (Coleoptera: Cerambycidae)

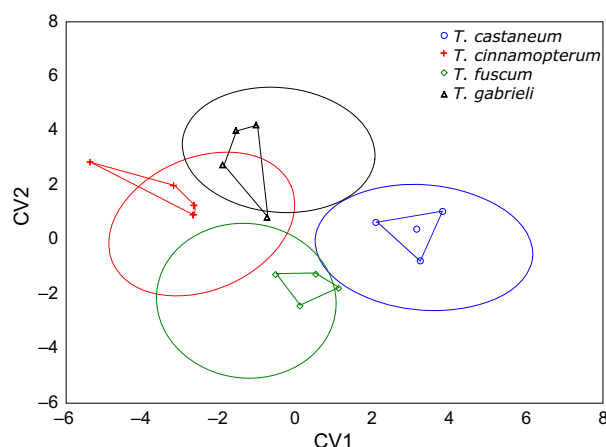
Species	<i>T. castaneum</i>	<i>T. cinnamopterum</i>	<i>T. fuscum</i>	<i>T. gabrieli</i>
<i>T. castaneum</i>	–	6.09	5.32	5.65
<i>T. cinnamopterum</i>	6.09	–	4.51	5.05
<i>T. fuscum</i>	5.32	4.51	–	5.63
<i>T. gabrieli</i>	5.65	5.05	5.63	–

**Table 2** Classification of *Tetropium* (Coleoptera: Cerambycidae) species based on hind wings measurements

Species	Correctly classified (%)	Classified as			
		<i>T. castaneum</i>	<i>T. cinnamopterum</i>	<i>T. fuscum</i>	<i>T. gabrieli</i>
<i>T. castaneum</i>	94.7	71	0	2	2
<i>T. cinnamopterum</i>	92.5	0	49	2	3
<i>T. fuscum</i>	98.7	0	1	74	0
<i>T. gabrieli</i>	95.8	1	1	0	46

**Table 3** Percent of correctly classified specimens of *Tetropium* (Coleoptera: Cerambycidae) when different operators conducted various identification steps or when images were obtained using different devices

Identification step	Operator or device	Correctly classified (%)
Image acquisition	Microscope	94.7
	Scanner HP	97.4
	Scanner Epson	94.7
Preparation	Author (JG)	100.0
	Volunteer 1	100.0
	Volunteer 2	97.4
	Volunteer 3	100.0
Landmark determination	Author (JG)	94.7
	Author (RR)	100.0
	Volunteer 1	100.0
	Volunteer 2	92.1
	Volunteer 3	100.0
	Volunteer 4	97.4
All identification steps	Volunteer 5	94.7
	Author (JG)	97.4
	Volunteer 1	94.7
	Volunteer 2	89.5
	Volunteer 3	94.7

**Fig. 5** Variation of canonical scores when the same specimen of *Tetropium* (Coleoptera: Cerambycidae) was identified by four different operators. Each specimen is represented by a convex hull. Ellipses indicate 95% confidence intervals of the sample used for estimation of identification model. Only one specimen from each species was shown to improve clarity. [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

invasive species (for a review see Dickinson et al. 2010). It should be noted that monitoring programmes based on cooperation with citizens also have several additional benefits, such as reducing costs, increasing the participants' knowledge, helping researchers to identify possible modes of transmission and providing information from private property,

which may not have been accessible to professional scientists previously (Trumbull et al. 2000; Danielsen et al. 2005; Lepczyk 2005; Gallo and Waitt 2011; Crall et al. 2013). On the other hand, it has been shown that the effectiveness of citizen monitoring declines rapidly when the taxonomical difficulty of a monitored group increases (Starr et al. 2014).

In general, there are two main strategies to overcome this problem. In the first approach, called 'working with parataxonomists', citizens do not identify species. Their work is limited to collecting samples in the field (Basset et al. 2004; Sheil and Lawrence 2004), sorting specimens to recognizable taxonomic units and sending them to experienced taxonomists who then identify the species. In the second approach, citizens perform all of the monitoring steps themselves: they collect specimens, identify them and send the data to a database. This approach minimizes the involvement of scientists and highly trained personnel, but carries a greater risk of error or bias in the data. This risk can be reduced by correct training of volunteers. Despite the development of modern, more effective training methods, this approach takes time and its results depend on the attitude of students and complexity of problem.

There is, however, an third alternative to the first two approaches called 'automated species identification', which includes different methods including image analysis (Gaston and O'Neill 2004) and DNA-based approaches (Armstrong and Ball 2005; Darling and Blum 2007). In this case, species identification is carried out automatically, and the user receives information about the name of the species after the analysis. Species identification based on molecular markers is currently considered to be one of most reliable methods, but its costs may still be prohibitive. For example, taxonomic analysis using current DNA bar-coding approaches (Sanger sequencing method) may cost between 1.7 and 3.4 times more than traditional morphology-based approaches (Stein et al. 2014). Apart from the higher costs, molecular methods require sophisticated equipment that is unavailable to citizen scientists.

Automated species identification based on image analysis is much more accessible to the average person. It requires only three simple steps to successfully identify a *Tetropium* specimen. First, the hind wing hidden under the elytra should be carefully dissected from the body and straightened on a microscopic slide (for more details, see Video S1). Dry specimens should be placed in warm water for about 4 h to make the wings more flexible prior to dissection. The image of the wing can be simply captured by placing the

microscope slide directly on a desktop scanner or using a digital camera with the proper macro lens (see below). Finally, 17 landmarks (fig. 1) on the image of the hind wing are identified using a mouse and clicking on the wing image using IdentiFly software (Video S2). Species identification is automatic, and the software determines the probability that the specimen belongs to each of the four *Tetropium* species. Specimens identified with a probability lower than 0.001 should be classified as suspect and verified by an experienced entomologist. Such results may be caused by an error in measurement (e.g. damaged wing or improper landmark determination) or could indicate a species not included in the classification model (e.g. other longhorn beetle). Each identification is documented with the associated wing image and can be stored for subsequent verification if necessary. Specimens identified as native species would not raise a flag but any specimen identified as a possible exotic invasive species, for example *T. gabrieli* in Canada or *T. cinnamopterum* in Europe, could be sent to specialists by post for verification. In this way, the number of specimens requiring examination by entomologists would be greatly reduced, along with costs.

The equipment required for image acquisition is accessible to many citizen scientists in North America and Europe. Wing images can be obtained using various methods including scanner, microscope equipped with camera or digital camera equipped with a macro lens. In all cases, the wing should be illuminated with transmitted light. Our results showed that a microscope equipped with a camera as well as different desktop scanners may be used to obtain images of *Tetropium* wing preparations. However, a scanner is probably the best option for citizen scientists because it is easy to use and scale information can be obtained from its resolution. Moreover, the optical distortions of a scanner should be smaller than most other optical systems. Even a relatively inexpensive office scanner can be used, provided it is equipped with a slide adapter which is normally used for scanning diapositives. It is less likely that wing images can be obtained using a smartphone or hand camera because their optical distortions are higher and it is difficult to position them precisely in relation to the wing.

The semi-automated identification of *Tetropium* species can be affected by various factors, including the experience and motivation of the individual operator. We found that the largest source of variation among operators was the determination of landmarks. Different operators tended to place the landmarks on different places; however, the differences were smaller than

those between species and did not significantly affect species identification. A much smaller source of variation was preparation of the wings. Some operators did not take enough care to properly stretch the wings, and those specimens were usually misclassified. Furthermore, it should be noted that multiplication of errors made at different stages of analysis may finally generate relatively high level of errors in the identification. We found that operator motivation rather than entomological experience affects identification accuracy. Some specimens measured by volunteers for the first time were identified with higher accuracy than samples described by one of the authors (JG).

Both the left and the right wings can be used for identification as they do not differ in shape of venation. It is recommended to measure both wings in order to minimize measurement error. Higher accuracy can be also achieved by repeated determination of landmarks on the same wing.

In conclusion, we present an accurate method of distinguishing species of *Tetropium* spp. that is fast, relatively inexpensive and that can be performed by average citizens with little or no training in entomology. It does not require specialized laboratory equipment or specific taxonomical knowledge. All that is required is a genuine interest in citizen science and a lack of squeamishness with regard to insects; that is, participants must be willing to handle dead insects and carefully detach hind wings. Moreover, the semi-automated identification of species can be considered a method of training volunteers. They can compare specimens classified as different species and learn to recognize characters that were traditionally used for identification. Currently our method allows reliable identification of four *Tetropium* species, but in the future, IdentiFly software may be updated to identify a greater number of species. Therefore, we suggest that the development of this method may be a significant step in overcoming the taxonomical impediment issue in citizen monitoring of taxonomically challenging groups, including invasive species.

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### Supporting Information

Additional Supporting Information may be found in the online version of this article:

**Video S1.** Dissection and preparation of *Tetropium* wing.

**Video S2.** Semi-automated identification of *Tetropium* using IdentiFly software.