

## Effects of different weeding methods on the diversity of ground-dwelling organisms in organic tea gardens

Gorachad Goshami<sup>1</sup>, Kunwar Ishwor Jung<sup>2</sup>, Iwase Yuiko<sup>2</sup>, Inagaki Hidehiro<sup>2</sup>

<sup>1</sup> Faculty of Agriculture, United Graduate School of Agricultural Science, Gifu University, Japan

<sup>2</sup> Faculty of Agriculture, Graduate School of Science and Technology, Shizuoka University, Japan

### Abstract

Ground-dwelling organisms include natural enemies and predators that play major roles in the biological control of pests in crop fields. The conservation of ground-dwelling organisms in agricultural fields is, therefore, essential for functional biodiversity. Weed vegetation plays a vital role in maintaining the diversity of ground-dwelling organisms. This study aimed to investigate the effects of three weeding methods on the diversity of ground-dwelling organisms in an organic tea garden. Ground-dwelling organisms were investigated using pitfall traps in organic tea fields and three different weeding methods—frequency weeding, extensive weeding, and mechanical weeding. It was found that mechanical weeding increased the number of ground-dwelling spiders which are important natural enemies in agricultural ecosystems, compared with other weeding systems in the early summer season.

**Keywords:** Weed vegetation, weeding systems, organic tea gardens, ground-dwelling organisms, functional biodiversity

### Introduction

Tea (*Camellia sinensis*) is an economically important crop. Its production is increasing rapidly with the global high demand for organic tea (FAO 2014; Ministry of Agriculture, Forestry and Fisheries 2020 [28]; Nikhil 2017) [32]; therefore, the introduction of new techniques and the development of existing ones have become essential in organic tea farming (Lin 2016) [27]. Tea cultivation has been modernised and consolidated through the use of various machines and chemicals in Japan. However, in recent years, attempts have been made to convert conventional farming to organic methods to meet the demands of the global organic tea market (Inagaki and Iwase 2024) [21].

Although the demand for organic tea production is growing in Japan (Beveridge and Naylor, 1999 [4]; Yoshitaka and Kohsaka, 2022) [50], weed control remains the biggest obstacle to the expansion of organic tea production (Ichihara *et al.*, 2022b; Inagaki and Iwase, 2024) [21]. Inagaki and Iwase (2024) identified three successful weed management strategies employed by farmers in advanced organic tea cultivation areas: frequency weeding, extensive weeding, and mechanical weeding. Frequency weeding, the method used by most successful organic farmers, involves regularly removing small weed seedlings. Although effective in reducing weeds, this method still requires considerable effort. However, some farmers opt for extensive weeding, which focuses on removing only larger weeds to save labour. Mechanical weeding is a new method being tested by enterprising farmers. In contrast to the Japanese traditional practice of maintaining narrow furrows of tea plants to prevent weed growth, mechanical weeding involves widening the furrows and managing the weeds with a mower. Inagaki and Iwase (2024) [21] reported what kind of weed vegetation these three weed-control management methods induce.

On the other hands weed vegetation boosts the diversity of ground-dwelling organisms in crop fields and orchards (Shelton and Edwards, 1983 [41]; Iddris *et al.*, 2023; Kleiman

and Koptur, 2023) [25]. These ground-dwelling organisms, including predators and natural enemies, are crucial for sustaining functional biodiversity on agricultural land and controlling pests (Talukdar, 2021) [45]. Maintaining this functional biodiversity is crucial for providing agroecosystem services in organic agriculture (Rotchés-Ribalta *et al.*, 2023 [40]; Bàrberi, 2015) [3]. Additionally, cover crops are important for increasing the populations of natural enemies of pests and predators in tea gardens (Pokharel *et al.*, 2023 [37]; Chen *et al.*, 2021) [6]. We anticipate that controlling cover crops using three weed-control management methods classified by Inagaki and Iwase (2024) [21] may also affect the diversity of ground-dwelling functional organisms. In addition, mechanical weeding has been found to be the best method for maintaining good cover crops in organic tea gardens (Inagaki and Iwase 2024) [21]. We hypothesised that mechanical weeding also facilitates the growth of ground-dwelling organisms.

However, studies on the functional biodiversity of Japanese tea gardens containing ground-dwelling species are limited. Therefore, in this study, we investigated the effects of cover crops managed using various weeding techniques on the diversity of ground-dwelling organisms in organic tea fields.

### Material and methods

#### Research field

The current investigation involved sampling and analysing five fields from three farmers. The fields selected were in the Setoya area, located in Fujieda City, Shizuoka Prefecture, Japan. Three mature (production type) and two nursery (young type) tea gardens owned by three farmers using different weed-control methods were selected. The weed management methods followed were (i) frequency, where the weeds were removed thoroughly; (ii) extensive, which involved the removal of large weeds; and (iii) mechanical, using mowing machines with wide furrows used for weeding.

**Weed vegetation**

For the vegetation survey, three quadrats (0.5 m × 0.5 m) were installed between the three furrows. The coverage and maximum plant height of each grass species within the quadrats were investigated on 24 July and 27 September, 2023. The coverage was determined based on Penfound’s cover class. Harmful and non-harmful weeds were distinguished based on the work of Inagaki and Iwase (2024) [21].

**Pitfall trap**

For the sampling of ground-dwelling organisms, six pitfall traps 8.1 cm (height) × 7.3 cm (diameter) were positioned in each field and filled with 100 ml of 70% ethanol to exterminate and preserve the captured insects. Pitfalls were collected after two days. Weed vegetation surveys and pitfall placements were conducted on 24 July and 27 September, 2023.

**Identification**

Collected organisms were identified based on their feeding habitat and ecological indication status.

**Data analysis**

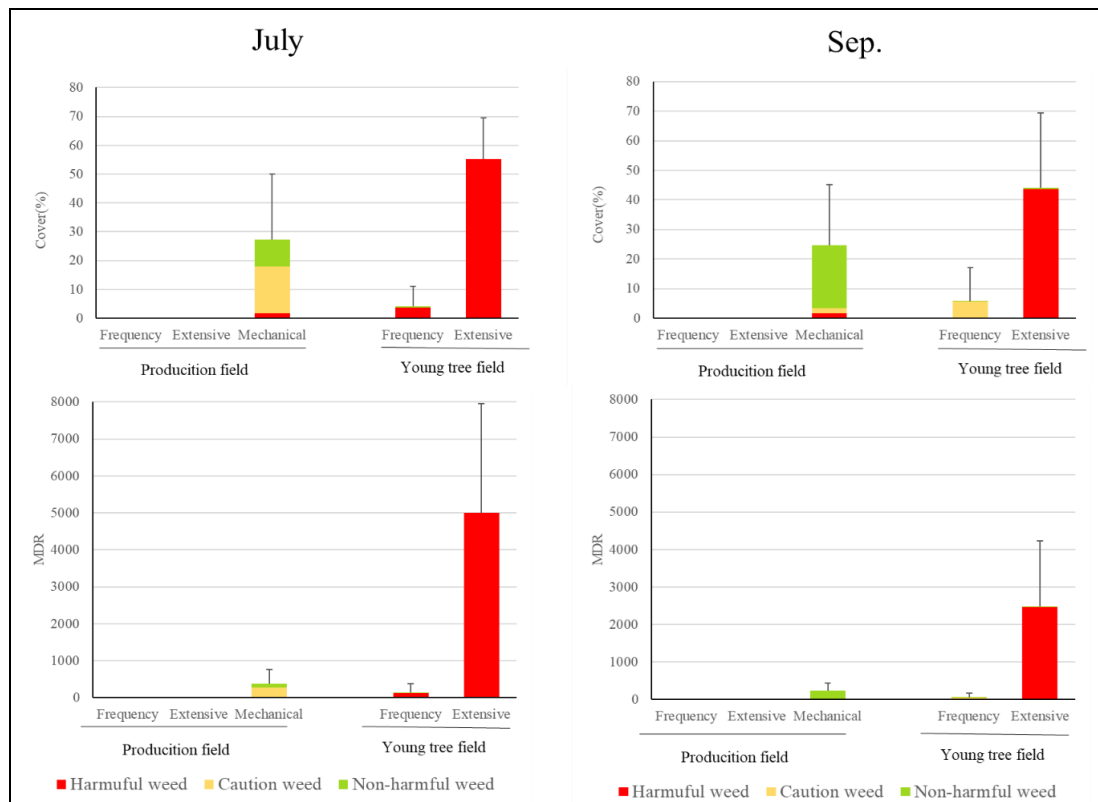
The average and percentage of collected organisms were analysed, and graphs were produced using Microsoft Excel

2016. The data obtained in this study were analysed using the Bell Curve for Excel 5.0 (Social Survey Research Information Co., Ltd.). After performing an analysis of variance, Tukey’s multiple range test was conducted to detect significant differences among the treatments with a confidence interval of 95% ( $\alpha = 0.05$ ).

**Results**

**Weed cover in different weeding management methods**

A total of 11 weed species were observed in July including *Digitaria ciliaris*, *Miscanthus sinensis*, *Crassocephalum crepidioides*, *Pteridium aquilinum* as harmful weeds, *Oxalis corniculata*, *Stellaria neglecta*, *Commelina communis* as caution weeds, and *Oplismenus hirtellus*, *Galinsoga quadriradiata*, *Persicaria longiseta*, and *Equisetum arvense* as non-harmful weeds. Fig 1 presents the weed cover and quantity (MDR) of the different weed management systems in July. No weeds were found in production fields with frequent and extensive weed management. On the other hand, mechanically managed tea-producing fields included *C. communis* and *S. neglecta*, and non-harmful weeds such as *E. arvense*. The frequency weed management methods used in young tea gardens demonstrated a 4% coverage of *D. ciliaris*. The young tea fields where extensive weed management method was used were covered with the noxious *C. crepidioides* and *M. sinensis*.



**Fig 1:** Weed cover and quantity (MDR) in different weed management systems on July (left) and September (right). Error bar indicates standard deviation.

A total of 15 weed species were observed in September including *D. ciliaris*, *M. sinensis*, *Panicum dichotomiflorum*, *Bidens pilosa*, *C. crepidioides*, *Rubus hirsutus*, *P. aquilinum* as harmful weeds, *O. corniculata*, *S. neglecta*, *C. communis* as caution weeds, and *O. hirtellus*, *G. quadriradiata*, *P. longiseta*, *Centella asiatica*, *E. arvense* as non-harmful weeds. Fig 2 presents the weed cover and quantity (MDR) under different weed management systems in September.

No weeds were found in the production fields with frequent and extensive weed management in September and July. In the mechanically managed tea-producing fields, non-harmful weeds such as *O. hirtellus*, *E. arvense*, *C. asiatica*, and *P. longiseta*. There are a few harmful weeds in the mechanically managed tea-producing fields. The most frequently used weed management method in young tea gardens presented *S. neglecta*, which is a cautionary weed.

The young tea field, where extensive weed management methods were used, was covered with harmful weeds such as *B. pilosa* and *M. sinensis*.

### Population of ground-dwelling organisms depending on their food habit in different weeding management

Fig 2 presents the number of individuals and population percentages of organisms depending on feeding habits in different weeding management systems. Although crickets are omnivorous, they are included in the herbivorous category because they are important seed predators in Japan (Ichihara *et al.*, 2011) [16]. In this study, we identified spiders and ground beetles as carnivores which are natural enemies; crickets which are seed predators as herbivores; pill bugs, millipedes, and earwigs as omnivores; and earthworms as detritivores. Some are shown in Fig 3. In this survey, ants, including seed predators, were captured. However, because ants were abundant, they were excluded from the analysis.

In July, the number of organisms was higher in the mechanically managed field than in the frequently and extensively managed fields. Mechanically managed fields are characterised by a high proportion of carnivorous organisms. In contrast, the population of herbivores was higher in extensively managed fields, and the population of omnivores was higher in frequency-managed fields. In July, the number of organisms was higher in the frequently managed fields than in the extensively managed fields. The frequently managed fields with young trees were characterised by a high proportion of carnivorous and omnivorous organisms.

The number of organisms was higher in the frequently and extensively managed fields in the production field in September. The frequency-managed field was characterised by a high proportion of carnivorous and omnivorous organisms, similar to the results in June. In the young tree field in September, there was little difference in the number of individuals and populations between the frequently and extensively managed fields.

### Status of functional group in different weeding methods

Fig 4 presents the number of ground-dwelling spiders found in each field for each observation using the three weeding methods. In July, a higher number of spiders was observed in the mechanically managed tea field than in the other weeding methods in the production fields. However, this decreased drastically in September. In contrast, the number of spiders slightly increased during frequency weeding from July to September. In the case of young trees, both frequency and extensive trees presented a larger number in September than in July, and the number was higher in frequency than in extensive trees (Fig 4).

Fig 5 shows the number of carnivorous beetles found in each field for each observation using the three weeding methods. In the production field, the number of beetles remained almost the same in the three weeding methods; however, the frequency of weeding showed a statistically large number of beetles in July in the young tree field, which drastically decreased in September (Fig 5).

Fig 6 shows the number of crickets which are weed seed predators, found in each field during each observation using the three different weeding methods. It was characterized by being more abundant than spiders, beetles and chafers, regardless of the differences in weed management practices. In the production field in September, the number of crickets

tended to be slightly higher in frequency with extensive weed management, while the number of crickets was higher than that in the extensive weed management field in the young tree field in September.

### Discussion

To date, Japanese research on weeds in tea fields has been limited to compiling lists of weeds in tea fields (Obata, 1973) [35] and examining weed management in tea field areas (Ichihara *et al.*, 2022a) [18]. However, weed management in tea fields has become increasingly important in recent years with the recent expansion of organic farming in Japan (Ichihara 2022b [19]; Inagaki and Iwase 2024) [21]. According to Inagaki and Iwase (2024) [21], because various weeds in tea fields do not have any adverse effects, it is important to distinguish between seriously harmful and non-harmful weeds and evaluate them accordingly. The authors classified the weed management of tea fields into three groups—frequency weeding, extensive weeding, and mechanical weeding. They reported that using a mowing machine for controlling weeds in the tea garden is a successful weeding method for organic tea production and short weed growth, such as cover crops. Their report is based on data from spring, which is the first tea harvest season when weed contamination of tea leaves becomes an issue. In contrast, our data indicate that even in summer, the untreated areas are overgrown with the growth of large harmful weeds *C. crepidioides*, *M. sinensis*, and *P. aquilinum* in extensive weeding fields, whereas short non-harmful weeds *C. communis*, *E. arvense*, *S. neglecta* were observed in tea gardens with mechanical weeding (Fig 1).

Research on the biota of tea plantations has been conducted primarily on pests that damage tea leaves (Dhanapati and Varatharajan, 2016 [8]; Hazarika, 2001 [11], 2009 [12]; Kawai, 1997) [23]. In recent years, functional biodiversity has been catching attention for utilising ecosystem services (Altieri, 1999 [1]; Bärberi, 2015 [3]; Duru *et al.*, 2015 [9]; Moonen and Bärberi, 2008 [30]; Rouphael, 2008) [39]. However, research on the biodiversity of tea plantations has primarily focused on arboreal spiders and flying parasitic wasps (Chen *et al.*, 2021 [6], Das *et al.* 2010 [7], Muraleedharan *et al.* 1988 [31]; Prasad *et al.*, 2020 [38]; Uesugi *et al.*, 2016 [46]; Yara *et al.*, 2019) [49], and there has been little research on ground-dwelling organisms. In contrast, the present study focused on ground-dwelling organisms, including beneficial pests and weed seed predators. Because ground-dwelling organisms have limited mobility, it is suggested that their habitat depends on the vegetation in the tea field. Cover crops and weed vegetation have been reported to increase the number of ground-dwelling organisms in orchards other than tea fields (Celette *et al.*, 2008) [5]. In contrast, few studies have investigated crops that enhance the diversity of ground-dwelling organisms in tea fields. Therefore, in this study, we hypothesised that weed vegetation in tea plantations maintains populations of ground-dwelling organisms.

The number of organisms was higher in the mechanically managed field in the production field in July, and the population of carnivorous organisms was higher (Fig 2). This was primarily because of the large spider population (Fig 4). Carnivorous wolf spiders are commonly found on agricultural farmlands in Japan and are among the most important natural enemies of agricultural ecosystems (Ministry of Agriculture, Forestry and Fisheries, Japan, 2012) [29]. Because wolf spiders are generalists that feed on

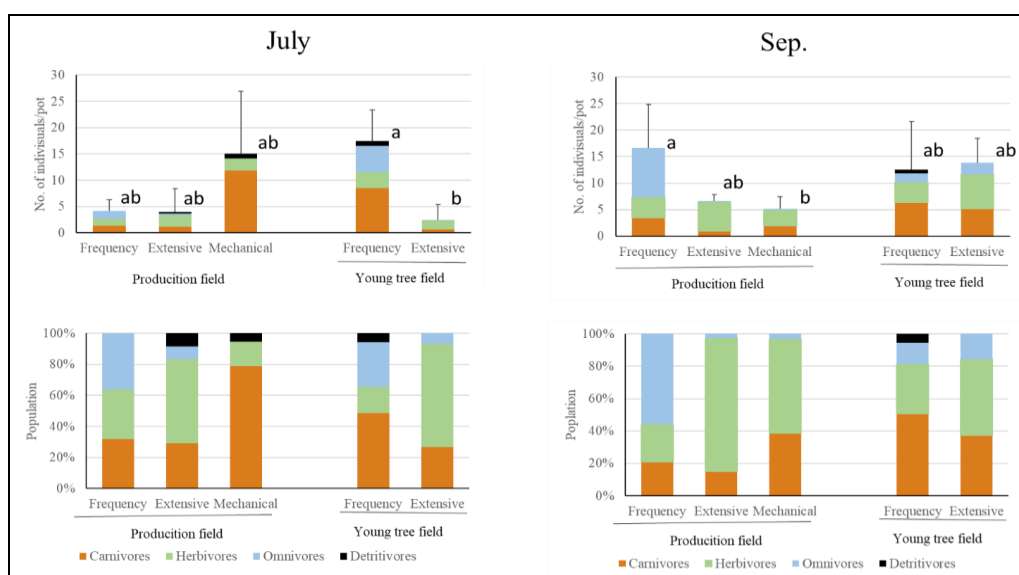
various pests (Kiritani and Kakiya, 1975 [24]; Suenaga and Hamamura, 2015 [43]; Takada *et al.*, 2012) [44], they are considered extremely important natural enemies of tea plantations. In this study, we found that the number of spiders was higher during mechanical weeding in July. This suggests that the maintenance of weed vegetation through mechanical weeding may have sustained the wolf spider population during spring and early summer. Inagaki and Saruta (2021) indicated that traditional rice straw mulch in tea fields did not affect wolf spiders. Overall, living mulch with non-harmful weed cover could be effective in maintaining wolf spider populations.

However, despite the amount of vegetation, the population of ground-dwelling carnivorous beetles did not significantly change in fields with different weed management practices. In contrast, the number of carnivorous beetles in July was higher in the field with frequent weeding, where the number of weeds was low. Chen *et al.* (2021) [6] pointed out that intercropping with *Chamaecrista rotundifolia* significantly increased the arboreal Coleoptera diversity. Our results suggest that maintaining cover crops using different weed management strategies may not affect ground-dwelling carnivorous beetles.

Although research on functional biodiversity has primarily focused on predators of pest insects, it has been shown in recent years that herbivorous ground-dwelling arthropods eat weed seeds (Pausch, 1979 [36]; Holland, 2002) [13] and play a significant role in the agroecosystem of weed seed predators (Ichiara *et al.*, 2015) [17]. Weed-seed predators are not listed as indicator species for the functional biodiversity in Japan because there are very few reports on the function of herbivorous arthropods (Ministry of Agriculture, Forestry and Fisheries *et al.*, 2012) [29]. However, in recent years, crickets have been reported to be the major weed seed predators in Japanese agricultural lands (Ichiara *et al.*, 2015; Ichiara *et al.*, 2014a [14]; Ichiara *et al.*, 2014b; Ichiara *et al.*, 2011; Ichiara *et al.*, 2012) [15]. In this study, the number of crickets tended to be slightly higher during frequent weeding and extensive weeding in September, when the number of weeds was low. It is well known that crickets prefer dark places. Although the mechanical

weeding fields have wider ridges to accommodate machinery, these two fields have narrower ridges to suppress weeds. Dark tea fields may, therefore, be a good environment for crickets. In addition, the cricket population was higher in young tree fields with extensive weeding. This may be because weeds grow larger and the ground becomes darker. Harpalinae species (ground beetles) feed on major weed seeds on agricultural lands, including tea gardens (Yahiro *et al.*, 1992 [47]; Kagawa *et al.*, 2008 [22]; Yamazaki *et al.*, 2003 [48] Lee *et al.*, 2008) [26]. However, herbivorous ground beetles were not observed.

Maintaining weed cover is considered to manage the biodiversity of agroecosystems and regulate ecosystem services by increasing the number of beneficial arthropods involved in biological control (Norris and Kogan, 2000 [34]; Norris and Kogan, 2005 [33]; Gurr *et al.*, 2016; Gurr *et al.*, 2017; Amoabeng *et al.*, 2020 [2]; Kleiman *et al.*, 2020; Shields *et al.*, 2019 [42]; Iddris *et al.*, 2023) [20]. In this study, short weed communities maintained by mechanical management demonstrated increased populations of an important natural enemy, the wolf spider. Inagaki and Iwase (2024) [21] pointed out that, mechanical management is effective in suppressing harmful weeds by allowing short weeds to dominate from the perspective of weed management. This study also revealed that mechanical management was effective in protecting useful spiders. However, the weed communities formed by mechanical weeding did not affect the numbers of carnivorous beetles and crickets. Therefore, we should consider using cover crops or insectary plants that attract beneficial arthropods, rather than relying on native weed communities, to maintain carnivorous beetles and crickets. There are various possible ways to increase the number of ground-dwelling carnivorous beetles and weed seed predator crickets in tea gardens. For crickets, live mulching with weeds, crop rotation, and soil cover to reduce weed seed germination are worth investigating. For carnivorous beetles, maintaining the beetle habitat would help increase the carnivorous beetle population. Maintaining weed cover and beneficial ground-dwelling organisms in tea fields can ensure sustainable agricultural ecosystems.



**Fig 2:** The number of individuals and population percentage of organisms depending on the feeding habit in different weeding management in July (left) and September (right). However, because ants are abundant, they are excluded from the graph. Carnivores, herbivores, omnivores and detritivores are illustrated by the colours orange, light green, light blue, and black respectively in the graph. Error bar indicates standard deviation. Different letters indicate significant differences at  $p < 0.05$  (Tukey's multiple range test).



Fig 3: Ground-dwelling organisms found in different tea fields

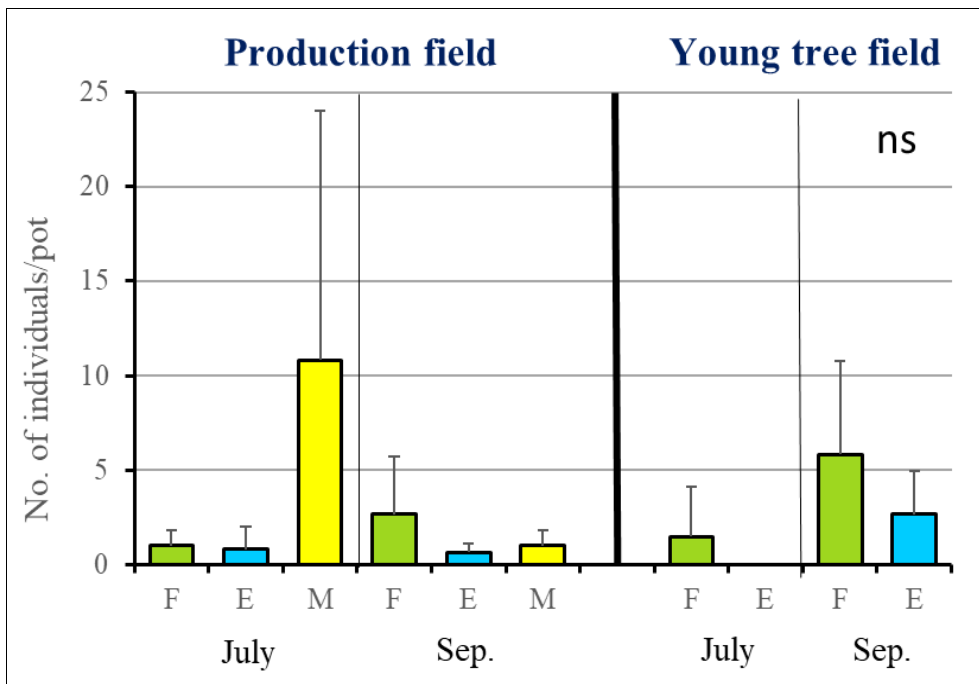
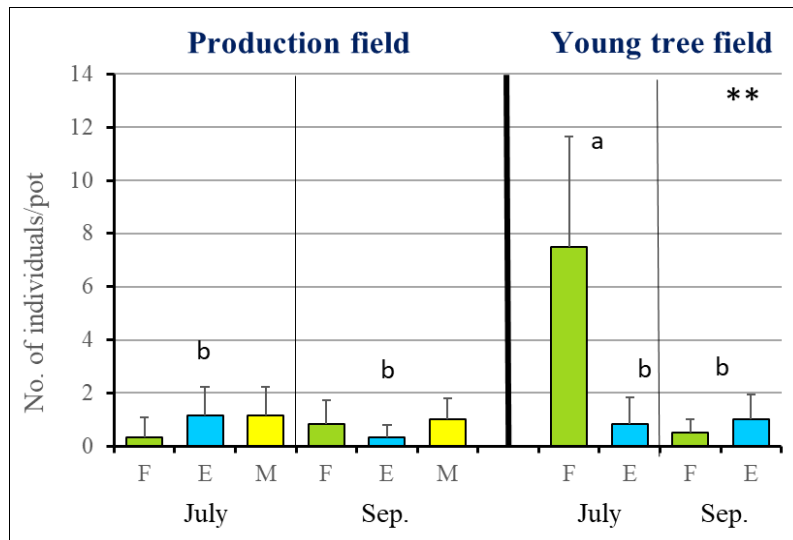
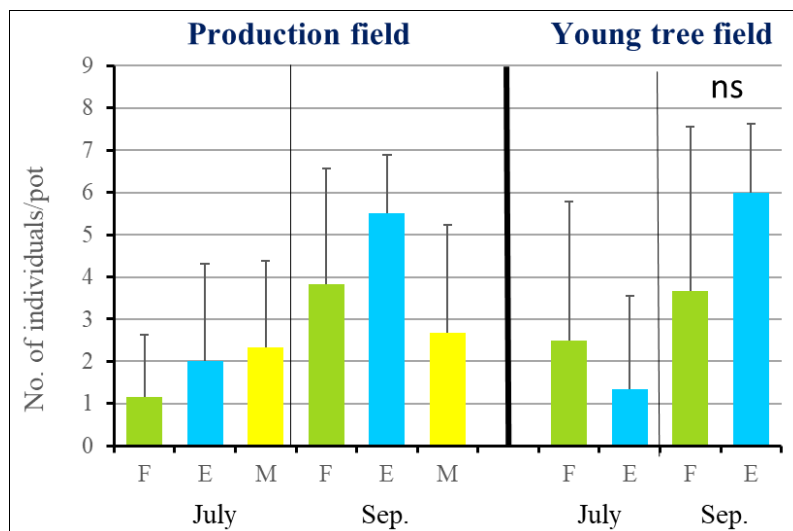


Fig 4: The number of spiders found in each field in each observation of three different weeding methods. F: Frequency management (Green), E: Extensive (Blue), and M: Mechanical management (Yellow). Error bar indicates standard deviation. ns indicates no significant difference according to the analysis of variance (ANOVA) at a confidence level of 5%. Different letters indicate significantly different at  $p < 0.05$  (Tukey's multiple range test)



**Fig 5:** The number of carnivorous beetles found in each field in each observation of three different weeding methods. F: Frequency management (Green), E: Extensive (Blue), and M: Mechanical management (Yellow). Error bar indicates standard deviation. \*\* indicates a significant difference according to the ANOVA at a confidence level of 1%. Different letters indicate significant differences at  $p < 0.05$  (Tukey’s multiple range test)



**Fig 6:** The number of crickets found in each field in each observation of three different weeding methods. F: Frequency management (Green), E: Extensive (Blue), and M: Mechanical management (Yellow). Error bar indicates standard deviation. ns indicates no significant difference according to the ANOVA at a confidence level of 5%. Different letters indicate significant differences at  $p < 0.05$  (Tukey’s multiple range test)

**Conclusion**

According to the present study, the number of spiders which are functional ground-dwelling arthropods that act as natural enemies, increased in tea gardens where mechanical weeding methods were used. This suggests that the type of undergrowth vegetation plays a vital role in enhancing functional biodiversity. However, weedy vegetation carries the risk of harmful weeds spreading. Finding an alternative method for increasing the number of functional groups is, therefore, essential. In addition, the extent to which natural enemies, such as spiders, suppress pests in tea gardens should be considered. Further research on the food types and predators of these arthropods is vital.

**Reference**

1. Altieri MA. The ecological role of biodiversity in agroecosystems. In: Paoletti GM, editor. *Invertebrate biodiversity as bioindicators of sustainable landscapes*. Elsevier, 1999, 19–31.

2. Amoabeng BW, Stevenson PC, Mochiah BM, Asare KP, Gurr GM. Scope for non-crop plants to promote conservation biological control of crop pests and serve as sources of botanical insecticides. *Scientific Reports*,2020:10.
3. Bàrberi P. Functional biodiversity in organic systems: the way forward? *Sustainable Agriculture Research*,2015:4(3):26–31. <https://doi.org/10.5539/sar.v4n3p26>
4. Beveridge LE, Naylor REL. Options for organic weed control—what farmers do. *Proceedings of the 1999 Brighton Conference-Weeds*, Brighton, UK,1999. p. 939–44.
5. Celette F, Gaudin R, Gary C. Spatial and temporal changes to the water regime of a Mediterranean vineyard due to the adoption of cover cropping. *European Journal of Agronomy*,2008:29:153–62.

6. Chen LL, Pozsgai G, Li XY, Li L, Reddy GV, You MS. Effects of cover crops on beetle assemblages in tea plantations. *Crop Protection*,2021:149:105783.
7. Das S, Roy S, Mukhopadhyay A. Diversity of arthropod natural enemies in the tea plantations of North Bengal with emphasis on their association with tea pests. *Current Science*,2010:99(10):1457–63.
8. Dhanapati K, Varatharajan R. Diversity and density of tea pests in the tea gardens of Manipur, NE India. *Journal of Plantation Crops*,2016:44(1):47–51.
9. Duru M, Therond O, Martin G, *et al.* How to implement biodiversity-based agriculture to enhance ecosystem services: A review. *Agronomy for Sustainable Development*,2015:35(4):1259–81.
10. Food and Agriculture Organization (FAO). Progress of the technical requirements for organic tea production. Report of the Working Group on Organic Tea, Intergovernmental Group on Tea, Intersessional Meeting, Rome, Italy,2014 May 5–6.
11. Hazarika LK, Puzari KC, Wahab S. Biological control of tea pests. In: Upadhyay RK, Mukerji KG, Chamola BP, editors. Biocontrol potential and its exploitation in sustainable agriculture. Springer, 2001.
12. Hazarika LK, Bhuyan M, Hazarika BN. Insect pests of tea and their management. *Annual Review of Entomology*,2009:54:267–84.  
<https://doi.org/10.1146/annurev.ento.53.103106.093359>
13. Holland JM. *The agroecology of carabid beetles*. Intercept Limited, 2002.
14. Ichihara M, Inagaki H, Matsuno K, *et al.* Postdispersal weed seed predation by crickets in a rice paddy field after irrigation water recedes. *Japan Agricultural Research Quarterly*,2014:48:63–9.
15. Ichihara M, Inagaki H, Matsuno K, *et al.* Postdispersal seed predation by *Teleogryllus emma* (Orthoptera: Gryllidae) reduces the seedling emergence of a non-native grass weed, *Lolium multiflorum* Lam. *Weed Biology and Management*,2012:12:131–5.
16. Ichihara M, Maruyama K, Yamashita M, *et al.* Quantifying the ecosystem service of non-native weed seed predation provided by invertebrates and vertebrates in upland wheat fields converted from paddy fields. *Agriculture, Ecosystems and Environment*,2011:140:191–8.
17. Ichihara M, Matsuno K, Inagaki H, *et al.* Creation of paddy levees to enhance the ecosystem service of weed seed predation by crickets. *Landscape and Ecological Engineering*,2015:11:227–33.
18. Ichihara M, Suzuki M, Haga H. Weed vegetation in tea field margins during spring in Shizuoka Prefecture, Japan. *Journal of Weed Science Technology*,2022a:67:21–4.
19. Ichihara M, Uchiyama M, Murakami G, *et al.* Weed vegetation in organic and conventional tea fields in Shizuoka Prefecture, Japan. *Journal of Weed Science Technology*,2022b:67:25–30.
20. Iddris NA-A, Formaglio G, Paul C, *et al.* Mechanical weeding enhances ecosystem multifunctionality and profit in industrial oil palm. *Nature Sustainability*,2023:6:683–95.
21. Inagaki H, Iwase Y. Effect of different weeding methods in organic tea gardens on weed vegetation. *Japanese Journal of Organic Agriculture Science*,2024:16:58–68.
22. Kagawa Y, Ito N, Maeto K. Species composition of ground beetles (Coleoptera: Carabidae and Brachinidae) in an agricultural landscape consisting of a mosaic of vegetation types. *Japanese Journal of Entomology (New Series)*,2008:11:75–84.
23. Kawai A. Prospect for integrated pest management in tea cultivation in Japan. *JARQ*,1997:31:213–7.
24. Kiritani K, Kakiya N. An analysis of the predator–prey system in the paddy field. *Researches on Population Ecology*,1975:17:29–38.
25. Kleiman B, Koptur S. Weeds enhance insect diversity and abundance and may improve soil conditions in mango cultivation of South Florida. *Insects*,2023:14(1):65.
26. Lee C, Nagai Y, Hirowatari T, Ishitani M, Ishii M. Change in structure of ground-beetle assemblage on levee of paddy field after the paddy reclamation in southern Osaka, Central Japan. *The Nature and Insects*,2008:43:6–10.
27. Lin ML. Technical development of production and products in organic tea farming. *International Journal of Tea Science*,2016:12(01):74–83.
28. Ministry of Agriculture, Forestry and Fisheries. Basic policy for promoting the tea industry and tea culture. Current situation and issues,2020. Available from: <https://www.maff.go.jp/j/seisan/tokusan/cha/attach/pdf/kihonhou-18.pdf>. Accessed 2024 Aug 8.
29. Ministry of Agriculture, Forestry and Fisheries, National Institute for Agro-Environmental Sciences, & National Institute of Agrobiological Sciences. Indicator animals of functional agrobiodiversity: A survey and evaluation manual, 2012. Available from: <http://www.niaes.affrc.go.jp/techdoc/shihyo/>. Accessed 2024 Aug 8.
30. Moonen A, Bàrberi P. Functional biodiversity: An agroecosystem approach. *Agriculture, Ecosystems and Environment*,2008:127(1–2):7–21.
31. Muraleedharan N, Selvasundaram R, Radhakrishnan B. Natural enemies of certain tea pests occurring in southern India. *International Journal of Tropical Insect Science*,1988:9:647–54.
32. Nikhil GH. Organic tea: Global market and forecast sales. *Journal of Tea Science Research*,2017:7:58–68.
33. Norris RF, Kogan M. Interactions between weeds, arthropod pests, and their natural enemies in managed ecosystems. *Weed Science*,2000:48(1):94–158.
34. Norris RF, Kogan M. Ecology of interactions between weeds and arthropods. *Annual Review of Entomology*,2005:50:479–503.
35. Obata K. Present status and some problems of weed control in tea field. *Weed Research Japan*,1973:32:1–6.
36. Pausch RD. Observations on the biology of the seed corn beetles, *Stenolophus comma* and *Stenolophus lecontei*. *Annals of the Entomological Society of America*,1979:72(1):24–8.
37. Pokharel SS, Yu H, Fang W, Parajulee MN, Chen F. Intercropping cover crops for a vital ecosystem service: A review of the biocontrol of insect pests in tea agroecosystems. *Plants*,2023:12(12):2361.
38. Prasad AK, Roy S, Sen S, Neave S, Nagpal A, Pandit V. Impact of different pest management practices on natural enemy population in tea plantations of Assam: Special emphasis on spider fauna. *International Journal of Tropical Insect Science*,2020:40:629–35.

39. Rouphael S, Moonen AC, Bàrberi P, Petacchi R, Boccaccio L. Landscape management for functional biodiversity expression of on-farm functional biodiversity as affected by management and multi-scale agroecosystem disturbance,2008:34:85–8.
40. Rotchés-Ribalta R, Marull J, Pino J. Organic farming increases functional diversity and ecosystem service provision of spontaneous vegetation in Mediterranean vineyards. *Ecological Indicators*,2023:147:110023.
41. Shelton MD, Edwards CR. Effects of weeds on the diversity and abundance of insects in soybeans. *Environmental Entomology*,1982:12(2):296–8.
42. Shields MW, Johnson AC, Pandey S, Cullen R, González-Chang M, Wratten SD, Gurr GM. History, current situation and challenges for conservation biological control. *Biological Control*,2019:131:25–35.
43. Suenaga H, Hamamura T. Effects of manipulated density of the wolf spider, *Pardosa astrigera* (Araneae: Lycosidae), on pest populations and cabbage yield: A field enclosure experiment. *Applied Entomology and Zoology*,2015:50(1):89–97.
44. Takada MB, Yoshioka A, Takagi S, Iwabuchi S, Washitani I. Multiple spatial scale factors affecting mirid bug abundance and damage level in organic rice paddies. *Biological Control*,2012:60:169–74.
45. Talukdar D. Biodiversity and conservation of arthropod natural enemies in tea plantations of India: An appraisal,2021.
46. Uesugi R, Yara K, Sato Y. Changes in population density of *Aleurocanthus camelliae* (Hemiptera: Aleyrodidae) and parasitism rate of *Encarsia smithi* (Hymenoptera: Aphelinidae) during the early invasion stages. *Applied Entomology and Zoology*,2016:51:581–8.
47. Yahiro K, Fujimoto T, Tokuda M, Yano K. Species composition and seasonal abundance of ground beetles (*Coleoptera*) in paddy fields. *Japanese Journal of Entomology*,1992:60:805–13.
48. Yamazaki K, Sugiura S, Kawamura K. Ground beetles (*Coleoptera: Carabidae*) and other insect predators overwintering in arable and fallow fields in central Japan. *Applied Entomology and Zoology*,2003:38:449–59.
49. Yara K, Uesugi R, Shimoda T, Sato Y. Distribution and population structure of two phylogroups of the parasitoid *Encarsia smithi* (Hymenoptera: Aphelinidae) in tea fields infested with the invasive camellia spiny whitefly *Aleurocanthus camelliae* (Hemiptera: Aleyrodidae) in Shizuoka Prefecture, Japan. *Applied Entomology and Zoology*,2019:54:55–62.
50. Yoshitaka M, Kohsaka R. Discourse of quality and place in geographical indications: Applying convention theory to Japanese tea. *Food Reviews International*,2022:39:4610–35.