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Citizen science to monitor the establishment and spread of a biological control agent: the case of *Pareuchaetes pseudoinsulata* (Lepidoptera, Erebidae) for the control of *Chromolaena odorata* (Asteraceae) in South and South-East Asia

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Abstract

Pareuchaetes pseudoinsulata Rego Barros (Lepidoptera, Erebidae) has been deliberately released in six countries in South and South-East Asia as a biological control agent for *Chromolaena odorata* (L.) R.M. King & H. Rob. (Asteraceae). To date, the scientific literature has records of establishment in only four of these countries: India, Indonesia, Malaysia and Sri Lanka. Georeferenced and dated images shared by citizen scientists on the iNaturalist.org platform were used to assess the establishment and spread of *P. pseudoinsulata*. Adding to our existing knowledge, it was found that *P. pseudoinsulata* is established in Thailand and Vietnam and has spread to China (Yunnan and Hainan provinces), Cambodia and West Malaysia (Penang). We discuss the value of using citizen science to track the establishment and spread of weed biological control agents, using *P. pseudoinsulata* as an example.

Keywords Ground-truthing, Identification, iNaturalist, Monitoring, Weed biological control

Background

In a broad sense, citizen science is the involvement of the public in scientific research—whether community-driven research or global investigations (CSA 2023). Public participation in scientific research may be directed towards the collection and analysis of data designed and led 'top down' by scientists to address specific questions, or it may be based on a 'bottom up' stand-alone citizen scientist activity generating and sharing scientific information based on their own interests, opportunities, and motivation, in the belief that this is a worthwhile activity in its own right, and will be valuable to scientists and other professionals for addressing research and data questions in the future.

There are now many examples of citizen science contributing to our knowledge of the natural world (e.g. National Geographic 2023). Equally, citizen science is already being used in addressing food and agriculture research (Ryan et al. 2018), to monitor the incidence of pest outbreaks (de Groot et al. 2023), and to document the introduction and spread of invasive alien species (Hulbert et al. 2023). The potential for monitoring the

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spread of pests is clear. However, we are not aware of any publications using this approach to monitor biological control agents that have been deliberately introduced or spread from neighbouring areas.

Here we consider one example of citizen science based on the observation-sharing platform iNaturalist (2023). iNaturalist describes itself as 'an online social network of people sharing biodiversity information to help each other learn about nature' and 'a crowd-sourced species identification system and an organism occurrence recording tool'. Observers upload georeferenced images with date and time, to which they or identifiers can add identifications using an iNaturalist nomenclature based on standard online lists of species. There are currently over 175 million observations from all over the world. Observers are not necessarily targeting particular species, although this could easily be organised, but rather they post observations of their own choice, which may be selected taxonomic groups, species from a particular location, species showing a particular behaviour (e.g. pollinators), etc.

Chromolaena odorata (L.) R.M. King & H. Rob. (Asteraceae) is a weedy pioneering shrub native to the Americas, from southern USA to Argentina, that has become one of the worst invasive plants in the Old World humid tropics and subtropics (Holm et al. 1977, Gautier 1992). In a survey of national perceptions of weeds (Waterhouse 1993), the Directors of Agriculture for Malaysia and the Philippines considered *C. odorata* to be 'very widespread and very important', while those for Myanmar, Thailand, Laos, Cambodia, Vietnam and Indonesia considered it 'widespread and important'. The scope for using classical biological control to manage *C. odorata* has been investigated since the 1960s (Zachariades et al. 2009). Since then, 13 insect biological control agent species have been introduced into 19 Old World countries or territories (Winston et al. 2023), and their combined impact is now reducing the weediness of *C. odorata* in parts of the invaded Old World (Zachariades et al. 2009; Winston et al. 2023). The first biological control agent to be studied and released was an erebid moth *Pareuchaetes pseudoinsulata* Rego Barros (Arctiinae, Arctiini, Phaegopterina) (Fig. 1), which in the 1960s was misidentified as *Ammalo arravaca* (Jordan) and in the 1970s as *A. insulata* (Walker) (Cock and Holloway 1982). The genus *Pareuchaetes* is naturally restricted to the Americas, and the several similar, plain yellow species can only be reliably separated by dissection and examination of their male genitalia (Cock and Holloway 1982; Espinoza et al. 2017). However, the several known *Pareuchaetes* species appear to be allopatric, and so in many cases they can be safely allocated to species based on their distribution; e.g. *P. pseudoinsulata* is restricted to northern South America, including Trinidad, whereas *P. insulata* occurs in the Greater Antilles, Central America and southern USA (Cock and Holloway 1982).

Pareuchaetes pseudoinsulata was released in Africa, South and South-East Asia and parts of the Pacific, and became established in parts of these three areas (Winston et al. 2023). More recently, *P. insulata* and *P. aurata* (Butler) were released in southern Africa where the former is established (Winston et al. 2023). For several releases of *P. pseudoinsulata*, the agent was reported not to have established (e.g. Thailand and Vietnam), or there have been no published follow-up studies to assess whether or not introductions were successful. However, there have been anecdotal reports of the moth being present in various countries in South and South-East Asia that have not been reported in the literature. This paper investigates the validity of some of these reports and also discusses

Fig. 1 Adult and caterpillar of *Pareuchaetes pseudoinsulata*. Adult, Thailand, Tak Province, 16 March 2023, dave_sargeant, iNaturalist observation 155,619,887; © dave_sargeant, under CC BY-NC. Caterpillar, India, Tamil Nadu, Salem, Elavarasan M, iNaturalist observation 75731899; © Elavarasan M, under CC BY-NC

the value of using citizen science to monitor the establishment and spread of weed biological control agents.

Methods

Observations posted on iNaturalist can be filtered by species and location. To locate records of *P. pseudoinsulata*, this approach is dependent on iNaturalist identifiers having already recognised the genus. Where this is not the case, observations may be misidentified, unidentified, or identified to a higher taxonomic level, i.e. Arctiinae, Erebidae, Noctuoidea or Lepidoptera. To check for such partially identified material for specific countries or areas, we reviewed all observations categorised by iNaturalist as 'Needs ID'at selected higher taxonomic levels, chosen to try and keep the number of observations to review manageable: 2,271 Erebidae from Vietnam, 4,627 Noctuoidea from East Malaysia, and 766 Lepidoptera from Brunei. Based on the very small number of partially identified observations located by this approach, we considered it unnecessary to review all unidentified material for all countries. Correct identifications were added on iNaturalist for the partially identified observations of *Pareuchaetes* spp. found, and misidentifications of *Pareuchaetes* were downgraded.

In April 2023, observations on iNaturalist were filtered for records of *Pareuchaetes* spp. in all countries or regions where the moth has been released (Table 1), as well as neighbouring countries. All records were checked and identifications corrected or confirmed where necessary. The total accepted results were tabulated and mapped against the known release areas using Esri ArcGIS Online, and resultant figure edited in Adobe Photoshop.

Results

Seven, 300 and four *Pareuchaetes* spp. observations in Africa, South and South East Asia, and the Pacific respectively were retrieved from the iNaturalist database. Filtering iNaturalist observations from selected areas to review all Arctiinae or all Noctuoidea yielded very few observations of *P. pseudoinsulata* that had not already been identified to genus: 2 out of 2,271 Erebidae from Vietnam, 0 out of 4,627 Noctuoidea from East Malaysia, and 0 out of 766 Lepidoptera from Brunei. On the other hand, there were a small number (not recorded) of observations misidentified as *Pareuchaetes* in several countries, which we corrected.

The number of observations of *Pareuchaetes* in Africa and the Pacific was relatively small (11 in total) and do

Table 1 Documented releases, establishment and iNaturalist observations of *Pareuchaetes pseudoinsulata* in South and South-East Asia

Release country and dates of release (Winston et al. 2023)	Reported result (Winston et al. 2023 and references therein)	iNaturalist *Pareuchaetes* observations/total Lepidoptera observations = percentage	Implications of iNaturalist observations (regions)
Countries with deliberate releases			
India, 1973, 1984	Established	163/448,347 = 0.04%	Establishment confirmed (Andhra Pradesh, Karnataka, Kerala, Tamil Nadu)
Indonesia, 1992	Established in Sumatra, East Kalimantan and South Sulawesi; not established in Java, West Timor where released	0/58,823	Establishment not confirmed
Malaysia, 1970	East Malaysia (Sabah): established West Malaysia: not released, not present	East: 0/26,144 West: 3/181,920 ≤ 0.01%	East Malaysia: establishment not confirmed West Malaysia: presence demonstrated in Penang
Sri Lanka, 1973	Established	22/17,768 = 0.12%	Establishment confirmed (widespread)
Thailand, 1987, 2006	Not established	72/88,942 = 0.08%	Establishment demonstrated (widespread)
Vietnam, 1988	Not established	3/15,181 = 0.02%	Establishment demonstrated (Ho Chi Min City, Haiphong)
Countries with no official releases			
Brunei	No releases; established	0/1,207	Presence not confirmed
Cambodia	No releases	1/12,876 = 0.01%	Presence demonstrated (Koh Kong)
China	No releases	6/83,780 ≤ 0.01%	Presence demonstrated (Yunnan, Hainan provinces)
Philippines	No releases; present on Palawan, Mindanao, Bohol and Leyte islands	9/23,880 = 0.04%	Presence confirmed (Cebu and Leyte islands in Visayas, Mindanao island)

not add to our knowledge of reported establishments, so we do not document these here, but rather concentrate on South and South-East Asia where the results are more robust and add to our knowledge of the moth's distribution. The published information on releases and establishment of *P. pseudoinsulata* in South and South-East Asia are summarised in Table 1 and Fig. 2, together with an overview of the observations on iNaturalist.

Discussion

The results extracted from the observations shared by citizen scientists on iNaturalist add to our knowledge of the establishment and distribution of the introduced biological control agent *P. pseudoinsulata*. In addition, the widespread establishment of *P. pseudoinsulata* in southern India and Sri Lanka is confirmed (Table 1, Fig. 2).

Pareuchaetes pseudoinsulata was released in Thailand in 1987 at six locations in the northern highland areas of Chiang Mai and Chiang Rai provinces and at four locations at Khao Yai National Park (Nakhon Ratchasima and Prachinburi provinces) in the central region, and further releases were made in 2006. These were reported in the literature as having failed to establish (Napompeth et al. 1988, Napompeth and Winotai 1991, Kernasa et al. 2013, Winston et al. 2023). Nevertheless, 72 iNaturalist observations indicate that *P. pseudoinsulata* is established and widespread in Thailand. We believe this represents establishment that was overlooked, rather than spread from an area where establishment was confirmed, such as Sumatra, India or Sri Lanka. An observation from Cambodia (Koh Kong), close to the border with Thailand, suggests that *P. pseudoinsulata* has spread eastwards. Similarly, observations from Yunnan province, southern China, indicate that the moth has apparently spread northwards into that country. There were no identified observations of *P. pseudoinsulata* from the other surrounding countries of Myanmar or Laos, despite numerous observations of Lepidoptera from both. However, it is quite likely that *P. pseudoinsulata* has spread to both. Similarly, releases in Vietnam (no locations reported) in 1988 were considered to have failed (Winston et al. 2023), but iNaturalist observations from Ho Chi Min City in the south and Haiphong in the north suggest that either these releases were successful, or the population established in Thailand has also spread to Vietnam. Observations from Hainan Island, China, are closest to the observation at Haiphong and may represent spread from Vietnam or a separate introduction of unknown origin.

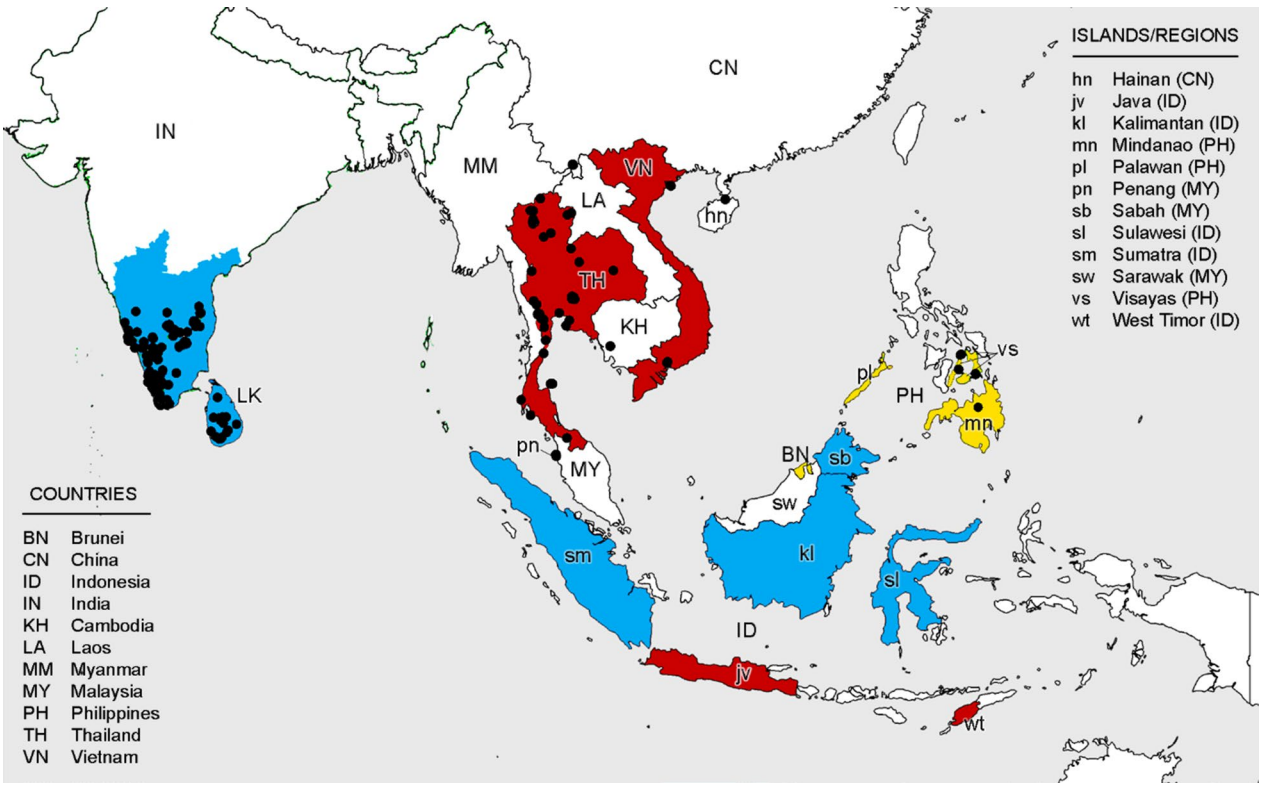

Fig. 2 *Pareuchaetes pseudoinsulata* in South and South-East Asia. *Pareuchaetes pseudoinsulata* release areas with reported successful establishment (blue), release areas with reported failed establishment (red) and areas with reported establishment without intentional releases (yellow) are shown (Table 1). Black points indicate iNaturalist observations of *P. pseudoinsulata* until 30 May 2023. For observation data see Additional file 1

The results from Malaysia were somewhat surprising. Although releases conducted at four sites in Sabah (East Malaysia) were considered to have led to establishment (Syed 1979, Ooi et al. 1988), we found no records of this species from East Malaysia on iNaturalist, even when over 4,000 observations identified as Noctuoidea were screened. Similarly, there were no iNaturalist observations from Brunei or from Kalimantan (Indonesian Borneo), Sumatra or Sulawesi in Indonesia where the scientific literature indicates the moth had established (Chenon et al. 2002; Winston et al. 2023). It seems likely that *P. pseudoinsulata* remains present at a low density, such that it has not been documented by iNaturalist observers. However, it is also possible, albeit unlikely, that the populations have died out and gone locally extinct. There have been no releases of *P. pseudoinsulata* in Western Malaysia, and no previous reports of its presence, but we found iNaturalist observations from Penang Island. We suggest this probably represents spread from southern Thailand or northern Indonesia (Sumatra), and that in future, *P. pseudoinsulata* will also be found on the peninsula of Western Malaysia.

Pareuchaetes pseudoinsulata was reported from Palawan, Philippines in 1985, and it was assumed this represented natural spread from the nearby island of Borneo (Aterrado and Talatala-Sanico 1988; Aterrado and Bachiller 2002). Subsequent surveys found this species in Zamboango City (eastern Mindanao Island) and Bohol and Leyte islands in the Visayas (Aterrado and Talatala-Sanico 1988). iNaturalist observations from northern Mindanao, Leyte and Cebu Island (Visayas, adjacent to Bohol) indicate these populations have persisted and spread.

iNaturalist observations provide evidence of the presence of *P. pseudoinsulata* in several countries, in some cases where not previously reported. The absence of records from areas where *P. pseudoinsulata* has been reported as established is not evidence of absence, and may reflect scarcity or simply the small total number of observations; e.g. only slightly more than 1,000 observations of Lepidoptera in total have been reported from Brunei. Equally, these observations cannot provide evidence regarding impact on *C. odorata*.

Our analysis was only practical because iNaturalist identifiers had already identified almost all of the observations that we examined. In that sense, these are not new records, but rather records that had not entered the biological control literature. We have only superficially considered to what extent there may be records of *Pareuchaetes* in iNaturalist that are unidentified. Images of larvae were identified based on their appearance, as rarely was the food plant documented or identified. It would be good practice for observers posting images of herbivorous larvae on iNaturalist to also document and link observations of the food plant.

As a tool for monitoring other classical biological control agents, the images on iNaturalist are only likely to be useful in situations where the agent can be accurately identified from an image. There are few of these that are sufficiently distinct that they can be reliably differentiated from similar or related species. In one such example, *Actinote* spp. (Nymphalidae) were released and established in Indonesia for the control of *C. odorata* (Winston et al. 2023). Adults and caterpillars are distinctive, and there are recent images of *A. anteas* (Doubleday) from Sumatra on iNaturalist. However, images of other biological control agents released for *C. odorata* (families Agromyzidae, Brentidae, Buprestidae, Curculionidae, Pyralidae, Tephritidae) (Winston et al. 2023) are not so easily recognised. This is not to suggest that citizen science by image sharing cannot be useful for these species, but it will need to be organised in a more targeted way so that naturalists are looking for particular species in particular situations and taking images designed to facilitate recognition of individual targeted biological control agents.

Conclusions

The images shared by citizen scientists on iNaturalist confirm the presence of *P. pseudoinsulata* in several areas, including some where it had not been previously reported. Areas where it has been reported as established but there were no images to confirm this indicate opportunities for a more targeted citizen science project or some other form of on-the-ground truthing involving biological control researchers. We conclude that iNaturalist can provide an additional source of information regarding the incidence and spread of introduced species, including biological control agents, but will be most effective where the subjects are readily identifiable from photographs. There is the added constraint that if an introduced species is not known to the community, it will not be identified to genus or species, and it will be necessary to search all relevant images at a higher taxonomic level such as subfamily, family or superfamily, which can be very time consuming. These factors are likely to limit the usefulness of this approach for many small, hidden species, unless a targeted campaign is organised.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43170-023-00171-5.

Additional file 1. Geographical data for Fig. 2. This spreadsheet includes details and geographical data for observations of *Pareuchaetes pseudoinsulata* in South and South-East Asia, downloaded from iNaturalist for Fig. 2.

This includes all observations made until the end of May 2023, and posted and identified as *Pareuchaetes* sp. or *P. pseudoinsulata* by 7 June 2023. Observations 'needing ID' or identified as *Pareuchaetes* sp. were confirmed as *P. pseudoinsulata* by the authors.

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Author contributions
MJWC conceived the study, analysed the iNaturalist observations and cowrote the paper. MDD collated information on previous research and co-wrote the paper. RLW also collated information on previous research, and contributed substantially to the editing and finalisation of the paper, including the figure. All authors read and approved the final manuscript.

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All data generated or analysed during this study are included in this published article and its supplementary information file.

Declarations

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The authors declare that they have no competing interests.

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